Chapter 8: Evolution
Lesson 8.2: Biological Evidence for Evolution

How did dark deer mice become lighter over time? A species changes color over time if its environment changes. Many other types of changes can take place, too. The darker deer mice evolved into the lighter deer mice in some locations. What do you think changed about the environment?

Lesson Objectives
• Explain how scientists learn about the history of life on Earth.
• Describe how fossils help us understand the past.
• Explain how evidence from living species gives clues about evolution.
• Outline how the first organic molecules arose.
• Describe the characteristics of the first cells.
• Explain how eukaryotes are thought to have evolved.
• State how biogeography relates to evolutionary change.

Vocabulary
• absolute dating
• analogous structure
• comparative anatomy
• comparative embryology
• extinction
• fossil
• fossil record
• geologic time scale
• homologous structure
• Last Universal Common Ancestor (LUCA)
• molecular clock
• paleontologist
• relative dating
• RNA world hypothesis
• vestigial structure

Introduction
Earth formed 4.6 billion years ago, and life first appeared about 4 billion years ago. The first life forms were microscopic, single-celled organisms. From these simple beginnings, evolution gradually produced the vast complexity and diversity of life today. The evolution of life on Earth wasn’t always smooth and steady—far from it. Living things had to cope with some astounding changes. Giant meteorites struck Earth’s surface. Continents drifted and shifted. Ice ages buried the planet in snow and ice for millions of years at a time. At least five times, many, if not most, of Earth’s living things went extinct. Extinction occurs when a species completely dies out and no members of the species remain. But life on Earth was persistent. Each time, it came back more numerous and diverse than before.
Earth in a Day

It’s hard to grasp the vast amounts of time since Earth formed and life first appeared on its surface. It may help to think of Earth’s history as a 24-hour day, as shown in Figure 8.9. Humans would have appeared only during the last minute of that day. If we are such newcomers on planet Earth, how do we know about the vast period of time that went before us? How have we learned about the distant past?

How Earth Formed: We Are Made of Stardust!

We’ll start the story of life at the very beginning, when Earth and the rest of the solar system first formed. The solar system began as a rotating cloud of stardust. Then, a nearby star exploded and sent a shock wave through the dust cloud, increasing its rate of spin. As a result, most of the mass became concentrated in the middle of the disk, forming the sun. Smaller concentrations of mass rotating around the center formed the planets, including Earth. You can watch a video showing how Earth formed at this link: https://www.youtube.com/watch?v=BzRd4qzyS1c

At first, Earth was molten and lacked an atmosphere and oceans. Gradually, the planet cooled and formed a solid crust. As the planet continued to cool, volcanoes released gases, which eventually formed an atmosphere. The early atmosphere contained ammonia, methane, water vapor, and carbon dioxide but only a trace of oxygen. As the atmosphere became denser, clouds formed and rain fell. Water from rain (and perhaps also from comets and asteroids that struck Earth) eventually formed the oceans. The ancient atmosphere and oceans represented by the picture in Figure 8.10 would be toxic to today’s life, but they set the stage for life to begin.
The First Organic Molecules

All living things consist of organic molecules. Therefore, it is likely that organic molecules evolved before cells, perhaps as long as 4 billion years ago. How did these building blocks of life first form? Scientists think that lightning sparked chemical reactions in Earth’s early atmosphere. They hypothesize that this created a “soup” of organic molecules from inorganic chemicals. In 1953, scientists Stanley Miller and Harold Urey used their imaginations to test this hypothesis. They created a simulation experiment to see if organic molecules could arise in this way (see Figure 8.11). They used a mixture of gases to represent Earth’s early atmosphere. Then, they passed sparks through the gases to represent lightning. Within a week, several simple organic molecules had formed. You can watch a dramatization of Miller and Urey’s experiment at this link: https://www.youtube.com/watch?v=mF9U5x6Nxnw.

Recently, the findings of Miller and Urey have come into question due to discrepancies in the composition of the early atmosphere, allowing a number of other ideas to surface on the formation of the first organic molecules. One idea states that the active volcanoes on early Earth gave the necessary materials for life. Despite the simplified account discussed above, the problem of the origin of the first organic compounds remains. Despite tremendous advances in biochemical analysis, answers to the problem remain. But whatever process did result in the first organic molecules, it was probably a spontaneous process, with elements coming together randomly to form small compounds, and small compounds reacting with other elements and other small compounds to make larger compounds. So, which organic molecule did come first?

Which Organic Molecule Came First?

Living things need organic molecules to store genetic information and to carry out the chemical work of cells. Modern organisms use DNA to store genetic information and proteins to catalyze chemical reactions. So, did DNA or proteins evolve first? This is like asking whether the chicken or the egg came first.
first. DNA encodes proteins and proteins are needed to make DNA, so each type of organic molecule needs the other for its own existence. How could either of these two molecules have evolved before the other? Did some other organic molecule evolve first, instead of DNA or proteins?

**RNA World Hypothesis**

Some scientists speculate that RNA may have been the first organic molecule to evolve. In fact, they think that early life was based solely on RNA and that DNA and proteins evolved later. This is called the RNA world hypothesis. Why RNA? It can encode genetic instructions (like DNA), and some RNAs can carry out chemical reactions (like proteins). Therefore, it solves the chicken-and-egg problem of which of these two molecules came first. Other evidence also suggests that RNA may be the most ancient of the organic molecules. You can learn more about the RNA world hypothesis and the evidence for it at this link: [http://www.youtube.com/watch?v=sAkgb3yNgog](http://www.youtube.com/watch?v=sAkgb3yNgog).

**The First Cells**

How organic molecules such as RNA developed into cells is not known for certain. Scientists speculate that lipid membranes grew around the organic molecules. The membranes prevented the molecules from reacting with other molecules, so they did not form new compounds. In this way, the organic molecules persisted, and the first cells may have formed. Figure 8.12 shows a model of the hypothetical first cell.

![Figure 8.12: Hypothetical First Cell. The earliest cells may have consisted of little more than RNA inside a lipid membrane.](image)

**LUCA**

No doubt there were many early cells of this type. However, scientists think that only one early cell (or group of cells) eventually gave rise to all subsequent life on Earth. That one cell is called the Last Universal Common Ancestor (LUCA). It probably existed around 3.5 billion years ago. LUCA was one of the earliest prokaryotic cells. It would have lacked a nucleus and other membrane-bound organelles. To learn more about LUCA and universal common descent, you can watch the video at the following link: [http://www.youtube.com/watch?v=G0UGpcea8Zg](http://www.youtube.com/watch?v=G0UGpcea8Zg).

**Photosynthesis and Cellular Respiration**

The earliest cells were probably heterotrophs. Most likely they got their energy from other molecules in the organic “soup.” However, by about 3 billion years ago, a new way of obtaining energy evolved. This new way was photosynthesis. Through photosynthesis, organisms could use sunlight to make food from carbon dioxide and water. These organisms were the first autotrophs. They provided food for themselves and for other organisms that began to consume them. After photosynthesis evolved, oxygen started to accumulate in the atmosphere. This has been dubbed the “oxygen catastrophe.” Why? Oxygen was toxic to most early cells because they had evolved in its absence. As a result, many of them died out. The few that survived evolved a new way to take advantage of the
oxygen. This second major innovation was cellular respiration. It allowed cells to use oxygen to obtain more energy from organic molecules.

**Evolution of Eukaryotes**

The first eukaryotic cells probably evolved about 2 billion years ago. This is explained by endosymbiotic theory. As shown in Figure 8.13, endosymbiosis came about when large cells engulfed small cells. The small cells were not digested by the large cells. Instead, they lived within the large cells and evolved into cell organelles.

![Endosymbiosis in a nutshell:](image)

**Figure 8.13:** From Independent Cell to Organelle. The endosymbiotic theory explains how eukaryotic cells evolved.

The large and small cells formed a symbiotic relationship in which both cells benefited. Some of the small cells were able to break down the large cell’s wastes for energy. They supplied energy not only to themselves but also to the large cell. They became the mitochondria of eukaryotic cells. Other small cells were able to use sunlight to make food. They shared the food with the large cell. They became the chloroplasts of eukaryotic cells. With their specialized organelles, eukaryotic cells were powerful and efficient. They would go on to evolve additional major adaptations. These adaptations include sexual reproduction, cell specialization, and multicellularity. Eventually, eukaryotic cells would evolve into the animals, plants, and fungi we know today.

**Arsenic in Place of Phosphorus - New Biochemicals for Life?**

In late 2010, NASA scientists proposed the notion that the elements essential for life - carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur - may have additional members. Scientists have trained a bacterium to eat and grow on a diet of arsenic, in place of phosphorus. Phosphorus chains form the backbone of DNA, and ATP, with three phosphates, is the principal molecule in which energy is stored in the cell. Arsenic is directly under phosphorus in the Periodic Table, so the two elements have similar chemical bonding properties. This finding raises the possibility that organisms could exist on Earth or elsewhere in the universe using biochemicals not currently known to exist. These results expand the notion of what life could be and where it could be. It could be possible that life on other planets may have formed using biochemicals with elements different from the elements used in life on Earth.

In a classic example of the scientific community questioning controversial information, in the immediate six months after the original publication in the scientific journal *Nature*, the scientific community has raised various technical and theoretical issues concerning this finding. And as a response, the NASA team dismisses the criticism and stands by their data and interpretations.

Learning About the Past

In his book *On the Origin of Species*, Darwin included a lot of evidence to show that evolution had taken place. He also made logical arguments to support his theory that evolution occurs by natural selection. Since Darwin's time, much more evidence has been gathered. The evidence includes a huge number of fossils that are different from the organisms living on present day Earth thus providing us with strong evidence that organisms have changed over time. Much of what we know about the history of life on Earth is based on the fossil record. It also includes more detailed knowledge of living things, and how they develop and grow, and similar structures that have in common right down to their DNA. Detailed knowledge of modern organisms also helps us understand how life evolved.

Fossil Evidence

Fossils are a window into the past because it is the remains or traces of an organisms that died many years ago. They provide clear evidence that evolution has occurred. Scientists who find and study fossils are called paleontologists. The fossils themselves have been formed in many different ways. Fossils are the preserved remains or traces of organisms that lived in the past. The soft parts of organisms almost always decompose quickly after death. On occasion, the hard parts—mainly bones, teeth, or shells—remain long enough to mineralize and form fossils. One way fossils are formed is when an organism's remains fall into soft mud or sand and are buried leaving behind an impression. The mud or sand hardened into rock over time preserving the impression of the fallen organism. Another way fossils can be formed is when a whole organism gets trapped and preserved in substances, like tar, amber, or ice. Fossils formed in these two ways are typically known as body fossils. Figure 8.14 shows you samples of these type of fossils.

![Figure 8.14: Examples of body fossils. The fossil on the left is that of a primitive bat retrieved from the Green River rock beds in Colorado. The fossil on the right is of a spider that was trapped in tree sap (amber) that hardened over time preserving the entire spider.](image)

Paleontologists also studied another type of fossils to learn more about how past organisms lived, these fossils are known as trace fossils and they are preserved remains from the activities of organisms, such as preserved footprints, egg shells, skin, and nests.

How do they use fossils to understand the past? First you need to have a general understanding of how scientists deciphered the age of fossils and how they use where they find fossil distributions to ascertain past life information about the organisms that left the fossils behind.

Deciphering the Age of Fossils

Today we ascertain the age of a fossil using the *Geologic Time Scale*, which was developed in the 1700s by geologists. The development of the *Geologic Time Scale* is based upon the principle of superposition developed by a Danish scientists Nicolaus Steno in 1669. The principle of superposition states that if strata (layers of rock) at a location have not been disturbed, the lowest stratum (singular form of strata) was formed before the strata above it. Figure 8.15 on the next page shows you the strata layers found in the Grand Canyon.
The *Geologic Time Scale* was created by scientists who compared different strata (levels of rock disposition) from different locations on Earth and the types of fossils they found distributed within the strata. From the data that they collected, they formed a timeline of when the different fossils found on Earth existed (Figure 8.16). The geologic time scale divides Earth’s history into divisions (such as eons, eras, and periods) that are based on major changes in geology, climate, and the evolution of life. It organizes Earth’s history and the evolution of life on the basis of important events instead of time alone. It also allows more focus to be placed on recent events, about which we know the most.
Geologists use the Geologic Time Scale and the principle of superposition to derive the relative age and absolute age of fossils. Relative age is the age of a fossil compared to that of other fossils by referring to the geologic time scale and to records of known fossils. Absolute age is established by radiometric dating or other means the age of the rocks where the fossils are found. Both are described below. You can also learn more about dating methods in the video at this link: http://www.youtube.com/watch?v=jM7vZ-9bBc0.

You can learn more about carbon-14 dating by watching the animation at this link: http://www.absorblearning.com/media/attachment.action?quick=bo&amp;att=832.

- **Relative dating** determines which of two fossils is older or younger than the other, but not their age in years. Relative dating is based on the positions of fossils in rock layers. Lower layers were laid down earlier, so they are assumed to contain older fossils. This is illustrated in Figure 8.17.

- **Absolute dating** determines about how long ago a fossil organism lived. This gives the fossil an approximate age in years. Absolute dating is often based on the amount of carbon-14 or other radioactive element that remains in a fossil. This is also illustrated in Figure 8.17.

![Figure 8.17: Relative Dating Using Rock Layers. Relative dating establishes which of two fossils is older than the other. It is based on the rock layers in which the fossils formed.](image)

Additionally scientists use the geologic time scale, relative age data, and absolute age data to infer how species have species have differed in a gradual sequence of forms over time. This gradual change over time has become the basis of inferences of transitional species. Consider the example of the horse, shown in Figure 8.18 on the next page. The fossil record shows how the horse evolved.

The oldest horse fossils show what the earliest horses were like. They were about the size of a fox, and they had four long toes. Other evidence shows they lived in wooded marshlands, where they probably ate soft leaves. Through time, the climate became drier, and grasslands slowly replaced the marshes. Later fossils show that horses changed as well.

- They became taller, which would help them see predators while they fed in tall grasses.
- They evolved a single large toe that eventually became a hoof. This would help them run swiftly and escape predators.
- Their molars (back teeth) became longer and covered with cement. This would allow them to grind tough grasses and grass seeds without wearing out their teeth.

*Does The Fossil Record Support Evolution?* This video can be seen at http://www.youtube.com/watch?v=QWVoXZPOCGk.

**Evidence from Living Species**

Just as Darwin did, today’s scientists study living species to learn about evolution. They compare the anatomy, embryos, and biological molecules found in modern organisms to understand how they evolved.
Comparative anatomy is the study of the similarities and differences in the structures of different species. Similar body parts may be homologies, analogies, or vestigial structures. All of which provide evidence for evolution.

Homologies or homologous structures are structures that are similar in related organisms because they were inherited from a common recent ancestor. These homologous structures or homologous organs may or may not have the same function in the descendants. Figure 8.19 shows the hands of several different mammals. They all have the same basic pattern of bones. They inherited this pattern from a common recent ancestor. However, their forelimbs now have different functions.

![Figure 8.19: Hands of Different Mammals. The forelimbs of all mammals have the same basic bone structure.](image)

Analogies or analogous structures are structures that are similar in unrelated organisms. The structures are similar because they evolved to do the same job, not because they were inherited from a common ancestor. For example, the wings of bats and birds, shown in Figure 8.20, look similar on the outside. They also have the same function. However, wings evolved independently in the two groups of animals. This is apparent when you compare the pattern of bones inside the wings.

![Figure 8.20: Wings of Bats and Birds. Wings of bats and birds serve the same function. Look closely at the bones inside the wings. The differences show they developed from different ancestors.](image)
Vestigial structures are structures that seem to serve no function but resemble structures with functionality in related organisms. Evolution has reduced their size because the structures are no longer used. The mostly widely known example of this is the human tailbone, or coccyx, that is made up of four fused vertebrae similar in structure to the bones in the tails of animals, see Figure 8.21. The human appendix is another example of a vestigial structure. It is a tiny remnant of a once-larger organ. In a distant ancestor, it was needed to digest food. It serves no purpose in humans today. Why do you think structures that are no longer used shrink in size? Why might a full-sized, unused structure reduce an organism’s fitness?

![Figure 8.21: Tailbone structure; on the left you can see the tailbone structure of humans, and on the right the tailbone structures of felines.](image)

-Comparative Embryology

Comparative embryology is the study of the similarities and differences in the embryos of different species. Similarities in embryos are evidence of common ancestry. All vertebrate embryos, for example, have gill slits and tails, as shown in Figure 8.22. All of the animals in the figure, except for fish, lose their gill slits by adulthood. Some of them also lose their tail. In humans, the tail is reduced to the tail bone. Thus, similarities organisms share as embryos may be gone by adulthood. This is why it is valuable to compare organisms in the embryonic stage.

![Figure 8.22: Comparative embryology of a vertebral fish, reptile, bird, and human shows that during the development stages all of the embryo types have gill slits and tails.](image)
Comparing Biological Molecules

Darwin could compare only the anatomy and embryos of living things. Today, scientists can compare DNA, RNA, proteins, and other biological molecules from a variety of organisms. As they study these different biological molecules they look for similarities and differences. The more similarities found in biological molecule make-up between two different species the more closely the species are related to one another through a common ancestor. Similar DNA sequences are the strongest evidence for evolution from a common ancestor. Look at the cladogram (diagram based on patterns of shared or derived traits that shows evolutionary relationships) in Figure 8.23. It shows how birds and other species are related based on their DNA sequences. The more similarities in DNA sequences, and therefore amino acid sequences, the more closely-related the organisms are to each other. Evolution and molecules are discussed at http://www.youtube.com/watch?v=nvJFl3ChOUU. Keep in mind the study of biological molecules is a new scientific method of establishing evolutionary ties and scientists still debate how to interpret this type of evidence.

Figure 8.23: Cladogram of Birds and Other Species. This cladogram is based on DNA comparisons. It shows how birds are related to crocodiles, rabbits, primates, amphibians, ray-finned fish, and sharks by descent from common ancestors.

Cladograms help scientists to establish phylogeny or the relationship by ancestry among the vast variety of organisms found on Earth. An enormous amount of varied types of evidence have been used to develop the phylogenetic diagram or “tree” of life on Earth. This phylogenetic diagram can be seen in Figure 8.24 on the next page. The “trunk” represents a past species that could have been the ancestor of all of these organisms and is noted as the “progenote” on this diagram. The assumed “progenote” or LUCA (Last Universal Common Ancestor) of life on Earth today was previously discussed on page 229 of this lesson. There are two major conjectures associated with this entity: (1) the progenote's genome is based on RNA rather than DNA and (2) the replication, transcription and translation of this RNA organism had a much higher error rate than the ensuing DNA-based cells. The “branches” represent each separate population or lineage. The closer together groups of organisms are on the phylogenetic tree of life the more closely related they are thought to be. For example, Eukaryotes are more closely related to Archaea than they are to Bacteria.
Using various types of information to understand evolutionary relationships is discussed in the following videos: [http://www.youtube.com/watch?v=aZc1t2Os6UU](http://www.youtube.com/watch?v=aZc1t2Os6UU) (building cladograms), [http://www.youtube.com/watch?v=6IRz85QNjz0e](http://www.youtube.com/watch?v=6IRz85QNjz0e) (classification of organisms), and [http://www.youtube.com/watch?v=JgyTVT3dqGY&feature=related](http://www.youtube.com/watch?v=JgyTVT3dqGY&feature=related) (why scientists accept theory of evolution).

Further Evidence for Common Ancestry - Universal Genetic Code and Molecular Clocks

The instructions for life are encoded in our DNA. All organisms contain the same 4 nitrogenous bases in their DNA molecules, Adenine (A), Thymine (T), Cytosine (C), and Guanine (G). While all organisms contain the same bases, the quantities and sequences of these bases differs from one species to another and these differences account for the different traits each species exhibits. Despite these differences in all forms of life, the fact that all organisms encode the directions for inheritance in DNA molecules and share a universal genetic code suggests they all share a common ancestor. Codons of DNA code for the same amino acids regardless of the species in which the DNA exists.

Evidence from the fossil record can be combined with data from molecular clocks. A molecular clock uses DNA sequences (or the proteins they encode) to estimate how long it has been since related species diverged from a common ancestor. Molecular clocks are based on the assumption that mutations accumulate through time at a steady average rate for a given region of DNA. Species that have accumulated greater differences in their DNA sequences are assumed to have diverged from their common ancestor in the more distant past. Molecular clocks based on different regions of DNA may be used together for more accuracy. Consider the example in Table 8.2 on the next page. The table shows how similar the DNA of several animal species is to human DNA. Based on these data, which organism do you think shared the most recent common ancestor with humans?
**Table 8.2: Comparing DNA: Humans and Other Animals**

<table>
<thead>
<tr>
<th>Organism</th>
<th>Similarity with Human DNA (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chimpanzee</td>
<td>98</td>
</tr>
<tr>
<td>Mouse</td>
<td>85</td>
</tr>
<tr>
<td>Chicken</td>
<td>60</td>
</tr>
<tr>
<td>Fruit Fly</td>
<td>44</td>
</tr>
</tbody>
</table>

If you assumed that according to the data presented in Table 8.2 that the chimpanzee would be most closely related to humans you are correct.

**-KQED: The Reverse Evolution Machine**

In search of the common ancestor of all mammals, University of California Santa Cruz scientist David Haussler is pulling a complete reversal. Instead of studying fossils, he’s comparing the genomes of living mammals to construct a map of our common ancestors’ DNA. His technique holds promise for providing a better picture of how life evolved. See [http://www.kqed.org/quest/television/the-reverse-evolution-machine](http://www.kqed.org/quest/television/the-reverse-evolution-machine) for more information.

**Lesson Summary**

- Earth formed about 4.6 billion years ago. At first, Earth was molten and lacked an atmosphere and oceans. Gradually, the atmosphere formed, followed by the oceans.
- The first organic molecules formed about 4 billion years ago. This may have happened when lightning sparked chemical reactions in Earth’s early atmosphere. RNA may have been the first organic molecule to form as well as the basis of early life.
- The first cells consisted of little more than an organic molecule such as RNA inside a lipid membrane. One cell (or group of cells), called the last universal common ancestor (LUCA), gave rise to all subsequent life on Earth.
- Photosynthesis evolved by 3 billion years ago and released oxygen into the atmosphere. Cellular respiration evolved after that to make use of the oxygen.
- Eukaryotic cells probably evolved about 2 billion years ago. Their evolution is explained by endosymbiotic theory. Eukaryotic cells would go on to evolve into the diversity of eukaryotes we know today.
- Fossils provide a window into the past. They are evidence for evolution. Scientists who find and study fossils are called paleontologists.
- The geologic time scale is another important tool for understanding the history of life on Earth.
- Scientists compare the anatomy, embryos, and DNA of living things to understand how they evolved. Evidence for evolution is provided by homologous structures. These are structures shared by related organisms that were inherited from a common ancestor. Other evidence is provided by analogous structures. These are structures that unrelated organisms share because they evolved to do the same job.
- Much of what we know about the history of life on Earth is based on the fossil record. Molecular clocks are used to estimate how long it has been since two species diverged from a common ancestor.
References/ Multimedia Resources


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