Evolution and Life on Earth

Evolution is the core theme of biology.

Blooms on a *Banksia*.
These flower buds are arranged in pairs and orderly rows on a *Banksia* shrub, native to Australia. Centuries ago, patterns like these inspired naturalists to seek explanations about their origin. We now know that evolutionary processes are the fundamental driving force underlying life's patterns.

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Topics Covered in this Module
- Life on Earth
- Evolution: The Core Theme in Biology

Major Objectives of this Module
- Identify evolution as the core theme and unifying concept in biology.
- Distinguish between the biological and common meanings of the word "evolution."
- Explain how evolution has led to both the unity and diversity of life forms.
- Explain biological classification in terms of evolutionary history.
Life on Earth

The cuttlefish is remarkably sensitive to the colors of its background and can respond by changing its body color to match them (Figure 1). How does this organism adjust to its background in such specific ways? How do scientists explain why a certain fungus lives only on the wings of a certain species of beetle that lives only in certain limestone caves in southern France? The answer to these questions is, simply, evolution. Biological evolution explains the enormous diversity of life, and it also explains its unity. How can one process explain both the unity and the diversity of something as complex as biological life?

Figure 1: A cuttlefish, Sepia sp., which is a member of the class Cephalopoda.

This cuttlefish senses its surroundings through its W-shaped eye. The eye sends information to the brain, which quickly relays messages to small elastic sacs near the skin's surface that contain pigments of different color. By contracting and relaxing muscles attached to these sacs, the cuttlefish can rapidly change its colors in very fine detail. In this case, the cuttlefish displays tan and brown stripes that provide contrast that would resemble the sandy seafloor to a would-be predator.

D.P. Wilson/FLPA/Science Source.

It is easy to understand the concept of diversity. On any given day, a person will interact with up to 10,000 or more species, either directly or indirectly. For example, almost all of what you eat and drink comes directly from other organisms, such as the chicken that laid your breakfast eggs, the rice you had for lunch, and the corn that provides the sweetness for your soda; other species you interact with include your pet cat or dog and the birds outside your window; the tree you take a nap under and the grass you nap upon; and dozens of other easily recognizable species. However, most of the species that you interact with are microscopic bacteria and other microscopic organisms that live on and within the human body (collectively known as microbes). Although we are just beginning to understand their interrelationships, most of these microbes are probably harmless, and many are simply along for the ride, although some are quite beneficial; for
example, many species of bacteria in your gut are necessary for you to extract sufficient nutrients from your food. Other microbes can be quite harmful; some of the most debilitating diseases of humans are caused by bacteria. These species that you interact with each day are diverse; in other words, they bear little resemblance to each other. But what does the "unity" of life mean? How does a tree resemble a dog or a chicken resemble a bacterium?

Every living thing shares certain characteristics. For example, every organism is composed of one or more cells (Figure 2). Every organism requires energy, conducts metabolism, grows, responds to stimuli, and reproduces. All living cells contain DNA, cell membranes, and ribosomes, which will be examined later. For now, consider DNA, the molecule that contains the universal code of life.

DNA is enclosed in a nucleus in eukaryotes but not in prokaryotes. The nucleus itself is a membrane-enclosed sub-compartment of the cell. The DNA in every cell is made of the same building blocks (called nucleotides), has the same general structure (a double helix) and codes for thousands of proteins that are necessary for life's functions. Remarkably, the structure and function of DNA are quite similar across living things; moreover, all life has DNA, so it is a defining characteristic of life.

![Figure 2: Cells, the basic units of life.](image)

All cells have cell membranes, ribosomes and DNA. The DNA is packaged differently in eukaryotic and prokaryotic cells, but it has the same basic structure and function. Note that the cells are not to scale (most prokaryotic cells are much smaller than eukaryotic cells), and not all structures are labeled.

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What does DNA have to do with evolution? In every organism, DNA provides the blueprint for life. DNA is relatively stable inside individual cells. However, the sequence of the DNA molecule can become changed by mistakes in DNA replication (the process by which DNA copies itself) or by the effects of some environmental agents such as ultraviolet light; these changes are called mutations. While mutations change the sequence of nucleotides within the DNA, evolution can also act upon changes to combinations of DNA sequences that occur during meiosis and reproductive recombination. These processes combine to provide the genetic variation among individuals upon which evolution operates.

**Biological evolution** refers to changes in DNA sequences (usually genes and the traits they encode but also changes in regulatory sequences and pseudogenes) over time. There are many processes that lead to evolutionary changes, the most well known of which is natural selection. **Natural selection** occurs when the likelihood of individuals with certain traits
surviving and reproducing is higher than those with other traits, and the genes that encode for those traits are passed on from parent to offspring. For example, some individuals in a population of frogs might have a DNA sequence that codes for more cell growth in the limbs, giving these frogs slightly longer legs, while other individuals have DNA that codes for shorter legs. If a predatory snake slithers into the population of frogs, the longer-legged individuals might have a better chance of hopping out of the snake’s reach than the shorter-legged ones, allowing the longer-legged individuals to survive, reproduce, and pass on their DNA and the long-legged trait. However, if the longer-legged frogs’ genes for long legs become mutated in the gametes or lost due to recombination, their offspring will not have the trait, and the population as a whole will not have incrementally evolved as a result of natural selection.

Random processes can also determine which individuals survive to reproduce and pass on their DNA; evolution through this kind of random process is known as genetic drift. For example, a tree might fall in a forest after very high winds, crushing hundreds of seedlings below. The particular DNA sequence of those seedlings had nothing to do with whether they were crushed by the tree; the death of the seedlings was purely random. Likewise, a random seedling may benefit from this event. An individual seedling that happens to be in the right place and time — that is, near the falling tree but lucky enough to escape being crushed — will have a good chance of replacing the dead tree by growing towards the forest opening, and it will have a good chance of reproducing when it grows large enough. Its particular DNA sequence will then be passed on to the next generation, while the specific DNA sequences of the hundreds of less lucky individuals disappear.

Note that the word evolution in biology has a different meaning from the word evolution in ordinary language. When we talk about galaxies’ evolving or social relationships evolving, we mean simply that individual galaxies or social relationships change over time. In biology, evolution has the added dimension of heritability. Individual organisms are not capable of biological evolution; instead, it is a population of organisms that evolves over time.

Test Yourself

What do astronomers mean when they say galaxies evolve? How is this different from the biological meaning of the word evolution?

Ancient people began to classify life.

Although a formal definition of biological evolution based on DNA was not available until our relatively recent past, humans have long pondered the concepts of evolution and the origins of diversity. Some of the earliest evidence of conceptual thought about diversity dates to 30,000-year-old cave paintings in France, which show a variety of clearly distinct mammals (Figure 3).
Recognizing that diversity exists is the first step in classification, the task of sorting things into categories. The scientific practice of classification of the diversity of biological species is called taxonomy (from Greek taxis, meaning "arrangement," and nomia, meaning "method").

In many ancient cultures, philosophers classified animals and plants. Based on his observations of nature, the Greek philosopher Aristotle (384–322 BCE) developed a "Ladder of Life" (later given the Latin name Scala Naturae), in which he placed animals according to their function and complexity (Figure 4). Humans were at the top (apex) of the most complex animals.
Aristotle further proposed that all forms of nature were fixed. He assumed that a species — which he defined as a group of organisms that looked and behaved alike — could never change. This Doctrine of Fixed Species was very influential. Rediscovered during the Middle Ages, it remained the fundamental and unifying core of biology in the Western world for centuries. Aristotle is also credited with introducing the concept of a binomial nomenclature, which is a formal system of naming organisms according to two categories.

In the 1700s, the Swedish taxonomist Carl Linnaeus (1701–1778) developed a new system that classified organisms into nested hierarchies based on their similar gross morphological characteristics, including their external shape, structure, color, pattern, and internal features, such as bones and organs. Linnaeus's hierarchical classification and consistent use of binomial nomenclature remain in use today.

Linnaeus sought a unified name for each organism that could be used in any language. He chose Latin because it was a written language used across Europe. In Linnaeus' binomial nomenclature, the first category describes the organism's genus, and the second describes its species. Linnaeus further classified genera into orders, orders into classes and classes into kingdoms.
To further differentiate and classify organisms, biologists later added families (between orders and genera), phyla (between kingdoms and classes), and domains (the broadest categorization) (Figure 5). Linnaeus published the final edition of his classification system (*Systema Naturae*) in 1758.
Figure 5: The hierarchy of biological classification applied to humans.

Biological classification is a hierarchy in which smaller groups are nested into larger ones (species to genera, genera to families, families to orders, and so on). Species are named using both their genus and species names (both italicized). The first letter of the genus name is capitalized, while the first letter of the species name is not capitalized; in the case of humans, the species name is *Homo sapiens*. The genus to which humans belong, *Homo*, contains species that are now extinct but that have been described by fossils, such as *Homo neanderthalensis* (upper left) (though this is sometimes classified as a "subspecies" of modern humans, and *Homo sapiens* and *Homo neanderthalensis* likely interbred), *Homo habilis* (lower left) and *Homo erectus* (upper right). Classifications above the genus level are always capitalized but not italicized. In the largest grouping (the Eukarya domain), humans are grouped with all other animals, plants, fungi and a large number of unicellular organisms.

Since Linnaeus, scientists have discovered many thousands of new animals, plants and microorganisms, each of which is still classified in much the same way as Linnaeus proposed. Linnaeus's classification system organizes species into groups based on their physical appearances. For example, there are many species of oak trees, all of which are classified into the genus *Quercus*, and there are many species of *Salmonella* bacteria, some of which cause human disease (including many cases of food poisoning and typhoid fever). Within these groups, most species have very similar outward appearances and other characteristics, suggesting they probably evolved from a common ancestor. However, more recently, insights from embryology, paleontology, biochemistry, and genomics have enabled scientists to better understand the relationships among these organisms. In some cases, research in these fields has led scientists to move organisms from one group to another when evidence suggested the outward appearances might not reflect their evolutionary relationships.

The theory of evolution is the cornerstone of the modern scientific understanding of life.

Although we usually consider Charles Darwin (1809–1882) to be the father of modern-day thought on evolutionary relationships, he was by no means the first person to consider evolutionary relationships. For example, ancient Greeks, Arabs, Chinese and Indians wrote about the changing nature of life on Earth. Charles Darwin's grandfather, Erasmus Darwin (1731–1802), suggested that all living organisms might share a common ancestor. Jean Baptiste Lamarck (1744–1829) suggested that species change over the long term, but he believed the traits an individual acquires during its lifetime would be passed on to its offspring, leading to long-term changes in the shapes and functions of species. Aspects of Lamarck's view enjoyed broad support, and were even incorporated into Darwin's ideas, until it slowly became replaced by more modern concepts of evolution and heritability of genes, not acquired traits, over many decades (interestingly, modern molecular methods have discovered some genetic processes that do in fact behave more like Lamarck's view, where changes during an individual's lifetime can be passed on to offspring). Darwin's views were built upon the works of many other scientists who had pieced together parts of the puzzle he was trying to solve, including population biologists, geologists and even animal and plant breeders.

Darwin's contribution to the understanding of evolution was not just that species changed through time, as many others had recognized, but also how evolution occurred — specifically, through the process of natural selection. By understanding how this process worked, Darwin quickly realized the implications of his findings not just for biological understanding but also for
religion and society. That natural processes could explain the diversity and complexity of life on the planet, including humans, was firmly at odds with the beliefs of most people. As a result, Darwin did not disclose his theory for many years after he initially came up with it, except to a few close friends and colleagues. In fact, it wasn't until another British naturalist, Alfred Russell Wallace (1823–1913), sent Darwin a manuscript largely expressing the same ideas of natural selection that Darwin was convinced to publish his own ideas. (Darwin was a noted scientist even before he presented his theory of evolution, and Wallace considered him somewhat of a mentor, although they had not yet met.) On the advice of their colleagues, Darwin and Wallace presented their papers together at the Linnaean Society meeting in 1858 so that they would receive joint credit for the idea. However, because Darwin had had years to think and write about his ideas, with hundreds of observations supporting his theory, he was able to produce his longer and more detailed treatise on the evolutionary process and publish it a year later as the first edition of *On the Origin of Species* (1859). (Its full title was actually *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*.) As a result, Darwin is usually associated with the theory and its implications, and Wallace's contribution is rarely acknowledged outside of scientific circles. Although Wallace's contribution is now largely a historical footnote in the development of the theory of evolution by natural selection, Wallace was one of Darwin's biggest defenders after the publication of Darwin's book and the controversy that emerged from it at the time. Although some aspects of Darwin's ideas remain controversial for segments of the public population, most leaders of the world's religions have recognized biological evolution as a scientific principle as true as gravity or relativity in physics while still maintaining their core beliefs.

Just how did Darwin and Wallace develop their ideas that led to their discovery of one of the most important principles of biological evolution? As a young man, Darwin became the naturalist on a nearly five-year survey voyage on the HMS *Beagle* (Figure 6). As they docked in several places, began to note the similarities and differences of species he found as fossils and those which were alive. Likewise, he compared the similarities and differences of plants and animals from different regions of the Earth. From these observations of what appeared to be gradual changes in species traits through time and space, his ideas began to coalesce into what would later become the core of his theory of evolution by natural selection. Although the entire voyage shaped Darwin's views, as well as many of his experiences and observations before and after the voyage, many scientific historians believe that Darwin's ideas became most focused during the *Beagle*'s month-long visit to the Galápagos Islands. Although the Galápagos Islands were similar to many other island chains Darwin visited, their isolation from the mainland of South America as well as the size of each island and their distance from one another make them ideal for observing the outcome of evolutionary processes. For his part in the development of the theory, Wallace spent much of his 20s living in South America, collecting animal and plant specimens in the extremely diverse Amazon basin. Then, during the early part of his 30s, Wallace continued his studies in Malaysia and Indonesia, another extremely diverse part of the planet, which we now call a "biodiversity hotspot." It was there that Wallace developed his parallel theory of evolution by natural selection (although he used different words to describe the process), with his most important insights coming during a period when he was feverish and bedridden with malaria.
Darwin's observations made while he was a naturalist on the HMS Beagle helped him to develop his theory of evolution by natural selection.

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The idea central to both Darwin and Wallace’s theory is that individuals in a population vary in their traits and that many of these traits are heritable. These traits will influence how well an organism survives over time and to what extent it reproduces. Importantly, both Darwin and Wallace credited a book by Thomas Malthus entitled *An Essay on the Principle of Population*, which was first published in 1798, as critical to their ideas. Malthus’s book expressed the idea that populations cannot grow forever because they eventually reach a limit determined by the amount of resources available. Influenced by this idea, Darwin and Wallace realized that during the “struggle for existence,” organisms that were able to survive and reproduce slightly better would make up a larger proportion of the population, using a larger proportion of the available resources. For example, an individual animal might be slightly better at finding food than another in its population or slightly better at avoiding becoming food for a predator. Likewise, an individual plant might have slightly deeper roots, allowing it to access more nutrients and water than another in its population, or an individual pathogenic bacterium might be slightly less likely to be attacked by its host’s immune system than another in its population. In each of these cases, traits that allow an individual to have higher relative fitness — determined by the ability of an individual to pass its heritable traits to the next generation through survival and reproduction — will increase in the population, while traits that cause an individual to have lower relative fitness will decrease.

Figure 7 illustrates a classic example of natural selection that was observed over a very short period of time. In England, as in much of the developed world, the industrial revolution brought with it many types of environmental pollution. For example, burning coal to produce electricity led to a considerable amount of air pollution, which killed the light-colored lichens that lived on tree trunks. This loss of the lichens, combined with the soot that settled on the trees, made the trunks appear much blacker. Before trunks darkened, the most common form of the peppered moth (*Biston betularia*) that lived on tree trunks was light colored with black markings, allowing it to blend into the background of the light, lichen-colored trees. These light-colored individuals had higher survivorship and reproduction than the black form, which remained rare. However, after the trees blackened, the light-colored form of the moth became much more visible to predators than the black form; the black form then had higher survivorship and reproduction and became more common in the population, while the lighter form became rare. Although the original studies on this system were incomplete, more recent work showed that this was indeed a case of rapid natural selection in response to an environmental change. (Since the implementation of clean air laws, the trees have recovered their lighter appearance, and the light form of the moth has also recovered in its frequency.)
As illustrated by the peppered moth example in Figure 7, natural selection can lead to changes in the frequency of traits in a population, even over a relatively short period of time (e.g., a few generations). Over much longer periods of time, natural selection and several other factors that influence the evolutionary process, such as mutations, genetic drift and reproductive isolation, can lead to the formation of new species. We now know that these processes generated the vast diversity of organisms we see today.

Test Yourself

How did classification systems change after scientists accepted Darwin's theory of evolution by natural selection?

When Darwin published the first edition of his book in 1859, he meticulously laid out evidence to support his theory. Today, scientists consider *On the Origin of Species* to be one of the most important books ever written, but Darwin was not completely satisfied. He could not explain exactly how natural selection worked. He did not know how trait variation arose, and he did not know how traits could be passed from parent to offspring.

Unknown to Darwin, the monk Gregor Mendel (1822–1884) was taking the first steps in uncovering the basic principles of heredity in his monastery’s garden in what is today the Czech Republic. In his selective cross-breeding of pea plants (*Pisum sativum*), Mendel found evidence for “discrete particles” of inheritance, one from each parent. Here, in Mendel's particles, later renamed genes, was a mechanism for the transmission of the traits that were at the core of Darwin's theory.

The merging of genetics with Darwin's theory of natural selection took decades. But by the 1940s, a mathematical interpretation of natural selection as an adaptive process in breeding populations was fully accepted, and the modern evolutionary synthesis, sometimes called "neo-Darwinism," was in place. During this time, scientists recognized that natural selection was one of a variety of processes that interact to influence how the frequencies of genes within a population evolve.
Test Yourself

How does natural selection differ from evolution?

Submit

Scientists generally recognize two different timescales on which evolution operates: the microevolutionary timescale and the macroevolutionary timescale. The mechanisms of genetic change in a population over a microevolutionary timescale are mutations, natural selection, gene flow and genetic drift. Through time, these mechanisms result in altered gene frequencies within populations; that is, they result in microevolution. By contrast, macroevolution happens on much larger and longer timescales and can result in speciation, the divergence of one or more new species from a previously existing species.

Macroevolution relies on the same fundamental mechanisms of evolutionary change as microevolution. However, because it occurs over longer timescales, it also includes factors that eventually lead to reproductive isolation among populations that were formerly the same species. Often, this reproductive isolation can arise as a result of geographic separation, such as when populations on different islands diverge (like many of the species Darwin and Wallace observed), when new mountain ranges form during tectonic processes, or when the climate changes (e.g., glaciation). Under these conditions, two geographically separated populations can become reproductively isolated and may evolve independently in response to differing environmental and genetic conditions; this is what occurred with the subpopulations of tassel-eared squirrels (Sciurus aberti) from opposite ends of the Grand Canyon in New Mexico (shown in Figure 8).

Figure 8: The geographic isolation of squirrels.
Repeated cycles of glacier advance/retreat during the Pleistocene epoch physically isolated populations of tassel-eared squirrels into two subspecies. Each population is evolving independently and has a distinct appearance. The Abert’s squirrel (Sciurus aberti, left, with white torso) lives on the south rim of the canyon, and the Kaibab squirrel (Sciurus aberti kaibabensis, right, no white torso) lives on the north rim of the canyon. By preventing gene flow among populations, geographic isolation often leads to population divergence and speciation.

WHY DOES THIS TOPIC MATTER?

A Sea of Microbes Drives Global Change
Do floating microbes in the ocean’s surface waters play an outsized role in global climate?

The Climate Connection
How is life on Earth reacting to climate change?

PRIMARY LITERATURE

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Body plan innovation in treehoppers through the evolution of an extra wing-like appendage.

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Classic paper: The discovery of Australopithecus africanus
Australopithecus africanus: The Man-Ape of South Africa.
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SCIENCE ON THE WEB

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Evolution: The Core Theme in Biology

One of the founders of the modern evolutionary synthesis, Theodosius Dobzhansky (1900-1975), wrote in 1973, "Nothing in biology makes sense except in the light of evolution." It is only because of evolution that we are able to understand the vast array of colors, shapes, sizes, reproductive strategies and social behaviors of life. Without the conceptual foundations provided by evolution, biology is simply the study of a collection of diverse and often very odd-looking organisms.

Evolution explains the unity of life.

Evolution is a conservative process: instead of forming each new species from scratch, evolution modifies the same basic design again and again. For example, consider the similarity of the forelimb bones among different mammalian species (Figure 9). The forelimb has the same general structure among species that differ considerably in how they use their forelimbs because it is the result of evolution from a common ancestor.

Figure 9: Homologies.

Despite having very different functions, the human arm (top) and bat wing (bottom) share the same basic bone structure. The colors trace homologous bone structures between these two mammals.

The existence of homologies (from Greek homo, meaning "same," and logos, meaning "relation") was one of many arguments that Darwin used in his book On the Origin of Species to explain the interrelatedness of life. Today, we know that mammalian forelimb bones are all coded for by a similar set of genes, conserved with only minor alterations through evolutionary time. The differences in these genes, and in their expression, are enough to produce a fin, an arm, a leg or a wing. How can a single set of genes produce such
incredible variety?

It all comes down to DNA. Bound to proteins in chromosomes, DNA contains genetic information in long, ladder-like strands containing different sequential arrangements of four nucleotides (Figure 10). A single gene is a segment of a DNA strand with its bases arranged in a specific order. Like letters in a word, the sequence of bases in a gene determines the gene’s product. The immediate product of a gene is one of several forms of RNA, which has a molecular structure similar to DNA. Using the information contained in messenger RNAs, ribosomes house a suite of chemical reactions that result in the synthesis of a corresponding chain of amino acids. These chains of amino acids, called polypeptides, compose proteins, which are essential for the structure and function of cells.

**Figure 10: DNA.**

Panel a): DNA is bound to proteins in chromosomes (left). Bases in DNA are attached to a sugar-phosphate backbone. The bases bind to each other in specific ways: adenine (A) binds to thymine (T), and guanine (G) binds to cytosine (C). DNA contains the information on how to make a protein. Panel b): A type of RNA called messenger RNA (mRNA) carries the genetic code to a ribosome, where the amino acid chain is synthesized to form polypeptides.

The genetic code consists of sequences of just three bases, called codons, all but three of which code for amino acids (Table 1). The genetic code is the Rosetta Stone of biology; before its discovery, scientists could not decipher how the information in DNA was used to make proteins. With this code, scientists now know how nearly all the proteins that make up every organism on Earth are built from only 20 amino acids.

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The basic structure of the cell membrane is the same in all cells. Phospholipids are arranged in two mirrored rows (a bilayer). Proteins (not shown) are embedded throughout the membrane and help regulate the passage of materials into and out of a cell.

Organisms are made of cells. Cells differ widely by structure and function, but they are all enclosed by cell membranes. Strikingly, the membranes have the same basic structure in every cell. As shown in Figure 11, pairs of phospholipid molecules arrange themselves within the cell membrane such that their hydrophilic (or "water-loving") heads are exposed to the interior and exterior areas of the cell's surface. This arrangement means that membrane surfaces can interact with water. The hydrophobic (or "water-fearing") tails of the phospholipids are buried in the interior of the cell membrane. This phospholipid bilayer arrangement is central to the function of membranes because it restricts the movement of water, and substances dissolved in water, across the membrane (Figure 11). Instead, proteins embedded in the cell membrane serve as transport machinery, enabling the controlled transport of water and other essential compounds into and out of cells. In this way, the cell membrane serves an important function in maintaining a balanced, stable cellular environment where metabolic life processes can occur.

**Table 1: The standard genetic code.**
Sixty-four different combinations of three DNA bases are possible, but they code for only 20 amino acids. All but two of the amino acids (methionine and tryptophan) are encoded by more than one codon. Some codons do not code for an amino acid but instead are "stop" signals, which signal the release of the amino acid chain from the ribosome. ATG, which codes for methionine, also signals "start." The genetic code is nearly universal among living organisms; only a few exceptions are known.

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Metabolism (from Greek *metabolē*, meaning "change") refers to all the chemical reactions occurring within an organism, such as the processes involved in the breakdown of food into energy or the harvesting of sunlight to produce carbohydrates. Many metabolic processes are the same in all cells. For example, nearly all organisms use the same metabolic pathway, called glycolysis, to release energy from sugars. This energy is used through the ATP-ADP cycle (Figure 12). ATP stands for adenosine triphosphate, and the
Nearly all cells use and release energy in the same basic way. The chemical bonds between the phosphate groups release energy when hydrolyzed (that is, when H₂O molecules are inserted between them). Enzymes (a kind of protein) called ATPases remove a phosphate group from an ATP molecule, turning it into ADP (adenosine diphosphate), which releases energy that the cells use for “work.” During glycolysis, energy is liberated from sugars and used to convert ADP to ATP by reattachment of a phosphate. In this way, ATP functions as a fundamental energy molecule that facilitates the release of more energy from nutrient molecules such as sugars.

**Test Yourself**

How do DNA and other structures and processes in cells provide evidence that all organisms share a common ancestor?

Submit

**Evolution also explains the diversity of life.**

Darwin rarely used the word “evolution.” Instead, he described evolution as “descent with modification.” This phrase nicely summarizes the dual nature of evolution. The term "descent" explains the unity of life, whereas the term "modification" explains life's diversity. One need only look around to recognize the diversity of organisms existing today, and a look at the fossil record reveals how much diversification has occurred since life first arose on Earth.

Extinction can occur if the environment changes too quickly for adaptation by natural selection to occur within a species, if a species is simply rare and random processes drive it to extinction, or if catastrophe strikes. Several times in the Earth’s geological past, a combination of these three processes has led to mass extinctions. These mass extinctions are usually instigated by a global catastrophe, such as a meteorite strike that has immediate and long-term impacts by causing a change in Earth’s climate (Figure 13).

There have been five major mass extinction events over the last 500 million years. Of note, the extinction event that took place during the boundary
between the Cretaceous and Paleogene periods (or K-Pg) (~65.5 million years ago (MYA)) resulted in the extinction of most dinosaurs and around 75% of all other species. The other four major extinction events occurred during the Triassic-Jurassic (~205 MYA), Permian-Triassic (~251 MYA), Late Devonian (~375–360 MYA) and Ordovician-Silurian (~450–440 MYA) time periods. Many scientists now believe that we are in the midst of a sixth mass extinction as a result of dramatic changes caused by our own actions.

![Figure 13: Meteorite crater.](image)

This 2-km-wide crater in Arizona formed when a meteorite hit Earth 20,000 to 50,000 years ago. This small impact likely threw minimal debris into the atmosphere and altered only local environments. Scientists think that larger meteorite impacts were at least partly responsible for some mass extinction events in the Earth’s geological past.  
*Figure 13: Meteorite crater.*

It is important to note that evolution is not progressive. It does not have a goal, with simpler organisms inevitably evolving into complex organisms. Instead, evolution results from a series of processes, including mutation and genetic drift, that can lead to largely random variations among individuals and natural selection, which acts upon those random variations. A bacterium might be simpler than a hawk, but this does not mean it is less adapted to its environment. Though the hawk may be more adept at catching mice, a bacterium may be better suited to breaking down organic molecules in soil.

For hundreds of years, scientists had few tools to learn about the relatedness of species. They could only study fossils and the physical appearances of living organisms. The advent of molecular biology in the 1950s and 1960s provided new tools. By comparing mutation rates in conserved genes, for example, scientists can estimate when living species diverged from each other (in other words, when on the evolutionary tree they shared a common ancestor). The greater the difference in the sequence of bases in a gene, the longer the time since divergence occurred.

The study of the genes of a type of prokaryote called archaea, discovered in 1977, has been particularly influential. Archaea appear very similar to bacteria in terms of their morphology, biochemistry and metabolism. They are so similar, in fact, that for a long time they were classified with bacteria as "archaeobacteria." However, after comparing sequences of a conserved ribosomal gene in archaea with the same gene in other prokaryotes and eukaryotes, scientists found that archaea were so different from bacteria — and even from other prokaryotes — that they deserved an entirely new
classification category. Hence, scientists proposed a three-domain system, with archaea in one domain, bacteria in another and eukaryotes in the third (Figure 14). What is remarkable about this tree is that despite their morphological similarity to bacteria, members of Archaea are more closely related to eukaryotes. In fact, more recent evidence indicates that Archaea played an important role in the evolution of Eukarya through a symbiotic relationship.

Figure 14: Three-domain tree of life.
Based on evidence from molecular genetic studies, scientists separate organisms into three domains: Bacteria, Archaea, and Eukarya. © 2012 Nature Education All rights reserved.

Test Yourself
Where on the tree would you draw in the common ancestor of Archaea and Eukarya that does not include Bacteria?

Submit

Evolutionary processes influence all levels of biological organization. Although natural selection and other evolutionary processes act on genes within individuals and are expressed in terms of differences in gene frequencies at the population level, the causes and consequences of evolutionary change also involve interactions at the community and ecosystem level. A community is a group of interacting populations of different species, and these populations may strongly interact to influence one another's evolution. For example, in the peppered moth example given above, the predatory birds were the critical factor influencing how the population of moths changed from light- to dark-colored following the darkening of tree trunks. Likewise, in a forest, many species of trees compete for water and minerals in the soil and light from the sky, and the traits that allow them to access these resources can be subject to evolution. Species that engage in mutualistic relationships can also evolve in response to each other, such as brightly colored flowers that produce nectar in order to attract pollinators. Finally, population-level evolutionary interactions can link to the ecosystem level, when species evolve to differentially utilize abiotic resources such as nitrogen in the soil or carbon in the air.

IN THIS MODULE
- Life on Earth
- Evolution: The Core Theme in Biology
- Summary
WHY DOES THIS TOPIC MATTER?
A Sea of Microbes Drives Global Change
Do floating microbes in the ocean’s surface waters play an outsized role in global climate?
The Climate Connection
How is life on Earth reacting to climate change?

PRIMARY LITERATURE
Treehopper helmets vary the insect body plan
Body plan innovation in treehoppers through the evolution of an extra wing-like appendage.
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Classic paper: The discovery of Australopithecus afarensis (1925)
Australopithecus afarensis: The Man-Ape of South Africa.
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Unearthing the secrets of ancient human DNA
Ancient human genome sequence of an extinct Palaeo-Eskimo.
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SCIENCE ON THE WEB
Darwin’s publications
The world’s largest and most widely used resource on Charles Darwin
Summary

OBJECTIVE Identify evolution as the core theme and unifying concept in biology.

Charles Darwin formulated one mechanism of evolution, natural selection, in the mid-1800s by simple observation. Natural selection is a process that describes how traits change in a population over time as a result of the differential fitness of its members. Genetics was incorporated into the study of evolution in the mid-20th century, allowing the incorporation of several other fundamental components of the evolutionary process, such as mutations, genetic drift and gene flow. Today, scientists study evolution at scales ranging from molecules to ecosystems.

OBJECTIVE Distinguish between the biological and common meanings of the word "evolution."

Scientists define evolution as heritable changes in the genes and traits of a population over time. This definition is distinct from more common uses of the word "evolve" or "evolution." In common speech, evolution can refer to any change over time, such as a change in a person's character or the refinement of an idea.

OBJECTIVE Explain how evolution has led to both the unity and diversity of life forms.

Similarities in DNA, cellular structures and processes across different species support Darwin's original idea that all organisms share a common ancestor. Over time, life diverged and occupied Earth's environments. As Earth changed, life changed through a series of extinction and diversification events. The ultimate result of more than 3 billion years of evolution, starting with single-celled organisms, is the extraordinary diversity we see on Earth today. The intrinsic similarity between diverse species provides evidence of the unity of life through evolution. Specifically, the structure of the cell membrane, the uniformity of the base pairs that construct DNA, and even the homologous structure of limbs show the similarity between species.

OBJECTIVE Explain biological classification in terms of evolutionary history.

Scientists organize life based on evolutionary relationships. Evolutionary "trees of life" illustrate patterns of divergence over time. Because evolution explains the unity and diversity of life, it is at the core of biology.

Key Terms

biological evolution  A process that results in heritable changes in a population over time.

fitness  A description of an organism's ability to survive, reproduce, and contribute to the gene pool of the next generation.

gene flow  The process by which genes move between subpopulations of a species through dispersal.

genetic drift  Genetic changes in a population due to random processes, such as a founder event, in which only a few individuals (and their specific subset of the genes in a population) start a new population.
**macroevolution**
The evolution of new species or higher taxonomic orders from existing groups.

**microevolution**
Changes to allele frequencies within species or populations.

**mutation**
Accidental changes to a DNA sequence that can provide heritable genetic variation.

**natural selection**
Mechanism of evolution theorized by Darwin and Wallace based on fitness. Individuals with genes that allow them to achieve higher fitness are favored and their genes become proportionally more common in the following generation than individuals with genes that result in lower fitness. Can lead to adaptation to new and changing environments through time.
Principles of Biology

1 Evolution and Life on Earth

Test Your Knowledge

1. How does the modern system of biological classification differ from that of Linnaeus?
   - It is based on evolutionary relationships.
   - It uses binomial nomenclature.
   - It uses nested hierarchies.
   - It groups organisms based on similarities.
   - All answers are correct.

2. How is natural selection related to evolution?
   - Natural selection and evolution are the same.
   - Natural selection is not relevant to macroevolutionary change.
   - Natural selection is the only mechanism by which populations evolve.
   - Natural selection is not relevant to microevolutionary change.
   - Natural selection is one of several mechanisms by which populations evolve.

3. Penguins in Antarctica are superb swimmers, but they walk awkwardly and cannot fly. There is evidence that penguin ancestors could fly long ago. How might natural selection explain this?
   - Mutations in the genes for wings caused ancestral penguins to start swimming instead of flying.
   - The wings of ancestral penguins shrank because the penguins did not use them.
   - Penguins today have wings; they do not use them for flying because they do not need them.
   - Penguins today have no need to fly because they are better at swimming.
   - Shorter wings may have helped ancestral penguins survive in their environment by enabling them to swim better, and so genes for shorter wings became common.

4. Why do scientists who explore evolutionary relationships often study ribosomal genes?
   - because they are not conserved over time
   - because they are the same size in all cells
   - because they are easy to manipulate in all cells
   - because they are different in all cells
   - because they code for universal features of all organisms

5. How is DNA similar in prokaryotic and eukaryotic cells?
   - In both cells, DNA is a double helix.
   - In both cells, DNA contains the genetic information on how to make proteins for various life functions.
   - In both cells, ribosomes are needed to translate the information in DNA into proteins.
   - In both cells, DNA is made of the same bases.
   - All answers are correct.

6. Evolution is considered the core theme of biology. Which of the following would NOT be considered a valid argument for why this is so?
   - DNA is the same in all cells.
Natural selection is the only explanation for the diversity of life.
All cells use the same metabolic energy cycle.
The bones in the forearm of a bat and of a horse are arranged similarly.
Cell membranes in all cells are formed from proteins and lipids.