17–1 The Fossil Record

BI 8.e. Students know how to analyze fossil evidence with regard to biological diversity, episodic speciation, and mass extinction. **BIIE 1.i.** Analyze the locations, sequences, or time intervals that are characteristic of natural phenomena (e.g., relative ages of rocks, locations of planets over time, and succession of species in an ecosystem).

The history of life on Earth is filled with mystery, life-and-death struggles, and bizarre plants and animals as amazing as any mythological creatures. Studying life's history is one of the most fascinating and challenging parts of biology, and researchers go about it in several ways. One technique is to read the pieces of the story that are "written" in ancient rocks, in the petrified sap of ancient trees, in peat bogs and tar pits, and in polar glaciers. You may recall that these traces and preserved remains of ancient life are called fossils.

Guide for Reading

Key Concepts
- What is the fossil record?
- What information do relative dating and radioactive dating provide about fossils?
- What are the main divisions of the geologic time scale?

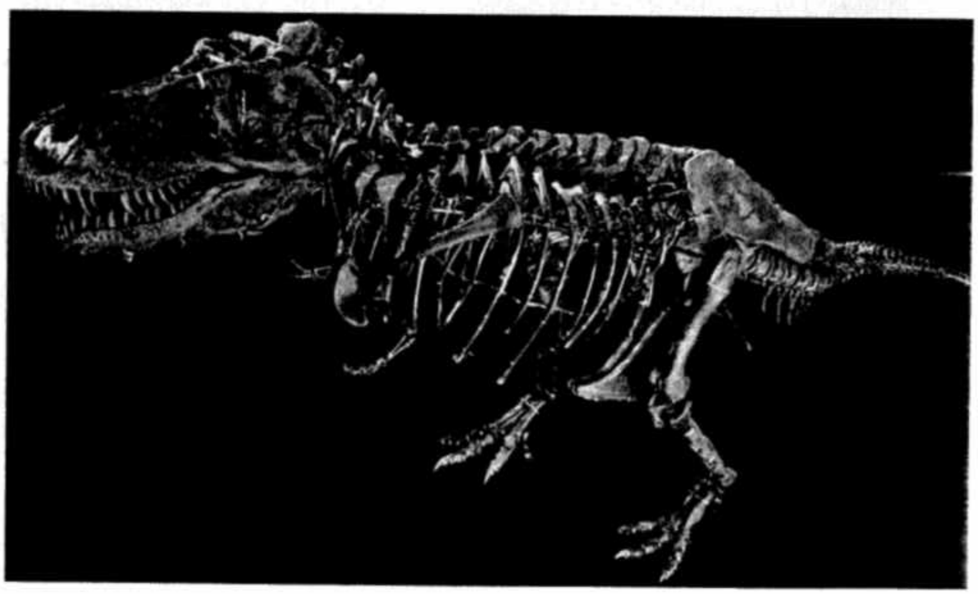
Vocabulary
paleontologist • fossil record
extinct • relative dating
index fossil • half-life
radioactive dating
geologic time scale • era
period

Reading Strategy: Finding Main Ideas Before you read, write down this idea: Scientists use the fossil record to learn about the history of life on Earth. As you read, make a list of the kinds of evidence that support this main idea.

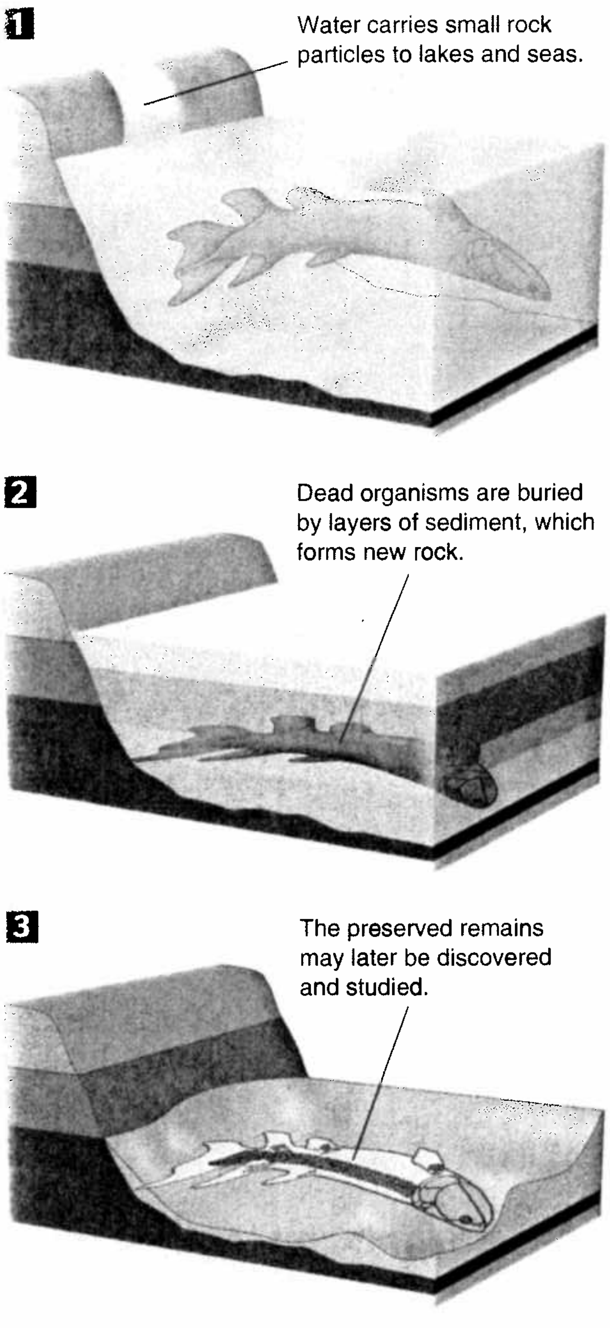
Fossils and Ancient Life

Paleontologists (pay-lee-un-TAHL-uh-jists) are scientists who study fossils. They collect fossils such as the one shown in **Figure 17–1.** From these fossils, they infer what past life-forms were like—the structure of the organisms, what they ate, what ate them, and the environment in which they lived. Paleontologists also classify fossil organisms. They group similar organisms together and arrange them in the order in which they lived—from oldest to most recent. Together, all this information about past life is called the **fossil record.** **The fossil record provides evidence about the history of life on Earth. It also shows how different groups of organisms, including species, have changed over time.**

The fossil record reveals a remarkable fact: Fossils occur in a particular order. Certain fossils appear only in older rocks, and other fossils appear only in more recent rocks. In other words, the fossil record shows that life on Earth has changed over time. In fact, more than 99 percent of all species that have ever lived on Earth have become **extinct,** which means the species died out. Meanwhile, over billions of years, ancient unicellular organisms have given rise to the modern bacteria, protists, fungi, plants, and animals that you will study in later units.



▶ **Figure 17–1** This remarkably complete dinosaur fossil reveals many characteristics of the original animal. **Observing** *What anatomical similarities can you observe between this fossil and any organism alive today?*



▲ **Figure 17–2** **The fossil record provides evidence about the history of life on Earth.** Most fossils are formed in sedimentary rock.

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How Fossils Form

A fossil can be as large and complete as an entire, perfectly preserved animal, or as small and incomplete as a tiny fragment of a jawbone or leaf. There are fossil eggs, fossil footprints, and even fossilized animal droppings. For a fossil to form, either the remains of the organism or some trace of its presence must be preserved. The formation of any fossil depends on a precise combination of conditions. Because of this, the fossil record provides incomplete information about the history of life. For every organism that leaves a fossil, many more die without leaving a trace.

Most fossils form in sedimentary rock, as shown in **Figure 17–2.** Sedimentary rock is formed when exposure to rain, heat, wind, and cold breaks down existing rock into small particles of sand, silt, and clay. These particles are carried by streams and rivers into lakes or seas, where they eventually settle to the bottom. As layers of sediment build up over time, dead organisms may also sink to the bottom and become buried. If conditions are right, the remains may be kept intact and free from decay. The weight of layers of sediment gradually compresses the lower layers and, along with chemical activity, turns them into rock.

The quality of fossil preservation varies. In some cases, the small particles of rock surrounding the remains of an organism preserve an imprint of its soft parts. In other cases, the hard parts are preserved when wood, shells, or bones are saturated or replaced with long-lasting mineral compounds. Occasionally, organisms are buried quickly in fine-grained clay or volcanic ash before they begin to decay, so they are perfectly preserved.

✓CHECKPOINT ***Why is the fossil record described as an incomplete record of life's history?***

Interpreting Fossil Evidence

The natural forces that form sedimentary rock can also reveal fossils that have been hidden in layers of rock for millions of years. Forces inside Earth lift rocks up into mountain ranges, where wind, rain, and running water erode the rock. Bit by bit, water and wind wear away the upper, younger layers, exposing the older fossil-bearing layers beneath.

When a fossil is exposed, a fortunate (and observant) paleontologist may happen along at just the right time and remove the fossil for study.

Paleontologists occasionally unearth the remains of an entire organism. More often, though, they must reconstruct an extinct species from a few fossil bits—remains of bone, a shell, leaves, or pollen. When paleontologists study a fossil, they look for anatomical similarities—and differences—between the fossil and living organisms. Also, a fossil's age is extremely important. Paleontologists determine the age of fossils using two techniques: relative dating and radioactive dating.

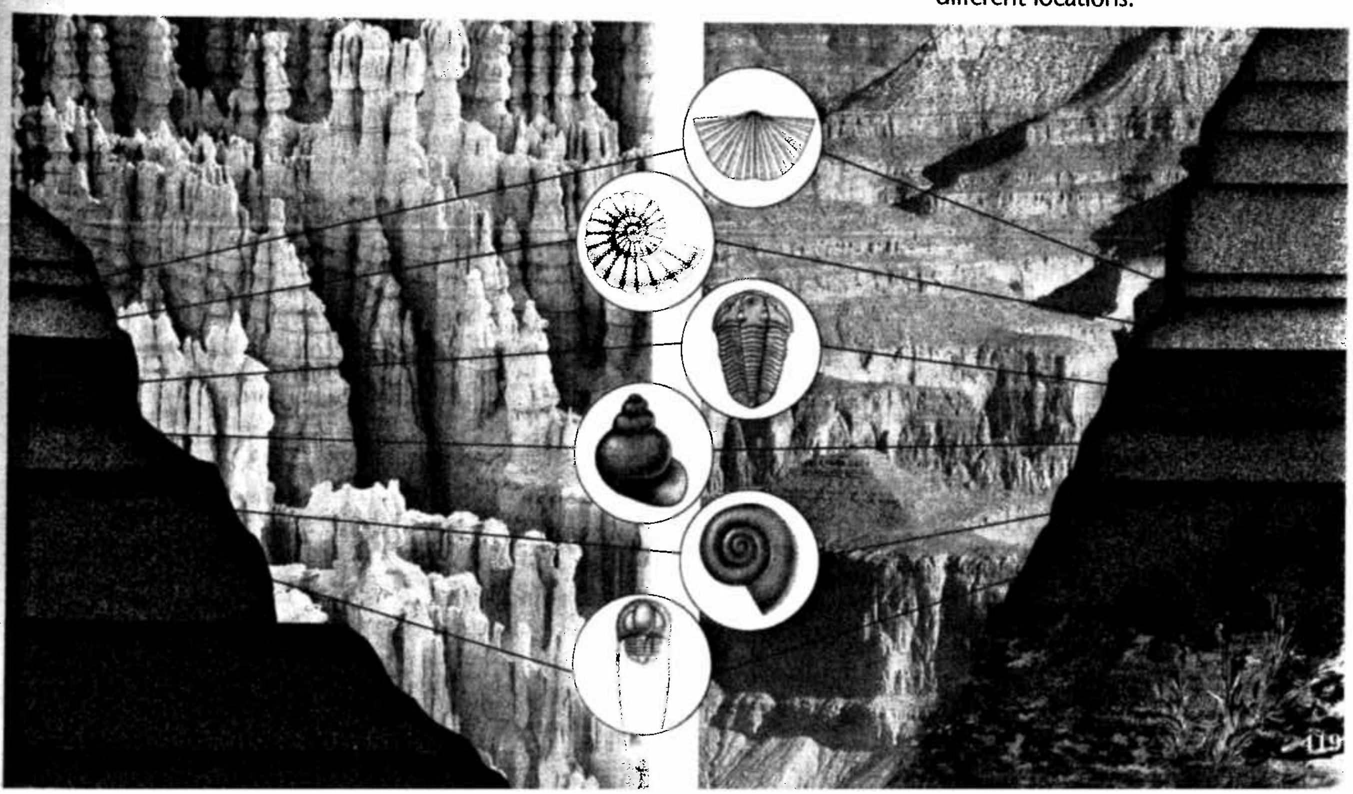
Relative Dating About two centuries ago, geologists noted that rock layers containing certain fossils consistently appeared in the same vertical order no matter where they were found. Also, a particular species of trilobite—a common fossil and an extinct relative of horseshoe crabs—might be found in one rock layer but be absent from layers above or below it. How might such a pattern be useful?

In **relative dating,** the age of a fossil is determined by comparing its placement with that of fossils in other layers of rock, as shown in **Figure 17–3.** Recall that sedimentary rock is formed from the gradual deposition of layers of sand, rock, and other types of sediment. The rock layers form in order by age—the oldest layers on the bottom, with more recent layers on top, closer to Earth's surface.

Scientists also use **index fossils** to compare the relative ages of fossils. To be used as an index fossil, a species must be easily recognized and must have existed for a short period but have had a wide geographic range. As a result, it will be found in only a few layers of rock, but these specific layers will be found in different geographic locations. **Relative dating allows paleontologists to estimate a fossil's age compared with that of other fossils.** However, it provides no information about its absolute age, or age in years.

Word Origins

The word part *paleo-* means "ancient" or "early," and *-zoic* means "life." The word part *meso-* means "middle." The word part *ceno-* means "recent." **Use this information to explain the meanings of *paleozoic, mesozoic,* and *cenozoic.***



▼ **Figure 17–3** **In relative dating, a paleontologist estimates a fossil's age in comparison with that of other fossils.** Each of these fossils is an index fossil. It enables scientists to date the rock layer in which it is found. Scientists can also use index fossils to date rocks from different locations.

Quick Lab

What is a half-life?

Materials 100 1-cm squares of paper, plastic or paper cup

Procedure

1. Construct a data table or spreadsheet with 2 columns and 5 blank rows. Label the columns "Spill Number" and "Number of Squares Returned."
2. Place an *X* on each square of paper, and put all the squares in the cup.
3. Mix up the squares in the cup. Then, spill them out and separate all squares that overlap.
4. Remove the squares that have an *X* showing. Record the number of squares remaining and return them to the cup.
5. Repeat steps 3 and 4 until there are 5 or fewer squares remaining. Make a graph of your results with the number of spills on the *x*-axis and the number of squares remaining on the *y*-axis.

Analyze and Conclude

1. **Analyzing Data** How many spills were required to remove half of the squares? To remove three fourths?
2. **Calculating** If each spill represents one year, what is the half-life of the squares?

6IIE 7.c, **BIIE 1.a, BIIE 1.e**

Quick View Video

Discovery School Video To find out about radioactive dating, view track 6 "Mummies: Ties to the Past" on the *BioDetectives* DVD.

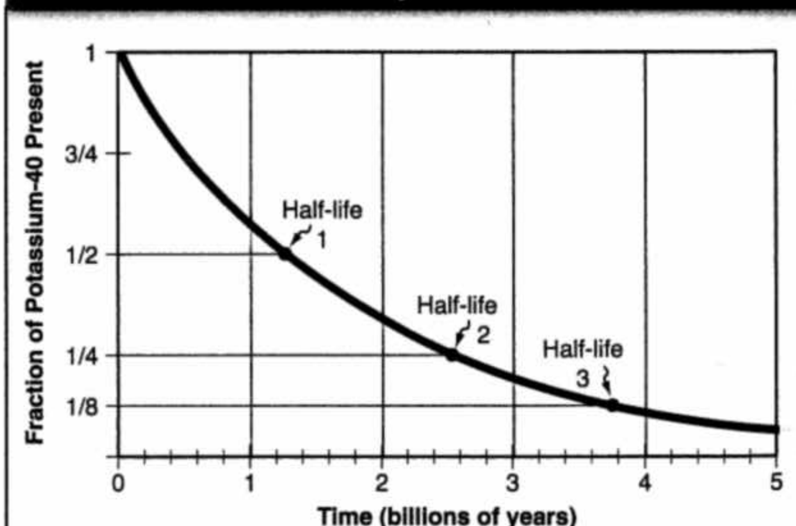
Radioactive Dating Scientists use radioactive decay to assign absolute ages to rocks. Some elements found in rocks are radioactive. Radioactive elements decay, or break down, into nonradioactive elements at a steady rate, which is measured in a unit called a half-life. A **half-life** is the length of time required for half of the radioactive atoms in a sample to decay. As shown in **Figure 17–4,** after one half-life, half of the original radioactive atoms in a sample have decayed. Of those remaining atoms, half again are decayed after another half-life.

Radioactive dating is the use of half-lives to determine the age of a sample. **In radioactive dating, scientists calculate the age of a sample based on the amount of remaining radioactive isotopes it contains.** Different radioactive elements have different half-lives and therefore provide natural clocks that "tick" at different rates. Carbon-14, for example, has a half-life of about 5730 years. Carbon-14 is taken up by living things while they are alive. After an organism dies, the carbon-14 in its body begins to decay to form nitrogen-14, which escapes into the air. Carbon-12, the most common isotope of carbon, is not radioactive and does not decay. By comparing the amounts of carbon-14 and carbon-12 in a fossil, researchers can determine when the organism lived. The more carbon-12 there is in a sample compared to carbon-14, the older the sample is.

Because carbon-14 has a relatively short half-life, it is useful only for dating fossils younger than about 60,000 years. To date older rocks, researchers use elements with longer half-lives. Potassium-40, for example, decays to the inert gas argon-40 and has a half-life of 1.26 billion years.

CHECKPOINT *What is a half-life?*

Radioactive Decay of Potassium-40



▲ **Figure 17–4** **Radioactive dating involves measuring the amounts of radioactive isotopes in a sample to determine its actual age.** Such measurements enable scientists to determine the absolute age of rocks and the fossils they contain.

Geologic Time Scale

Paleontologists use divisions of the **geologic time scale** to represent evolutionary time. **Figure 17–5** shows the most recent version of the geologic time scale. Scientists first developed the geologic time scale by studying rock layers and index fossils worldwide. With this information, they placed Earth's rocks in order according to relative age. As geologists studied the fossil record, they found major changes in the fossil animals and plants at specific layers in the rock. These times were used to mark where one segment of geologic time ends and the next begins—long before anyone knew how long these various segments actually were.

Years later, radioactive dating techniques were used to assign specific ages to the various rock layers. Not surprisingly, the divisions of the geologic time scale did not turn out to be of standard lengths, such as 100 million years. Instead, geologic divisions vary in duration by many millions of years. Scientists use several levels of divisions for the geologic time scale. Geologic time begins with Precambrian (pree-KAM-bree-un) Time. Although few multicellular fossils exist from this time, the Precambrian actually covers about 88 percent of Earth's history, as shown in **Figure 17–6** on the next page. **After Precambrian Time, the basic divisions of the geologic time scale are eras and periods.**

Eras Geologists divide the time between the Precambrian and the present into three **eras.** They are the Paleozoic Era, the Mesozoic Era, and the Cenozoic Era. The Paleozoic (pay-lee-oh-ZOH-ik) began about 544 million years ago and lasted for almost 300 million years. Many vertebrates and invertebrates—animals with and without backbones—lived during the Paleozoic.

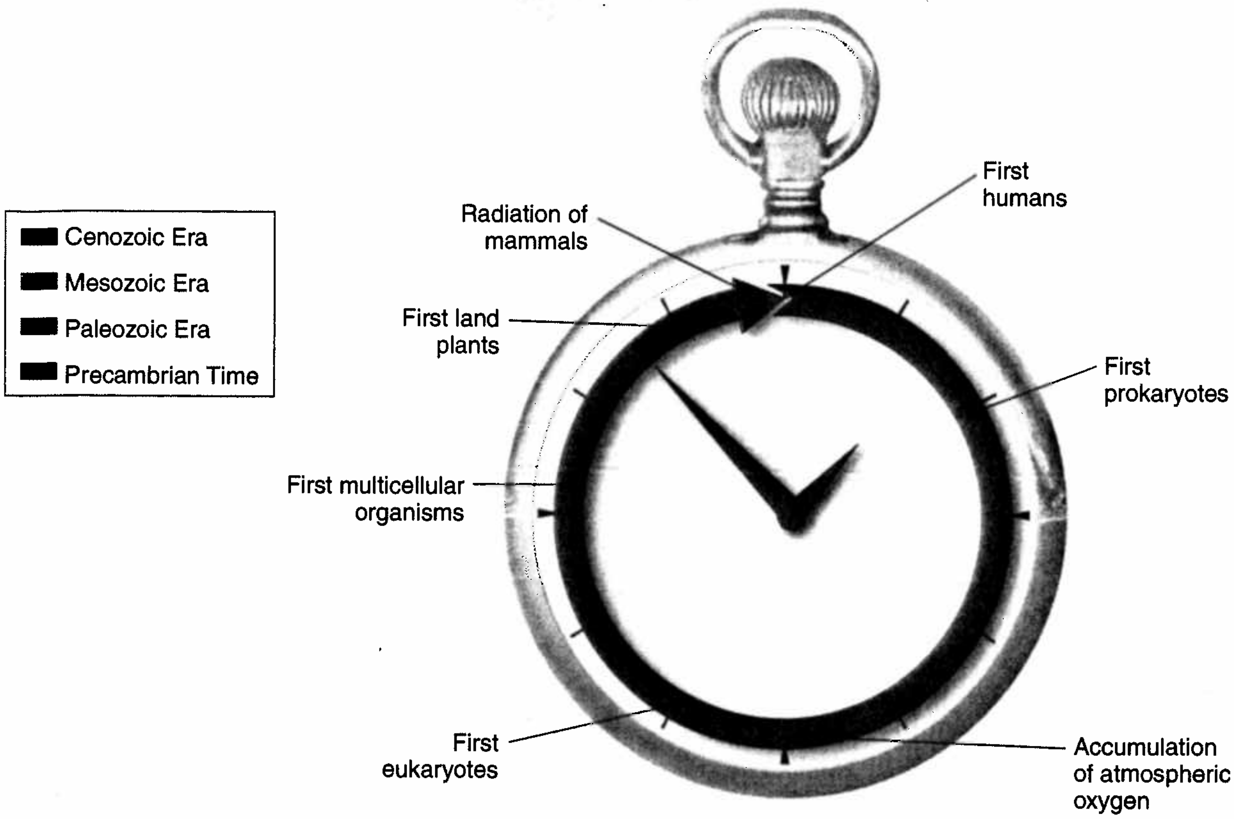
The Mesozoic (mez-uh-ZOH-ik) began about 245 million years ago and lasted about 180 million years. Some people call the Mesozoic the Age of Dinosaurs, yet dinosaurs were only one of many kinds of organisms that lived during this era. Mammals began to evolve during the Mesozoic.

Earth's most recent era is the Cenozoic (sen-uh-ZOH-ik). It began about 65 million years ago and continues to the present. The Cenozoic is sometimes called the Age of Mammals because mammals became common during this time.

Geologic Time Scale

Era	Period	Time (millions of years ago)
Cenozoic	Quaternary	1.8 – present
	Tertiary	65 – 1.8
Mesozoic	Cretaceous	145 – 65
	Jurassic	208 – 145
	Triassic	245 – 208
Paleozoic	[illegible]	[illegible]
	Carboniferous	360 – 290
	Devonian	410 – 360
	Silurian	440 – 410
	Ordovician	505 – 440
	Cambrian	544 – 505
Precambrian Time	Vendian	650 – 544

▲ **Figure 17–5** **The basic units of the geologic time scale after Precambrian Time are eras and periods.** Each era is divided into periods.



▲ **Figure 17–6** Earth's history is often compared to a familiar measurement, such as the twelve hours between noon and midnight. In such a comparison, notice that Precambrian Time lasts from noon until after 10:30 PM. **Interpreting Graphics** *Using this model, about what time did life appear? The first plants? The first humans?*

Periods Eras are subdivided into **periods,** which range in length from tens of millions of years to less than two million years. The Mesozoic Era, for example, includes three periods: the Triassic Period, the Jurassic Period, and the Cretaceous Period. Many periods are named for places around the world where geologists first described the rocks and fossils of that period. The name Cambrian, for example, refers to Cambria, the old Roman name for Wales. Jurassic refers to the Jura Mountains in France. The Carboniferous ("carbon-bearing") Period, on the other hand, is named for the large coal deposits that formed during that period.

17–1 Section Assessment

1. **Key Concept** What can be learned from the fossil record?
2. **Key Concept** Which type of dating provides an absolute age for a given fossil? Describe how this is done.
3. **Key Concept** How are eras and periods related?
4. How do fossils form?
5. What geologic era is known as the Age of Mammals? When did this era begin?
6. **Critical Thinking Drawing Conclusions** Many more fossils have been found since Darwin's day, allowing several gaps in the fossil record to be filled. How might this information make relative dating more accurate?

Thinking Visually

Constructing a Timeline
Create a timeline that shows the four main divisions in the geologic time scale and the key events that occurred during those divisions. Then, as you read Section 17–3, add more events to your timeline.

17–2 Earth's Early History

If life comes only from life, then how did life on Earth first begin? This section presents the current scientific view of events on the early Earth. These hypotheses, however, are based on a relatively small amount of evidence. The gaps and uncertainties make it likely that scientific ideas about the origin of life will change.

Guide for Reading

Key Concepts
- What substances made up Earth's early atmosphere?
- What did Miller and Urey's experiments show?
- What occurred when oxygen was added to Earth's atmosphere?
- What hypothesis explains the origin of eukaryotic cells?

Vocabulary
proteinoid microsphere
microfossil
endosymbiotic theory

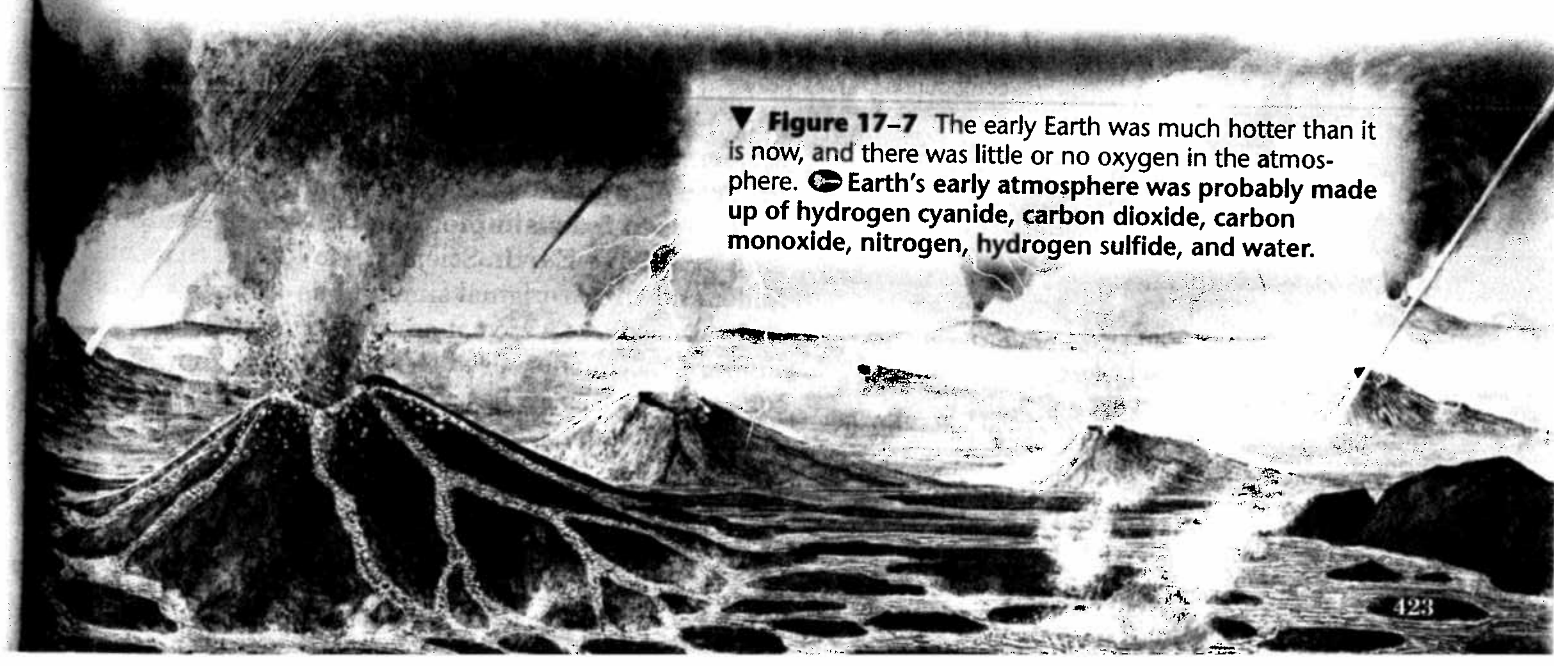
Reading Strategy: Making Comparisons
Before you read, write three sentences about Earth as it is today. As you read, write three sentences that describe how Earth was very different in the past.

Formation of Earth

Geologic evidence shows that Earth, which is about 4.6 billion years old, was not "born" in a single event. Instead, pieces of cosmic debris were probably attracted to one another over the course of about 100 million years. While the planet was young, it was struck by one or more objects, possibly as large as the planet Mars. This collision produced enough heat to melt the entire globe.

Once Earth melted, its elements rearranged themselves according to density. The most dense elements formed the planet's core. There, radioactive decay generated enough heat to convert Earth's interior into molten rock. Moderately dense elements floated to the surface, much as fat floats to the top of hot chicken soup. These elements ultimately cooled to form a solid crust. The least dense elements—including hydrogen and nitrogen—formed the first atmosphere.

This infant planet was very different from today's Earth. **Figure 17–7** shows how it might have looked. The sky was probably not blue but pinkish-orange. **Earth's early atmosphere probably contained hydrogen cyanide, carbon dioxide, carbon monoxide, nitrogen, hydrogen sulfide, and water.** Had you been there, a few deep breaths would have killed you!



▼ **Figure 17–7** The early Earth was much hotter than it is now, and there was little or no oxygen in the atmosphere. **Earth's early atmosphere was probably made up of hydrogen cyanide, carbon dioxide, carbon monoxide, nitrogen, hydrogen sulfide, and water.**

Geologists infer that about 4 billion years ago, Earth cooled enough to allow the first solid rocks to form on its surface. For millions of years afterward, violent volcanic activity shook Earth's crust. Comets and asteroids bombarded its surface. Oceans did not exist because the surface was extremely hot.

About 3.8 billion years ago, Earth's surface cooled enough for water to remain a liquid. Thunderstorms drenched the planet, and oceans covered much of the surface. Those primitive oceans were brown because they contained lots of dissolved iron. The earliest sedimentary rocks, which were deposited in water, have been dated to this period. This was the Earth on which life appeared.

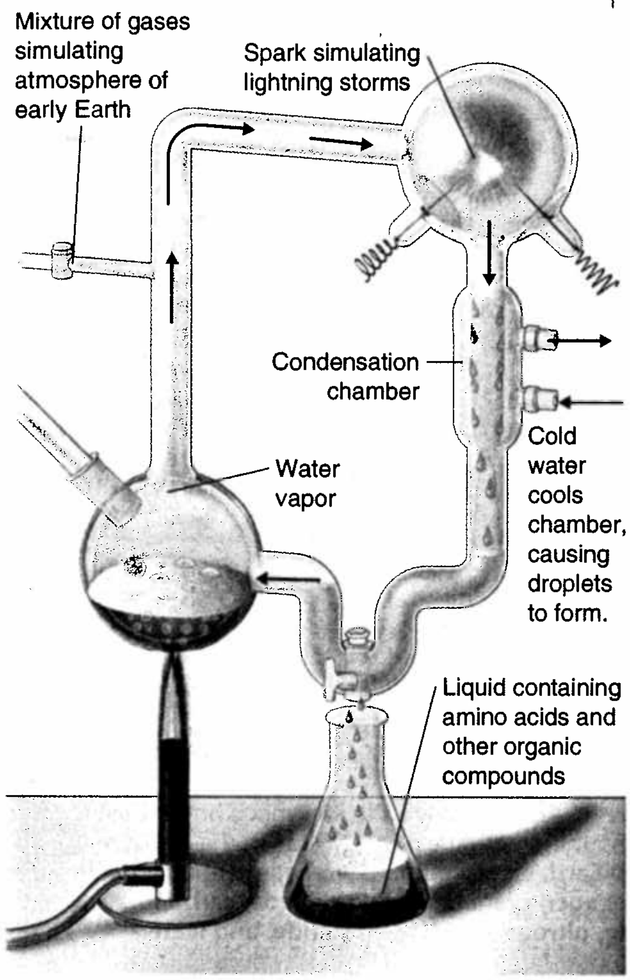
CHECKPOINT *Why did the early Earth not have oceans?*

The First Organic Molecules

For several reasons, atoms do not assemble themselves into complex organic molecules or living cells on Earth today. For one thing, the oxygen in the atmosphere is very reactive and would destroy many kinds of organic molecules not protected within cells. In addition, as soon as organic molecules appeared, something—bacteria or some other life form—would probably eat them! But the early Earth was a very different place. Could organic molecules have evolved under those conditions?

In the 1950s, American chemists Stanley Miller and Harold Urey tried to answer that question by simulating conditions on the early Earth in a laboratory setting. They filled a flask with hydrogen, methane, ammonia, and water to represent the atmosphere. They made certain that no microorganisms could contaminate the results. Then, as shown in **Figure 17–8,** they passed electric sparks through the mixture to simulate lightning.

The results were spectacular. Over a few days, several amino acids—the building blocks of proteins—began to accumulate. **Miller and Urey's experiments suggested how mixtures of the organic compounds necessary for life could have arisen from simpler compounds present on a primitive Earth.** Scientists now know that Miller and Urey's original simulations of Earth's early atmosphere were not accurate. However, similar experiments based on more current knowledge of Earth's early atmosphere have also produced organic compounds. In fact, one of Miller's experiments in 1995 produced cytosine and uracil, two of the bases found in RNA.



▲ **Figure 17–8** Miller and Urey produced amino acids, which are needed to make proteins, by passing sparks through a mixture of hydrogen, methane, ammonia, and water. **This and other experiments suggested how simple compounds found on the early Earth could have combined to form the organic compounds needed for life.**

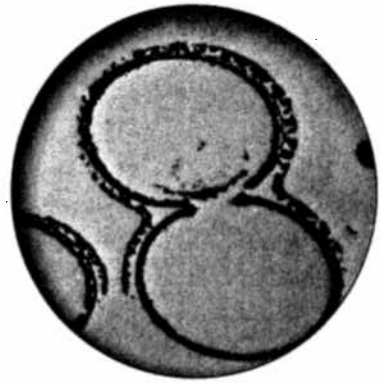
The Puzzle of Life's Origins

A stew of organic molecules is a long way from a living cell, and the leap from nonlife to life is the greatest gap in scientific hypotheses of Earth's early history. Geological evidence suggests that about 200 to 300 million years after Earth cooled enough to carry liquid water, cells similar to modern bacteria were common. How might these cells have originated?

Formation of Microspheres Under certain conditions, large organic molecules can form tiny bubbles called **proteinoid microspheres,** as shown in **Figure 17–9.** Microspheres are not cells, but they have some characteristics of living systems. Like cells, they have selectively permeable membranes through which water molecules can pass. Microspheres also have a simple means of storing and releasing energy. Several hypotheses suggest that structures similar to proteinoid microspheres might have acquired more and more characteristics of living cells.

Evolution of RNA and DNA Another unanswered question in the evolution of cells is the origin of DNA and RNA. Remember that all cells are controlled by information stored in DNA, which is transcribed into RNA and then translated into proteins. How could this complex biochemical machinery have evolved?

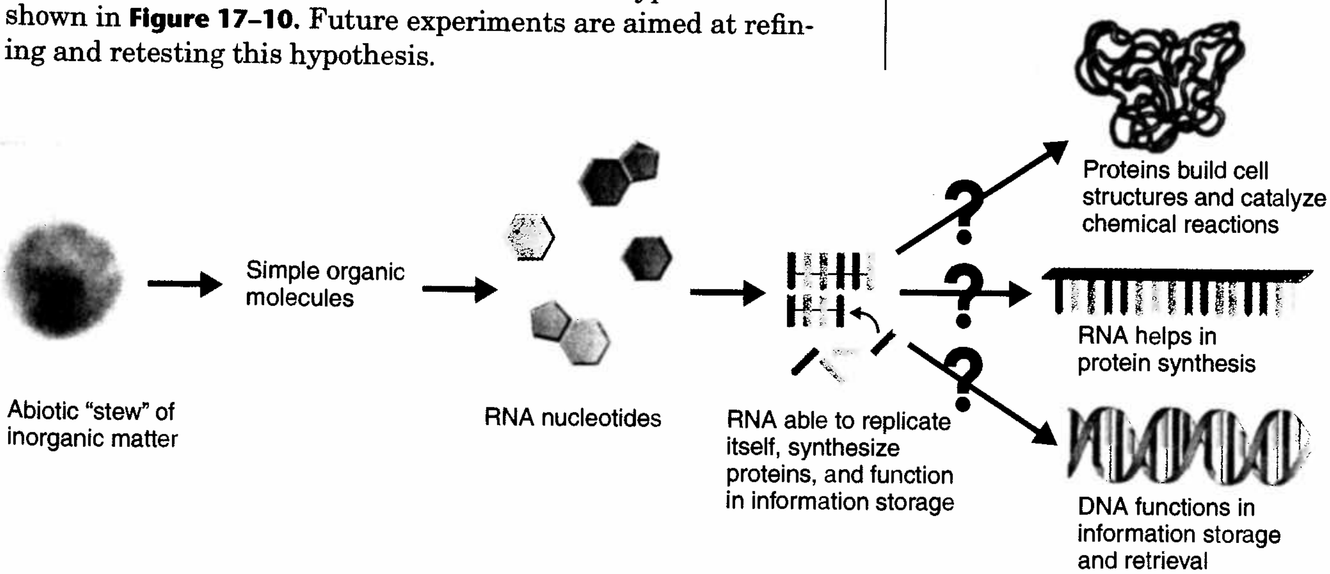
Science cannot yet solve this puzzle, although molecular biologists have made surprising discoveries in this area. Under the right conditions, some RNA sequences can help DNA replicate. Other RNA sequences process messenger RNA after transcription. Still others catalyze chemical reactions. Some RNA molecules can even grow and duplicate themselves—suggesting that RNA might have existed before DNA. A series of experiments that simulated conditions of the early Earth have suggested that small sequences of RNA could have formed and replicated on their own. From this relatively simple RNA-based form of life, several steps could have led to the system of DNA-directed protein synthesis that exists now. This hypothesis is shown in **Figure 17–10.** Future experiments are aimed at refining and retesting this hypothesis.

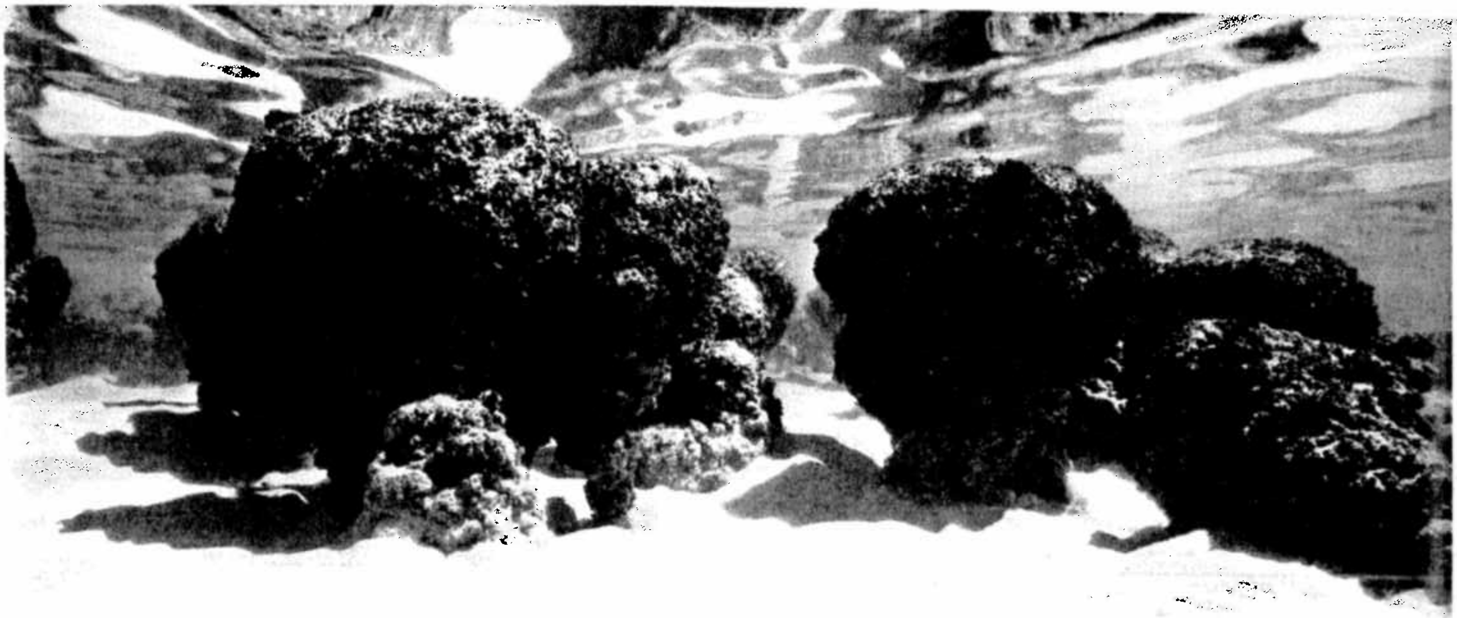


(magnification: about 10,000×)

▲ **Figure 17–9** Large organic molecules can sometimes form tiny proteinoid microspheres like the ones shown here. **Comparing and Contrasting** ***How are proteinoid microspheres similar to cells? How are they different?***

▼ **Figure 17–10** One hypothesis about the origin of life, illustrated here, suggests that RNA could have evolved before DNA. Scientists have not yet demonstrated the later stages of this process in a laboratory setting. **Interpreting Graphics** ***How might RNA have stored genetic information?***





▲ **Figure 17–11** **Ancient photosynthetic organisms produced a rise in oxygen in Earth's atmosphere.** These rocklike formations, called stromatolites, were made by cyanobacteria, which were probably among the earliest organisms to evolve on Earth.

Free Oxygen

Microscopic fossils, or **microfossils,** of unicellular prokaryotic organisms that resemble modern bacteria have been found in rocks more than 3.5 billion years old, as shown in **Figure 17–11.** Those first life-forms must have evolved in the absence of oxygen, because Earth's first atmosphere contained very little of that highly reactive gas.

Over time, as indicated by fossil evidence, photosynthetic bacteria became common in the shallow seas of the Precambrian. By 2.2 billion years ago at the latest, these organisms were steadily churning out oxygen, an end product of photosynthesis. One of the first things oxygen did was to combine with iron in the oceans. In other words, it caused the oceans to rust! When iron oxide was formed, it fell from the sea water to the ocean floor. There, it formed great bands of iron that are the source of most of the iron ore mined today. Without iron, the oceans changed color from brown to blue-green.

Next, oxygen gas started accumulating in the atmosphere. As atmospheric oxygen concentrations rose, concentrations of methane and hydrogen sulfide began to decrease, the ozone layer began to form, and the skies turned their present shade of blue. Over the course of several hundred million years, oxygen concentrations rose until they reached today's levels.

Biologists hypothesize that the increase in this highly reactive gas created the first global "pollution" crisis. To the first cells, oxygen was a deadly poison! **The rise of oxygen in the atmosphere drove some life-forms to extinction, while other life-forms evolved new, more efficient metabolic pathways that used oxygen for respiration.** Organisms that had evolved in an oxygen-free atmosphere were forced into a few airless habitats, where their anaerobic descendants remain today. Some organisms, however, evolved ways of using oxygen for respiration and protecting themselves from oxygen's powerful reactive abilities. The stage was set for the evolution of modern life.

✓CHECKPOINT *What process added oxygen to Earth's atmosphere?*

Origin of Eukaryotic Cells

Several important events in the history of life have been revealed through molecular studies of cells and their organelles. One of these events is the origin of eukaryotic cells, which are cells that have nuclei. About 2 billion years ago, prokaryotic cells—cells without nuclei—began evolving internal cell membranes. The result was the ancestor of all eukaryotic cells.

The Endosymbiotic Theory Then, something radical seems to have happened. Other prokaryotic organisms entered this ancestral eukaryote. These organisms did not infect their host, as parasites would have done, and the host did not digest them, as it would have digested prey. Instead, the smaller prokaryotes began living inside the larger cell, as shown in **Figure 17–12.** Over time, a symbiotic, or interdependent, relationship evolved. According to the **endosymbiotic theory,** eukaryotic cells formed from a symbiosis among several different prokaryotic organisms. One group of prokaryotes had the ability to use oxygen to generate energy-rich molecules of ATP. These evolved into the mitochondria that are now in the cells of all multicellular organisms. Other prokaryotes that carried out photosynthesis evolved into the chloroplasts of plants and algae. **The endosymbiotic theory proposes that eukaryotic cells arose from living communities formed by prokaryotic organisms.**

This hypothesis was proposed more than a century ago, when microscopists saw that the membranes of mitochondria and chloroplasts resembled the plasma membranes of free-living prokaryotes. Yet, the endosymbiotic theory did not receive much support until the 1960s, when it was championed by Lynn Margulis of Boston University.

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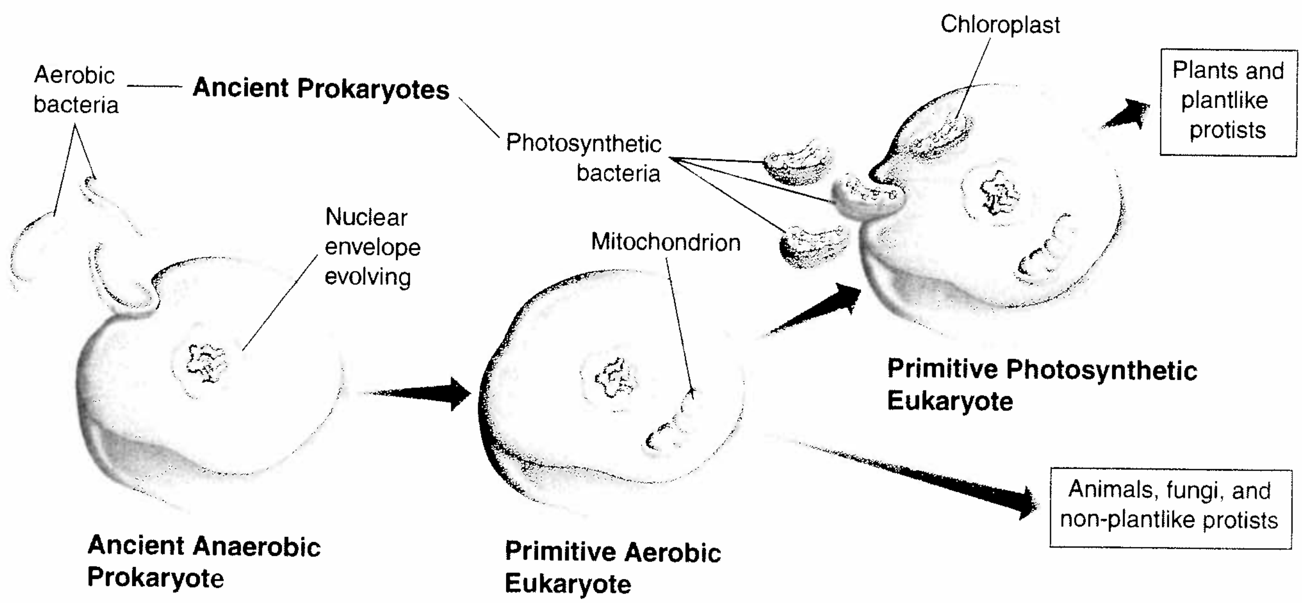
Visit: www.SciLinks.org
Web Code: cbn-5172

▼ **Figure 17–12 The endosymbiotic theory proposes that eukaryotic cells arose from living communities formed by prokaryotic organisms.** Ancient prokaryotes may have entered primitive eukaryotic cells and remained there as organelles.



▲ **Figure 17–13** This ancient jellyfish, an early multicellular animal from Precambrian Time, did not have bones or other hard parts, but it left behind a fossil that allowed biologists to infer its overall shape. **Observing** *What evidence shows that this organism had body parts arranged around a central point?*

The Evidence Lynn Margulis and her supporters built their argument on several pieces of evidence: First, mitochondria and chloroplasts contain DNA similar to bacterial DNA. Second, mitochondria and chloroplasts have ribosomes whose size and structure closely resemble those of bacteria. Third, like bacteria, mitochondria and chloroplasts reproduce by binary fission when the cells containing them divide by mitosis. Thus, mitochondria and chloroplasts have many of the features of free-living bacteria. These similarities provide strong evidence of a common ancestry between free-living bacteria and the organelles of living eukaryotic cells.

Sexual Reproduction and Multicellularity

Some time after eukaryotic cells arose, those cells began to reproduce sexually. This development enabled evolution to take place at far greater speeds than ever before. How did sexual reproduction speed up the evolutionary process?

Most prokaryotes reproduce asexually. Often, they simply duplicate their genetic material and divide into two new cells. Although this process is efficient, it yields daughter cells that are exact duplicates of the parent cell. This type of reproduction restricts genetic variation to mutations in DNA. Sexual reproduction, on the other hand, shuffles and reshuffles genes in each generation, much like a person shuffling a deck of cards. The offspring of sexually reproducing organisms, therefore, never resemble their parents exactly. By increasing the number of gene combinations, sexual reproduction increases the probability that favorable combinations will be produced. Favorable gene combinations greatly increase the chances of evolutionary change in a species due to natural selection.

A few hundred million years after the evolution of sexual reproduction, evolving life forms crossed another great threshold: the development of multicellular organisms from unicellular organisms. These first multicellular organisms, such as the one shown in **Figure 17–13,** experienced a great increase in diversity. The evolution of life was well on its way.

17–2 Section Assessment

1. **Key Concept** What substances probably made up Earth's early atmosphere?
2. **Key Concept** What molecules were the end products in Miller and Urey's experiments?
3. **Key Concept** How did the addition of oxygen to Earth's atmosphere affect life of that time?
4. **Key Concept** According to the endosymbiotic theory, how might chloroplasts and mitochondria have originated?
5. **Critical Thinking Predicting** You just read that life arose from nonlife billions of years ago. Could life arise from nonlife today? Explain.

Focus on the BIG Idea

Cellular Basis of Life
The endosymbiotic theory accounts for the evolution of mitochondria and chloroplasts in eukaryotic cells. Review the description of eukaryotic cells in Chapter 7, and then describe the structure and function of mitochondria and chloroplasts.

17–3 Evolution of Multicellular Life

BI 8.e. Students know how to analyze fossil evidence with regard to biological diversity, episodic speciation, and mass extinction.

Although the fossil record has missing pieces, paleontologists have assembled good evolutionary histories for many groups of organisms. Furthermore, the fossil record indicates that major changes occurred in Earth's climate, geography, and life-forms. In this section, you will get an overview of how multicellular life evolved from its earliest forms to its present-day diversity.

Precambrian Time

Recall that almost 90 percent of Earth's history occurred during the Precambrian. During this time, simple anaerobic forms of life appeared and were followed by photosynthetic forms, which added oxygen to the atmosphere. Aerobic forms of life evolved, and eukaryotes appeared. Some of those organisms gave rise to multicellular forms that continued to increase in complexity. Few fossils exist from this time because the animals were all soft-bodied. Life existed only in the sea.

Paleozoic Era

Rich fossil evidence shows that early in the Paleozoic Era, there was a diversity of marine life. Scientists once thought that those different forms of life evolved rapidly at the beginning of the Paleozoic, but increasing evidence from Precambrian fossils and DNA studies suggests that life began to diversify much earlier. Regardless of when these forms evolved, fossil evidence shows that life was highly diverse by the first part of the Paleozoic Era, the Cambrian Period. An artist's portrayal of Cambrian life, which included many kinds of invertebrate animals, is shown in **Figure 17–14.**

Guide for Reading

Key Concept

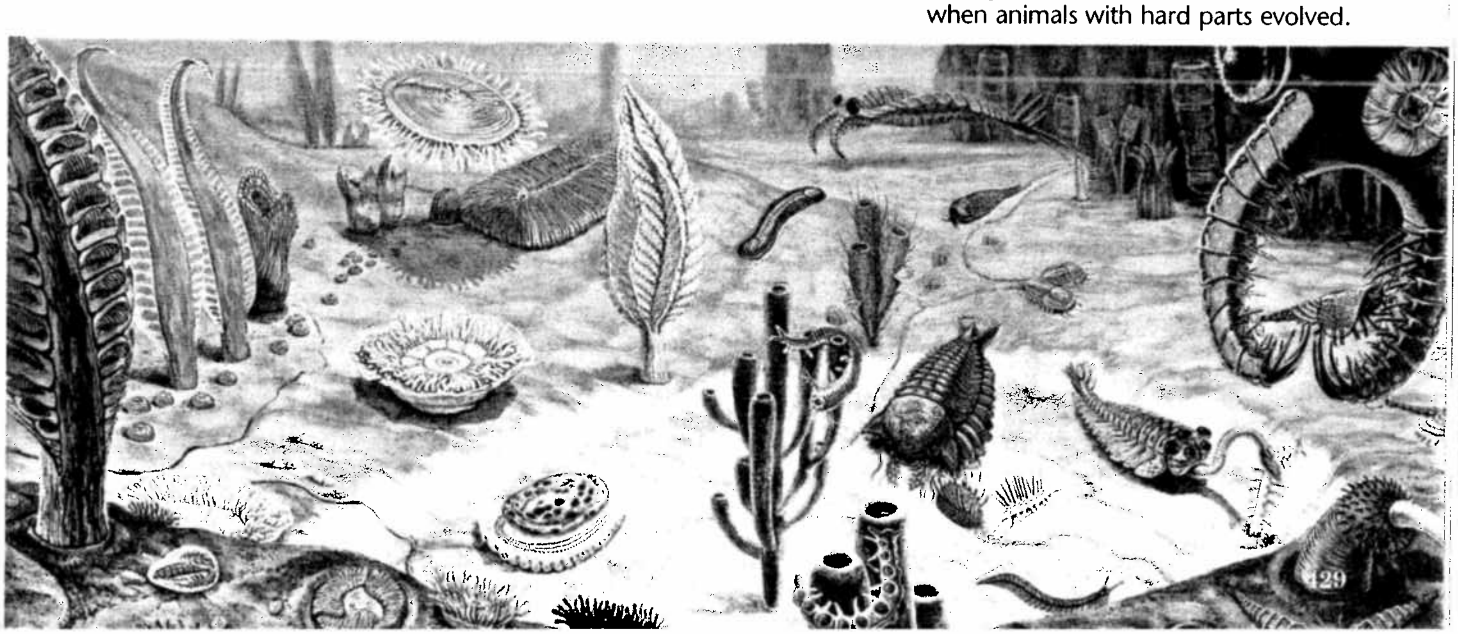
- What were the characteristic forms of life in the Paleozoic, Mesozoic, and Cenozoic eras?

Vocabulary

mass extinction

Reading Strategy: Using Graphic Organizers
As you read, make a table of the three geologic eras described in the section. Include information about the typical organisms and main evolutionary events of each era.

▼ **Figure 17–14 The fossil record shows evidence of many types of marine life early in the Paleozoic Era.** These and other unfamiliar organisms dwelt in the sea during the Cambrian Period, a time when animals with hard parts evolved.



Cambrian Period Paleontologists call the diversification of life during the early Cambrian Period the "Cambrian Explosion." For the first time, many organisms had hard parts, including shells and outer skeletons. During the Cambrian Period, the first known representatives of most animal phyla evolved. Invertebrates—such as jellyfishes, worms, and sponges—drifted through the water, crawled along the sandy bottom, or attached themselves to the ocean floors. Brachiopods, which were small animals with two shells, were especially common. They resembled—but were unrelated to—modern clams. Trilobites were also common. Trilobites were arthropods, which are invertebrates with segmented bodies, jointed limbs, and an external skeleton.

CHECKPOINT *What is the "Cambrian Explosion"?*

▲ **Figure 17–15** During the Ordovician Period, aquatic arthropods like this eurypterid evolved. Eurypterids had segmented bodies and lived in water. Some of them grew to a length of almost 13 meters. Eurypterids are now extinct. **Comparing and Contrasting** *Which of today's animals do eurypterids resemble?*

Ordovician and Silurian Periods During the Ordovician (awr-duh-VISH-un) and Silurian (sih-LOOR-ee-un) periods, the ancestors of the modern octopi and squid appeared, as did aquatic arthropods like the one in **Figure 17–15.** Some arthropods became the first animals to live on land. Among the first vertebrates (animals with backbones) to appear were jawless fishes, which had suckerlike mouths. The first land plants evolved from aquatic ancestors. These simple plants grew low to the ground in damp areas.

Devonian Period By the Devonian (dih-VOH-nee-un) Period, some plants, such as ferns, had adapted to drier areas, allowing them to invade more habitats. Insects, which are arthropods, appeared on land. In the seas, both invertebrates and vertebrates thrived. Even though the invertebrates were far more numerous, the Devonian is often called the Age of Fishes because many groups of fishes were present in the oceans. Most fishes of this time had jaws, bony skeletons, and scales on their bodies. Sharks appeared in the late Devonian.

During the Devonian, vertebrates began to invade the land. The first fishes to develop the ability to crawl awkwardly on leglike fins were still fully aquatic animals. Some of these early four-legged vertebrates evolved into the first amphibians. An amphibian (am-FIB-ee-un) is an animal that lives part of its life on land and part of its life in water.

Carboniferous and Permian Periods Throughout the rest of the Paleozoic Era, life expanded over Earth's continents. Other groups of vertebrates, such as reptiles, evolved from certain amphibians. Reptiles are animals that have scaly skin and lay eggs with tough, leathery shells. Winged insects evolved into many forms, including huge dragonflies and cockroaches. Giant ferns and other plants formed vast swampy forests, shown in **Figure 17–16.** The remains of those ancient plants formed thick deposits of sediment that changed into coal over millions of years, giving the Carboniferous its name.

At the end of the Paleozoic, many organisms died out. This was a **mass extinction,** in which many types of living things became extinct at the same time. **The mass extinction at the end of the Paleozoic affected both plants and animals on land and in the seas. As much as 95 percent of the complex life in the oceans disappeared.** For example, trilobites, which had existed since early in the Paleozoic, suddenly became extinct. Many amphibians also became extinct. Not all organisms disappeared, however. The mass extinction did not affect many fishes. Numerous reptiles also survived.

▲ **Figure 17–16** Ancient forests like this one from the Carboniferous Period were characterized by a huge variety of life-forms. **At the end of the Paleozoic Era, many types of animals and plants became extinct.**

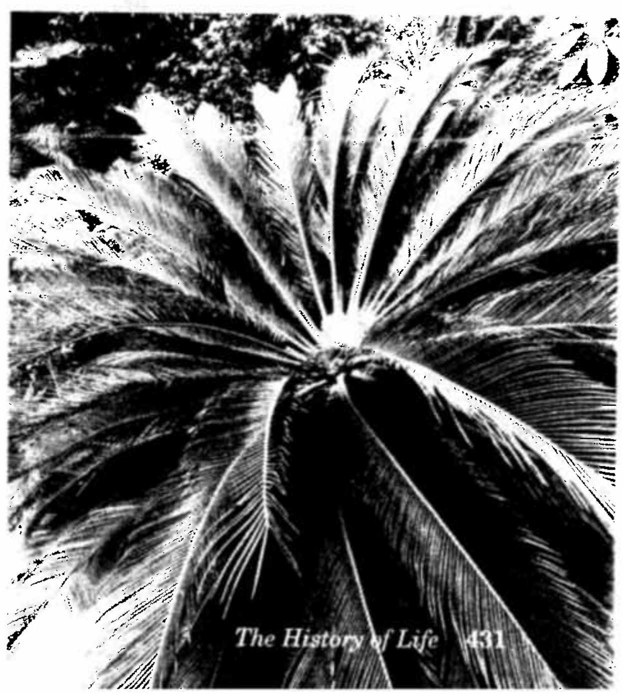
Mesozoic Era

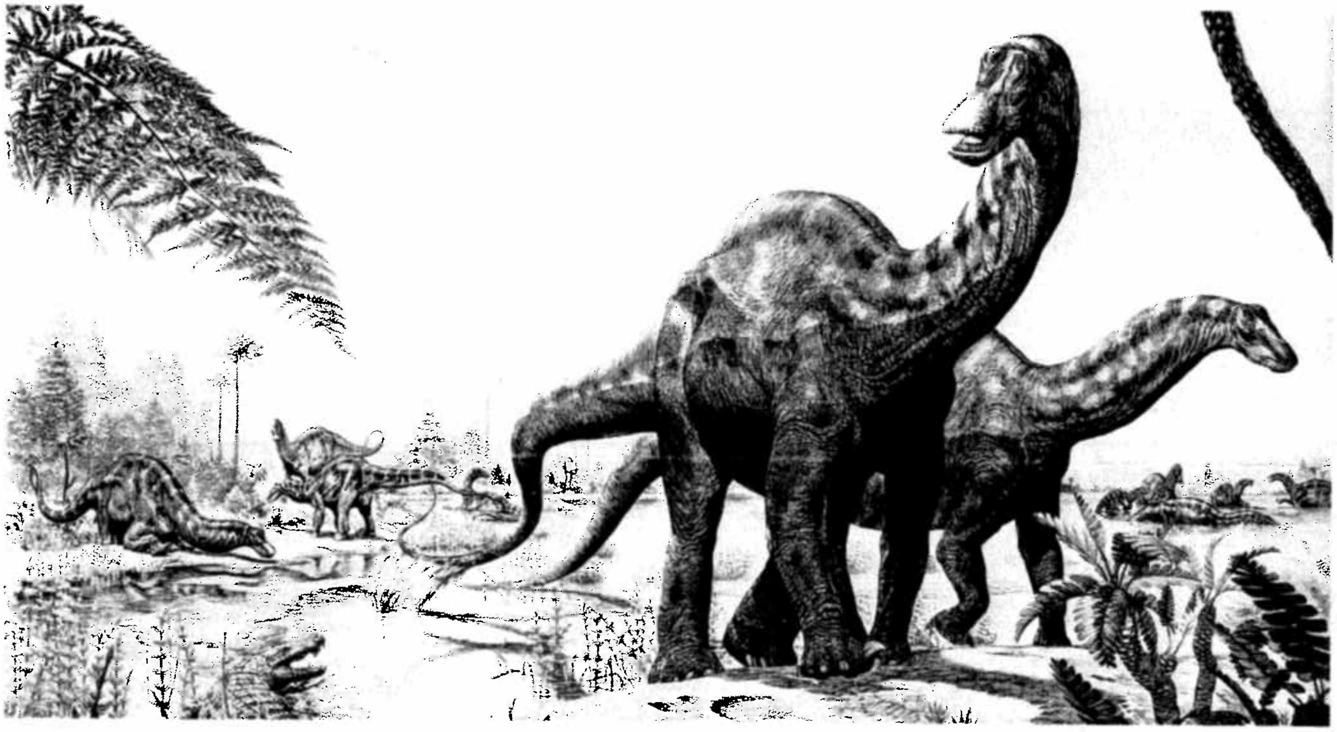
The Mesozoic Era lasted approximately 180 million years. **Events during the Mesozoic include the increasing dominance of dinosaurs. The Mesozoic is marked by the appearance of flowering plants.**

Those organisms that survived the Permian mass extinction became the main forms of life early in the Triassic (try-AS-ik) Period. Important organisms in this new ecosystem were fishes, insects, reptiles, and cone-bearing plants like the one in **Figure 17–17.** Reptiles were so successful during the Mesozoic Era that this time is often called the Age of Reptiles.

About 225 million years ago, the first dinosaurs appeared. One of the earliest dinosaurs, *Coelophysis,* was a meat-eater that had light, hollow bones and ran swiftly on its hind legs. Mammals also first appeared during the late Triassic Period, probably evolving from mammal-like reptiles. Mammals of the Triassic were very small, about the size of a mouse or shrew.

▼ **Figure 17–17** Among the seed plants of the Triassic Period were cone-bearing plants called cycads, which left this modern descendant. **Applying Concepts** *What other organisms were important in the Triassic Period?*





▲ **Figure 17–18** **During the Mesozoic Era, dinosaurs were dominant.** *Dicraeosaurus* (foreground) was a plant-eater that grew to about 20 meters in length.

Jurassic Period During the Jurassic (joo-RAS-ik) Period, dinosaurs became the dominant animals on land. Dinosaurs "ruled" Earth for about 150 million years, but different types lived at different times. At 20 meters long, *Dicraeosaurus*, shown in **Figure 17–18**, was one of the larger dinosaurs of the Jurassic Period.

One of the first birds, called *Archaeopteryx*, appeared during this time. Many paleontologists now think that birds are close relatives of dinosaurs. Since the 1990s, scientists working in China have found evidence for this hypothesis in other fossils that have the skulls and teeth of dinosaurs but the body structure and feathers of birds.

Cretaceous Period Reptiles were still the dominant vertebrates throughout the Cretaceous (krih-TAY-shus) Period. Dinosaurs such as the meat-eating *Tyrannosaurus rex* dominated land ecosystems, while flying reptiles and birds soared in the sky. Flying reptiles, however, became extinct during the Cretaceous. In the seas, turtles, crocodiles, and extinct reptiles such as plesiosaurs swam among fishes and marine invertebrates.

The Cretaceous also brought new forms of life, including leafy trees, shrubs, and small flowering plants like those you see today. Unlike the conifers, flowering plants produce seeds enclosed in a fruit, which protects the seed and aids in dispersing it to new locations.

At the close of the Cretaceous, another mass extinction occurred. More than half of all plant and animal groups were wiped out, including all of the dinosaurs.

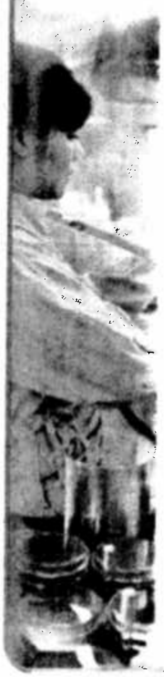
✓CHECKPOINT *When did flowering plants evolve?*

▶ **Figure 17–19** **During the Cenozoic Era, mammals evolved adaptations that allowed them to live on land, in water, and even in the air.** Two of the traits that contributed to the success of mammals were a covering of hair that provided insulation against the cold and the protection of the young before and after birth.

Cenozoic Era

During the Mesozoic, early mammals competed with dinosaurs for food and places to live. The extinction of dinosaurs at the end of the Mesozoic, however, created a different world. **During the Cenozoic, mammals evolved adaptations that allowed them to live in various environments—on land, in water, and even in the air.** One land mammal from the early Cenozoic is shown in **Figure 17–19.** Paleontologists often call the Cenozoic the Age of Mammals.

Tertiary Period During the Tertiary Period, Earth's climates were generally warm and mild. In the oceans, marine mammals such as whales and dolphins evolved. On land, flowering plants and insects flourished. Grasses evolved, providing a food source that encouraged the evolution of grazing mammals, the ancestors of today's cattle, deer, sheep, and other grass-eating mammals. Some mammals became very large, as did some birds.



Careers in Biology

Fossil Preparer

Job Description: work for private industries, museums, or universities to expose fossils covered by rock or soil or to construct missing fossil parts

Education: a college degree in biology or geology, knowledge about the fossils being worked on

Skills: be knowledgeable about many areas of science, ability to use fine tools under a microscope, self-motivated, patient, ability to handle very fragile specimens for long periods

Highlights: work with fossils; collaborate with many types of people—from amateur fossil collectors to professional paleontologists

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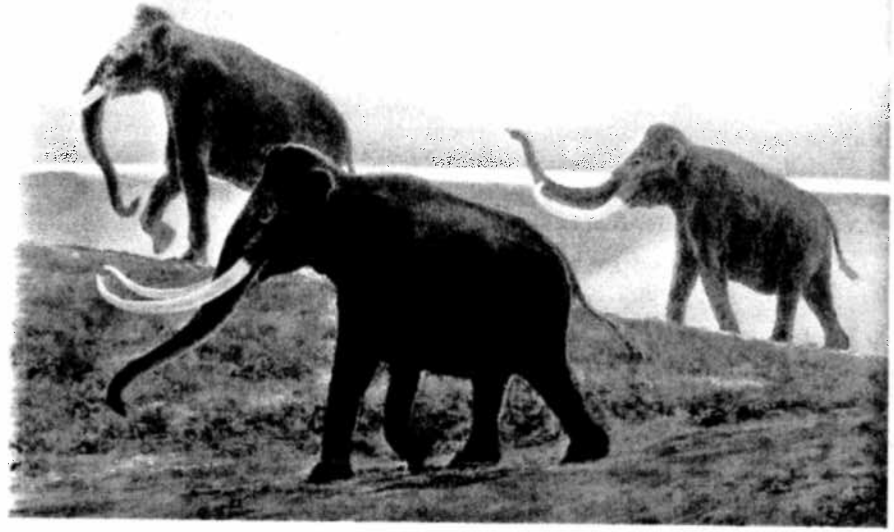
➤ **Figure 17–20** During the Quaternary Period, Earth's climate cooled, producing a series of ice ages. Among the characteristic animals of the time were these huge mammoths. **Inferring** ***How might the change to a colder climate have affected different types of organisms?***



Quaternary Period Mammals that had evolved during the Tertiary Period eventually faced a changing environment during the Quaternary Period. During this time, Earth's climate cooled, causing a series of ice ages. Repeatedly, thick continental glaciers advanced and retreated over parts of Europe and North America. So much of Earth's water was frozen in continental glaciers that the level of the oceans fell by more than 100 meters. Then, about 20,000 years ago, Earth's climate began to warm. Over the course of thousands of years, the continental glaciers melted. This caused sea levels to rise again.

In the oceans, algae, coral, mollusks, fishes, and mammals thrived. Insects and birds shared the skies. On land, mammals—such as bats, cats, dogs, cattle, and the mammoths shown in **Figure 17–20**—became common. The fossil record suggests that the early ancestors of our species appeared about 4.5 million years ago but that they did not look entirely human. The first fossils assigned to our own species, *Homo sapiens,* may have appeared as early as 200,000 years ago in Africa. According to one hypothesis, members of our species began a series of migrations from Africa that ultimately colonized the world.

17–3 Section Assessment

1. **Key Concept** Where did life exist during the early Paleozoic Era?
2. **Key Concept** What evolutionary milestone involving animals occurred during the Devonian Period?
3. **Key Concept** What are two key events from the Mesozoic Era?
4. **Critical Thinking Inferring** If you were a paleontologist investigating fossils from the Cenozoic Era, what fossils might you find?

Writing in Science

Creative Writing
Choose one of the periods described in this section. Then, write a story about life during that time. Include information about the life-forms, weather, and other characteristics.

17–4 Patterns of Evolution

7 3.c. Students know how independent lines of evidence from geology, fossils, and comparative anatomy provide the bases for the theory of evolution. BI 8.e. Students know how to analyze fossil evidence with regard to biological diversity, episodic speciation, and mass extinction.

Guide for Reading

Key Concept
- What are six important patterns of macroevolution?

Vocabulary
macroevolution
adaptive radiation
convergent evolution
coevolution
punctuated equilibrium

Reading Strategy: Summarizing
List the six patterns of macroevolution described in this section. As you read, write a statement describing each pattern.

Biologists often use the term **macroevolution** to refer to large-scale evolutionary patterns and processes that occur over long periods of time. **Six important topics in macroevolution are extinction, adaptive radiation, convergent evolution, coevolution, punctuated equilibrium, and changes in developmental genes.**

Extinction

More than 99 percent of all species that have ever lived are now extinct. Usually, extinctions happen for the reasons that Darwin proposed. Species compete for resources, and environments change. Some species adapt and survive. Others gradually become extinct in ways that are often caused by natural selection.

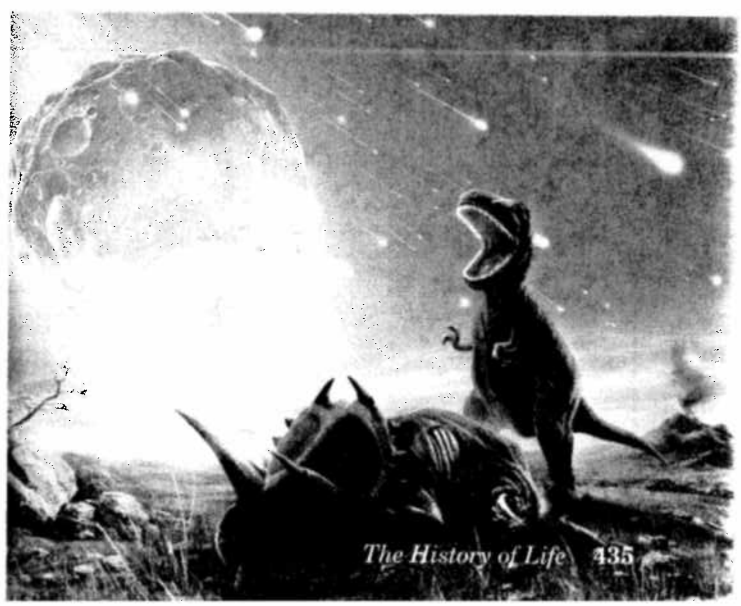
Several times in Earth's history, however, mass extinctions wiped out entire ecosystems. Food webs collapsed, and this disrupted energy flow through the biosphere. During these events, some biologists propose, many species became extinct because their environment was collapsing around them, rather than because they were unable to compete. Under these environmental pressures, extinction is not necessarily related to ordinary natural selection.

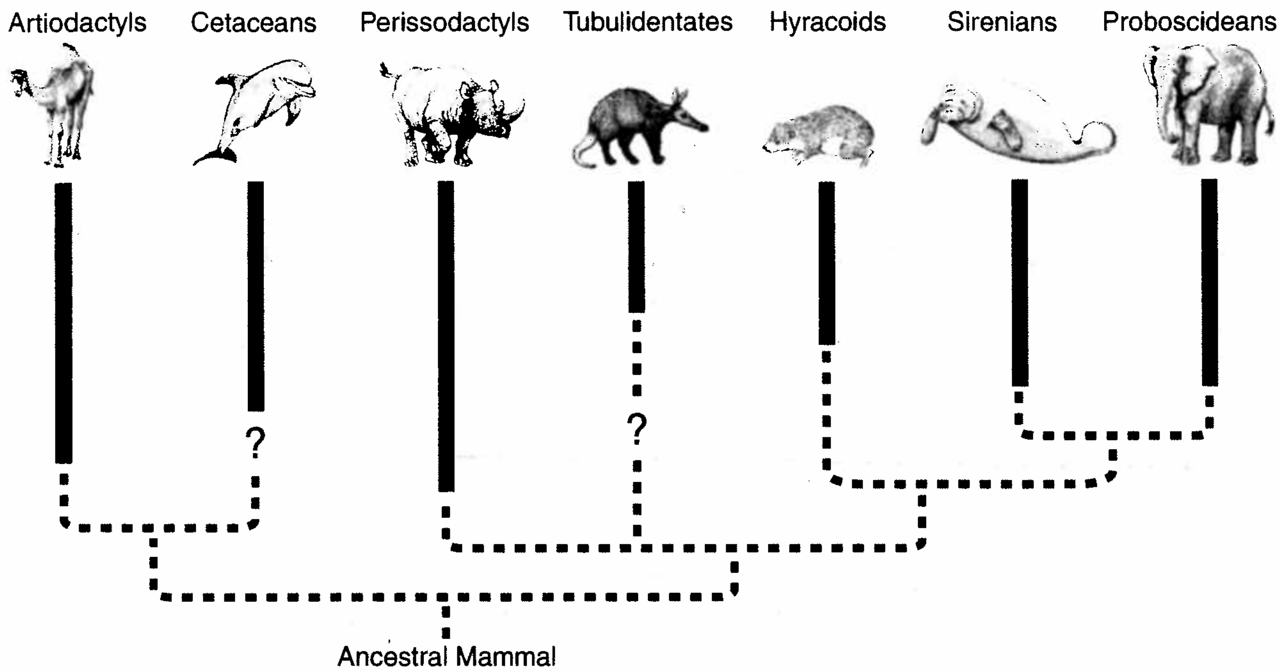
Until recently, most researchers looked for a single, major cause for each mass extinction. For example, one hypothesis suggests that at the end of the Cretaceous Period, the impact of a huge asteroid, as shown in **Figure 17–21**, wiped out the dinosaurs and many other organisms. Scientific evidence confirms that an asteroid did strike Earth at that time. The impact threw huge amounts of dust and water vapor into the atmosphere and probably caused global climate change. It is reasonable to assume that this kind of event played a role in the end of the dinosaurs.

Many paleontologists, however, think that most mass extinctions were caused by several factors. During several mass extinctions, many large volcanoes were erupting, continents were moving, and sea levels were changing. Researchers have not yet determined the precise causes of mass extinctions.

What effects have mass extinctions had on the history of life? Each disappearance of so many species left habitats open and provided ecological opportunities for those organisms that survived. The result was often a burst of evolution that produced many new species. The extinction of the dinosaurs, for example, cleared the way for the evolution of modern mammals and birds.

▼ **Figure 17–21** **Mass extinctions are one pattern of macroevolution.** A huge asteroid hitting Earth may have caused the extinction of the dinosaurs at the end of the Cretaceous Period. This illustration shows an artist's conception of that event.





▲ **Figure 17–22** This diagram shows part of the adaptive radiation of mammals, emphasizing current hypotheses about how a group of ancestral mammals diversified over millions of years into several related living orders. Note that the dotted lines and question marks in this diagram indicate a combination of gaps in the fossil record and uncertainties about the timing of evolutionary branching. **Interpreting Graphics** ***According to this diagram, which mammal group is the most closely related to elephants?***

Adaptive Radiation

Often, studies of fossils or of living organisms show that a single species or a small group of species has evolved, through natural selection and other processes, into diverse forms that live in different ways. This process is known as **adaptive radiation.** In the adaptive radiation of Darwin's finches, more than a dozen species evolved from a single species.

Adaptive radiations can also occur on a much larger scale. Dinosaurs, for example, were the products of a spectacular adaptive radiation among ancient reptiles. The first dinosaurs and the earliest mammals evolved at about the same time. Dinosaurs and other ancient reptiles, however, underwent an adaptive radiation first and "ruled" Earth for about 150 million years. During that time, mammals remained small and relatively scarce. But the disappearance of the dinosaurs cleared the way for the great adaptive radiation of mammals. This radiation, part of which is shown in **Figure 17–22,** produced the great diversity of mammals of the Cenozoic.

Convergent Evolution

Adaptive radiations can have an interesting evolutionary "side effect." They can produce unrelated organisms that look remarkably similar to one another. How does that happen? Sometimes, groups of different organisms, such as mammals and dinosaurs, undergo adaptive radiation in different places or at different times but in ecologically similar environments. These organisms start out with different "raw material" for natural selection to work on, but they face similar environmental demands, such as moving through air, moving through water, or eating similar foods.

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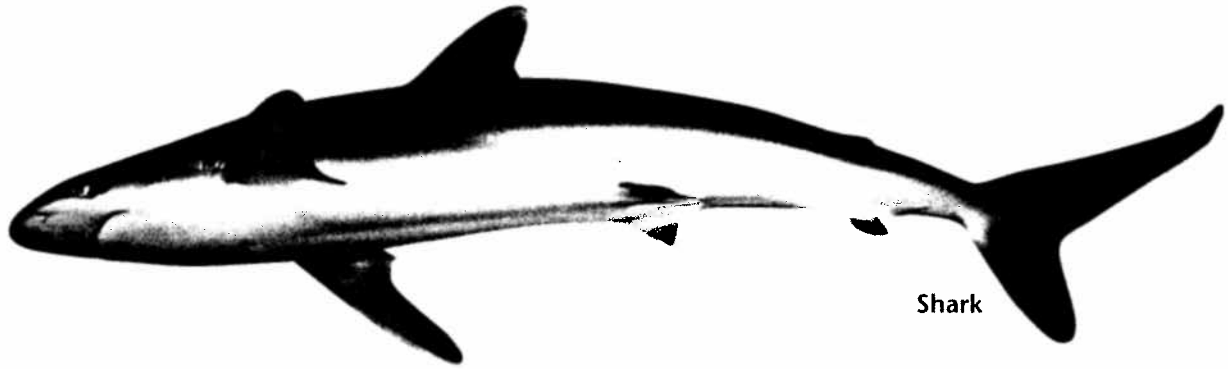


Figure 17–23 Each of these animals has a streamlined body and various appendages that enable it to move rapidly through water. Yet, the shark (above) is a fish, the penguin (center) is a bird, and the dolphin (bottom) is a mammal. **Applying Concepts** *How did these different animals come to resemble one another?*

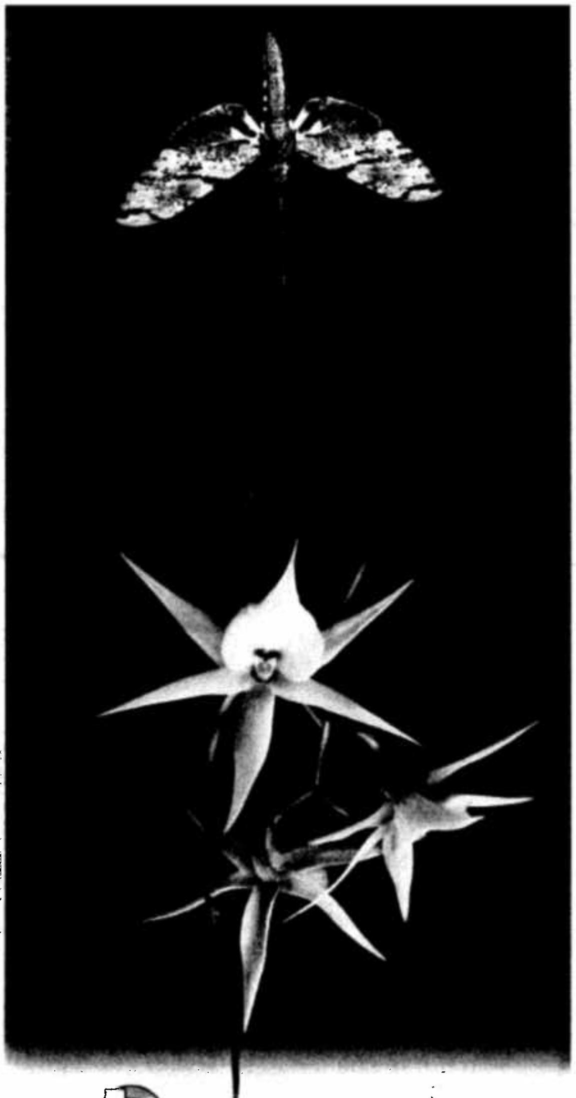
In these situations, natural selection may mold different body structures, such as arms and legs, into modified forms, such as wings or flippers. The wings or flippers function in the same way and look very similar. This process, by which unrelated organisms come to resemble one another, is called **convergent evolution.** Convergent evolution has occurred time and time again in both animals and plants.

Consider swimming animals, for example. An animal can move through the water rapidly with the least amount of energy if its body is streamlined and if it has body parts that can be used like paddles. That is why convergent evolution involving fishes, two different groups of aquatic mammals, and swimming birds has resulted in sharks, dolphins, seals, and penguins whose streamlined bodies and swimming appendages look a lot alike, as shown in **Figure 17–23.** Structures such as a dolphin's flukes and a fish's tail fin, which look and function similarly but are made up of parts that do not share a common evolutionary history, are called analogous structures. There are a surprising number of animals (including one of Darwin's finches) that have evolved adaptations analogous to those of woodpeckers for feeding on insects living beneath the bark of trees and in rotted wood.

✓CHECKPOINT *How do biologists explain the similar shapes of sharks and dolphins?*

Coevolution

Sometimes organisms that are closely connected to one another by ecological interactions evolve together. Many flowering plants, for example, can reproduce only if the shape, color, and odor of their flowers attract a specific type of pollinator. Not surprisingly, these kinds of relationships can change over time. An evolutionary change in one organism may also be followed by a corresponding change in another organism. The process by which two species evolve in response to changes in each other over time is called **coevolution.**



◀ **Figure 17–24** This orchid has an unusually long spur containing a supply of nectar within its tip. The hawk moth has an equally long feeding tube that enables it to feed on the nectar. The flower spur and the feeding tube are an example of coevolution. **Inferring** *How might natural selection bring about the evolution of this orchid and the moth?*

The pattern of coevolution involving flowers and insects is so common that biologists in the field often discover additional examples. When Charles Darwin saw an orchid like the one in **Figure 17–24,** he closely examined the long structure called a spur. Inside the tip of that 40-centimeter spur is a supply of nectar, which serves as food for many insects. Darwin predicted the discovery of a pollinating insect with a 40-centimeter structure that could reach the orchid's nectar. About fifty years later, researchers discovered a moth that matched Darwin's prediction.

Consider another example, the relationships between plants and plant-eating insects. Insects have been feeding on flowering plants since both groups emerged during the Mesozoic. Over time, a number of plants have evolved poisonous compounds that prevent insects from feeding on them. In fact, some of the most powerful poisons known in nature are plant compounds that have evolved in response to insect attacks. But once plants began to produce poisons, natural selection in herbivorous insects began to favor any variants that could alter, inactivate, or eliminate those poisons. In a few cases, coevolutionary relationships can be traced back over millions of years.

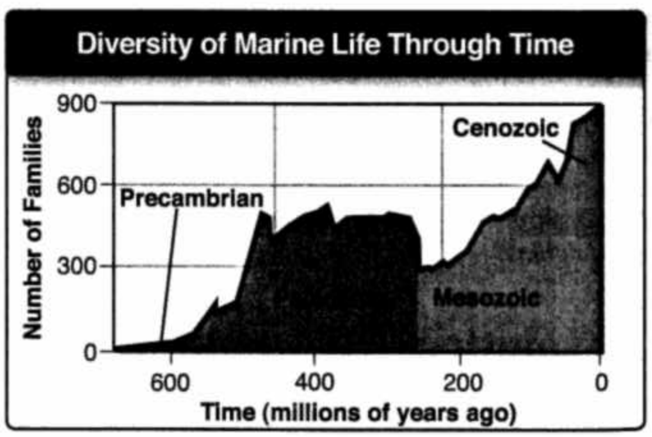
CHECKPOINT *What happens during coevolution?*

BIIE 1.k

Analyzing Data

Changing Number of Marine Families

Using fossil evidence, scientists make inferences about the kinds and number of organisms that lived at different times in the past. Further, they classify those organisms in ways that facilitate comparisons between past and present types. The graph on the right gives an estimate of the number of ocean-dwelling families over time. In biology, a family consists of several groups of related species.



1. **Using Tables and Graphs** What overall trend does this graph show?
2. **Calculating** What was the change in the number of marine families at the end of the Paleozoic Era? At the end of the Mesozoic?
3. **Inferring** What kind of event(s) might explain the changes at the end of the Paleozoic and Mesozoic eras?
4. **Predicting** What factors might cause this graph to change in the next 1000 years? The next 10,000,000 years? Explain.

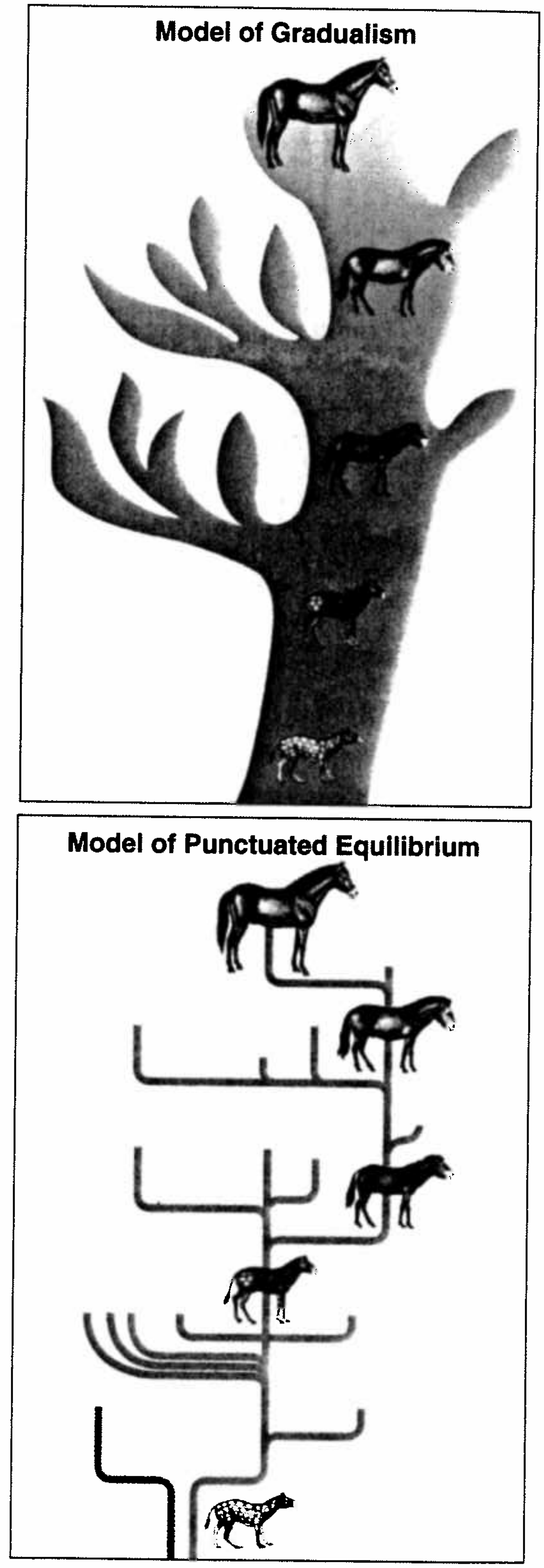
Punctuated Equilibrium

How quickly does evolution operate? Does it always occur at the same speed? These are questions on which some modern biologists would disagree with Darwin. Recall that Darwin was enormously impressed by the way Hutton and Lyell discussed the slow and steady nature of geologic change. Darwin, in turn, felt that biological change also needed to be slow and steady, an idea known as gradualism. In many cases, the fossil record confirms that populations of organisms did, indeed, change gradually over time.

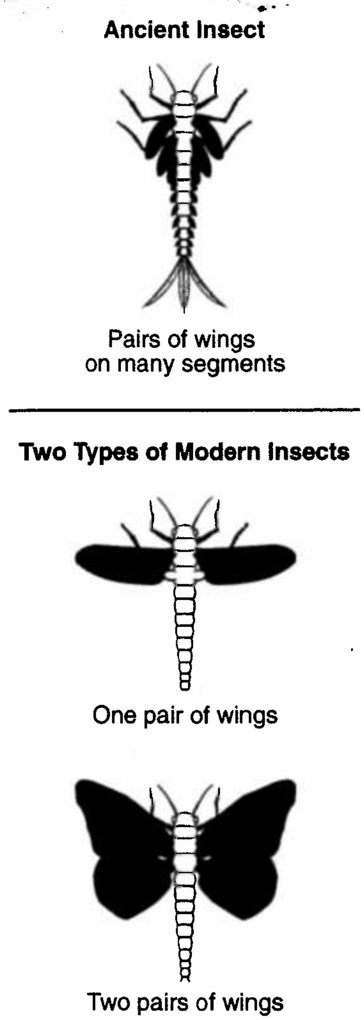
But there is also evidence that this pattern does not always hold. Some species, such as horseshoe crabs, have changed little from the time they first appeared in the fossil record. In other words, much of the time these species are in a state of equilibrium, which means they do not change very much. Every now and then, however, something happens to upset the equilibrium. At several points in the fossil record, changes in animals and plants occurred over relatively short periods of time. Some biologists suggest that most new species are produced by periods of rapid change. (Remember that "short" and "rapid" are relative to the geologic time scale. Short periods of time for geologists can be hundreds of thousands—even millions—of years!)

Rapid evolution after long periods of equilibrium can occur for several reasons. It may occur when a small population becomes isolated from the main part of the population. This small population can then evolve more rapidly than the larger one because genetic changes can spread more quickly among fewer individuals. Or it may occur when a small group of organisms migrates to a new environment. That's what happened with the Galápagos finches, for example. Organisms evolve rapidly to fill available niches. In addition, mass extinctions can open many ecological niches and provide new opportunities to those organisms that survive. Thus, it is not surprising that some groups of organisms have evolved rapidly following mass extinctions.

Scientists use the term **punctuated equilibrium** to describe this pattern of long, stable periods interrupted by brief periods of more rapid change. The concept of punctuated equilibrium, illustrated in **Figure 17–25,** has generated much debate and is still somewhat controversial among biologists today. It is clear, however, that evolution has often proceeded at different rates for different organisms at different times during the long history of life on Earth.



▲ **Figure 17–25** Biologists have considered two different explanations for the rate of evolution, as illustrated in these diagrams. Gradualism involves a slow, steady change in a particular line of descent. Punctuated equilibrium involves stable periods interrupted by rapid changes involving many different lines of descent. **Interpreting Graphics** ***How do the diagrams illustrate these explanations?***



▲ **Figure 17–26** Some ancient insects, such as the mayfly nymph (top), had winglike structures on many body segments. Modern insects have only four wings or two wings. **Changes in the expression of developmental genes may explain how these differences evolved.**

Developmental Genes and Body Plans

Biologists have long suspected that changes in the genes for growth and differentiation during embryological development could produce transformations in body shape and size. Until recently, however, researchers had only limited ability to affect gene activity in embryos. Therefore, they couldn't develop many of those hunches into testable scientific hypotheses. Molecular tools have changed all that. We can now perform experiments with gene expression by turning genes on or off and examining the results. These studies shed new light on how genetic change can produce major evolutionary transformations.

For example, as you saw in Chapter 12, "master control genes," called hox genes, guide development of major body structures in animals. Some determine which parts of an embryo become front and rear, or top and bottom. Others control the size and shape of arms, legs, or wings. Homologous control genes serve similar functions in animals as different as insects and humans—even though those animals haven't shared a common ancestor in at least 700 million years!

Small changes in the activity of control genes can affect many other genes to produce large changes in adult animals. If one gene, called "wingless," is turned on in an insect body segment, that segment grows no wings. This is interesting because some ancient insects, shown in **Figure 17–26,** had winglike structures on all body segments. Yet modern insects have wings on only one or two segments. Changes in the activation of this gene could have enabled many-winged ancestors of modern insects to evolve into four-winged and two-winged forms.

Small changes in the timing of cell differentiation and gene expression can make the difference between long legs and short ones, between long, slender fingers or short, stubby toes. In fact, recent studies suggest that differences in gene expression may cause many of the differences between chimpanzee brains and human brains. Small wonder that this new field is one of the hottest areas in all of evolutionary biology!

17–4 Section Assessment

1. **Key Concept** What is macroevolution? Describe two patterns of macroevolution.
2. What role have mass extinctions played in the history of life?
3. What is convergent evolution? Describe an example.
4. How might hox genes contribute to variation?
5. **Critical Thinking Comparing and Contrasting** Compare and contrast the hypotheses of gradualism and punctuated equilibrium.

Thinking Visually

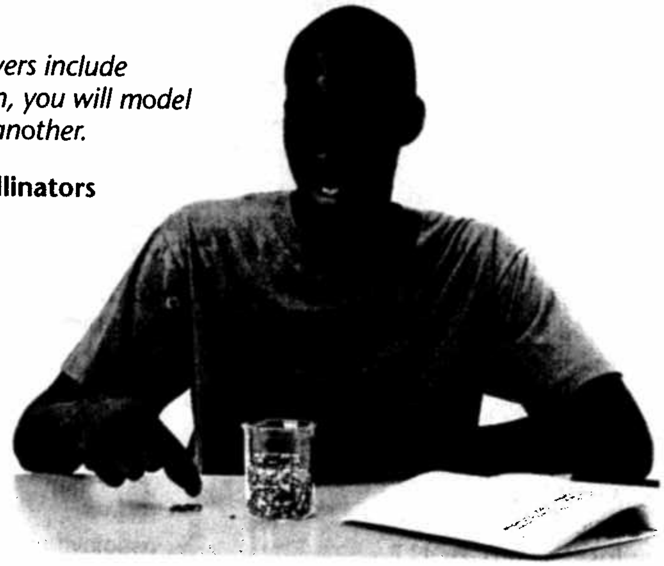
Making a Table
Create a table that lists each of the six patterns of macroevolution, explains each pattern, and gives one example for each. Add a title to your table.

Exploration

BIIE 1.d, BIIE 1.g

Modeling Coevolution

Flowering plants and the animals that pollinate their flowers include many examples of coevolving species. In this investigation, you will model how these plants and animals evolve in response to one another.



Problem How do flowering plants and their pollinators coevolve?

Materials

- long forceps
- spoon
- dried peas
- 3 25-mL graduated cylinders
- 3 100-mL beakers
- watch or clock with second hand

Skills Using Models, Inferring

Procedure

1. Work in groups of three. Each group member represents a different bird species. To represent the birds' beaks, one group member will use forceps, the second group member will use a spoon, and the third will use two fingertips.
2. On a separate sheet of paper, make a copy of the data table shown. The beakers represent short, open flowers and the graduated cylinders represent long, narrow flowers. The dried peas represent the flowers' nectar, which is the birds' food. Fill the beakers and the graduated cylinders halfway with dried peas. **CAUTION:** *Handle the beakers and graduated cylinders carefully. If one breaks, tell your teacher immediately.*
3. For 1 minute, use the method you chose in step 1 to remove the peas. Remove them one at a time from your beaker. Do not move or tip the beaker as you do this.
4. Record the number of peas you removed in your data table.
5. To produce seeds, a flower must be pollinated by a member of its own species. Assume that 1 flower was pollinated for every 5 peas removed. Record the number of pollinations for each bird.
6. Repeat steps 3 through 5, using the graduated cylinders instead of the beakers.
7. **Calculating** Exchange data with your classmates and record the class averages for each bird species in your data table.

Data Table

Beak Type	Individual Data		Class Average	
	Peas	Pollinations	Peas	Pollinations
Forceps				
Spoon				
Fingers				

Analyze and Conclude

1. **Analyzing Data** Which bird species obtained the most nectar from the beakers? From the graduated cylinders?
2. **Analyzing Data** From which type of flower was each bird most successful in obtaining food?
3. **Inferring** What is the benefit to a plant of short, open flowers?
4. **Inferring** What is the benefit to a bird of a long, narrow beak?
5. **Drawing Conclusions** Which type of bird is the best pollinator for long, narrow flowers?
6. **Evaluating and Revising** How does this model represent coevolution? How could you improve this model?

Go Further

Using Models Construct an alternative model of coevolution between flowering plants and birds that feed on their nectar. Then, compare your model to the one you used in this lab. Analyze the strengths and weaknesses of each model.

Chapter 17 Study Guide

17–1 The Fossil Record

BI 8.e, BIIE 1.i

Key Concepts

- The fossil record provides evidence about the history of life on Earth. It also shows how different groups of organisms, including species, have changed over time.
- Relative dating allows paleontologists to estimate a fossil's age compared with that of other fossils.
- In radioactive dating, scientists calculate the age of a sample based on the amount of remaining radioactive isotopes it contains.
- After Precambrian Time, the basic divisions of the geologic time scale are eras and periods.

Vocabulary

paleontologist, p. 417
fossil record, p. 417
extinct, p. 417
relative dating, p. 419
index fossil, p. 419
half-life, p. 420
radioactive dating, p. 420
geologic time scale, p. 421
era, p. 421
period, p. 422

17–2 Earth's Early History

Key Concepts

- Earth's early atmosphere probably contained hydrogen cyanide, carbon dioxide, carbon monoxide, nitrogen, hydrogen sulfide, and water.
- Miller and Urey's experiments suggested how mixtures of the organic compounds necessary for life could have arisen from simpler compounds present on a primitive Earth.
- The rise of oxygen in the atmosphere drove some life-forms to extinction, while other life-forms evolved new, more efficient metabolic pathways that used oxygen for respiration.
- The endosymbiotic theory proposes that eukaryotic cells arose from living communities formed by prokaryotic organisms.

Vocabulary

proteinoid microsphere, p. 425
microfossil, p. 426
endosymbiotic theory, p. 427

17–3 Evolution of Multicellular Life

Key Concepts

BI 8.e

- Rich fossil evidence shows that early in the Paleozoic Era, there was a diversity of marine life.
- During the Devonian, vertebrates began to invade the land.
- The mass extinction at the end of the Paleozoic affected both plants and animals on land and in the seas. As much as 95 percent of the complex life in the oceans disappeared.
- Events during the Mesozoic include the increasing dominance of dinosaurs. The Mesozoic is marked by the appearance of flowering plants.
- During the Cenozoic, mammals evolved adaptations that allowed them to live in various environments—on land, in water, and even in the air.

Vocabulary

mass extinction, p. 431

17–4 Patterns of Evolution

Key Concept

7 3.c, BI 8.e

- Six important topics in macroevolution are extinctions, adaptive radiation, convergent evolution, coevolution, punctuated equilibrium, and changes in developmental genes.

Vocabulary

macroevolution, p. 435
adaptive radiation, p. 436
convergent evolution, p. 437
coevolution, p. 437
punctuated equilibrium, p. 439

Thinking Visually

Use information from the chapter to create a flowchart that illustrates how natural selection can lead to the extinction of a species.

Chapter 17 Assessment

Interactive textbook with assessment at PHSchool.com

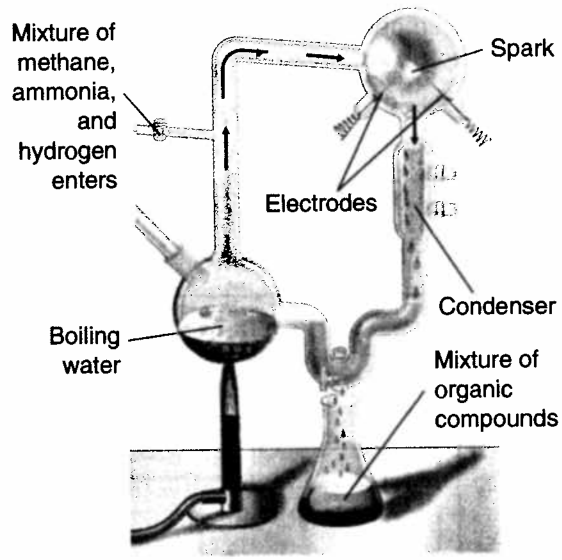
Reviewing Content

Choose the letter that best answers the question or completes the statement.

1. Scientists who specialize in the study of fossils are called
   a. biologists. c. zoologists.
   b. paleontologists. d. anthropologists.
2. Sedimentary rocks form when layers of small particles are compressed
   a. in the atmosphere. c. in mountains.
   b. in a snow field. d. under water.
3. Radioactive dating of rock samples
   a. is a method of absolute dating.
   b. is a method of relative dating.
   c. forms a geologic column.
   d. forms a geologic time scale.
4. Half-life is the length of time required for half the atoms in a radioactive sample to
   a. decay. c. expand.
   b. double. d. be created.
5. Earth's first atmosphere contained little or no
   a. hydrogen cyanide. c. nitrogen.
   b. hydrogen sulfide. d. oxygen.
6. In Miller and Urey's experiments with the origin of life-forms, electric sparks were passed through a mixture of gases to
   a. simulate temperature.
   b. simulate sunlight.
   c. sterilize the gases.
   d. simulate lightning.
7. Outlines of ancient cells that are preserved well enough to identify them as prokaryotes are
   a. microfossils. c. autotrophs.
   b. heterotrophs. d. phototrophic.
8. Which event occurred at the end of the Paleozoic Era?
   a. coevolution c. punctuated equilibrium
   b. mass extinction d. convergent evolution
9. The process that produces a similar appearance among unrelated groups of organisms is
   a. adaptive radiation. c. convergent evolution.
   b. coevolution. d. mass evolution.
10. As a group, the large-scale evolutionary changes that take place over long periods of time are called
    a. macroevolution. c. convergent evolution.
    b. coevolution. d. geologic time.

Understanding Concepts

11. How does relative dating enable paleontologists to estimate a fossil's age?
12. Explain how radioactivity is used to date rocks.
13. What is the geologic time scale? How was it developed?
14. Discuss what scientists hypothesize about Earth's early atmosphere and the way oceans formed.
15. Use the diagram below to explain the significance of Miller and Urey's experiment.



16. How are proteinoid microspheres like living cells?
17. How did the addition of oxygen to Earth's atmosphere affect the evolution of life?
18. Describe the endosymbiotic theory.
19. Describe life as it existed in Precambrian Time.
20. During what era did marine life become diverse?
21. What significant mammalian adaptations led to their success during the Cenozoic Era?
22. What events led to the diversification of mammals?
23. Explain the process of adaptive radiation. Give an example.
24. Explain the pattern known as punctuated equilibrium.
25. Use an example to explain the concept of coevolution.
26. How can hox genes provide evidence of evolution?

Critical Thinking

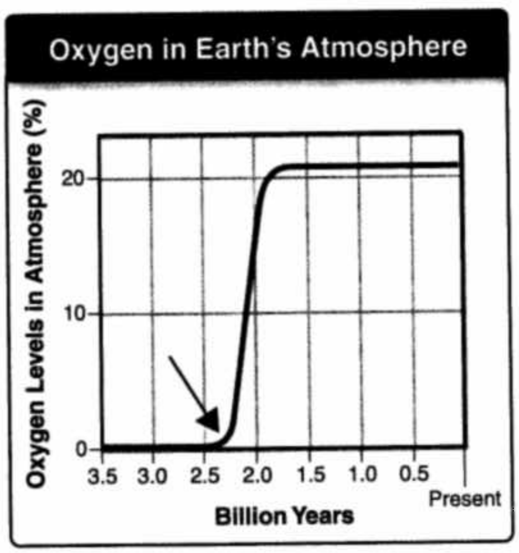
27. **Using Models** What part of Miller and Urey's apparatus represents rain? What important part would rain play in chemical evolution?

28. **Applying Concepts** In what way might the cells that took in the ancestors of mitochondria and chloroplasts have benefited from the relationship?

29. **Inferring** Geologic changes often accompany mass extinctions of life-forms. Why do you think this is true?

30. **Problem Solving** The half-life of carbon-14 is 5730 years. What is the age of a fossil containing 1/16 the amount of carbon-14 of living organisms? Explain your reasoning.

31. **Applying Concepts** The graph shows an approximation of the amount of oxygen in the atmosphere since life began. What event occurred at the point indicated by the arrow?



32. **Applying Concepts** Evolutionary biologists say that there is good reason for gaps in the fossil record. Can you explain why some extinct animals and plants were never fossilized?

33. **Comparing and Contrasting** Compare mass extinction to the extinction of species through the more typical processes of natural selection. Be sure to say how the processes are similar as well as different.

34. **Asking Questions** Suppose you are part of a scientific expedition searching for fossils. Someone brings you a fossilized bone that resembles one of the leg bones of a modern frog. What are some questions you would need to have answered in order to determine the age of the fossil? In what ways might the fossil provide evidence of change in species?

Focus on the BIG Idea

Matter and Energy Recall what you learned about chemistry in Chapter 2. When Earth's atmosphere first began to form, it did not contain oxygen (O_2), and hydrogen (H_2) was the most abundant element in the solar system. However, there is very little H_2 in the atmosphere today, and the element makes up less than 1 percent of Earth's mass. What might have happened to the H_2?

Writing in Science

When you compare two items, you explain how they are similar and different. Write a paragraph comparing conditions on early Earth (about 3.8 billion years ago) with those on modern Earth. (*Hint:* When you write a comparison, it isn't sufficient to summarize the characteristics of both items separately. Instead, you need to say specifically how the items are like each other and how they differ from each other.)

Performance-Based Assessment

Prepare a Booklet Suppose you could observe the formation and early history of Earth. Write your experiences in the form of a booklet four to six pages long to be read by middle-school students. Include a table of contents, color illustrations, and an activity at the end to evaluate students' understanding of the concept. The activity could be a puzzle, a completion activity, or another similar activity.

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Test-Taking Tip If you find particular questions difficult, put a light mark beside them and keep working. As you answer later questions, you may find information that helps you find the answers you still need. (Do not write in this book.)

Directions: Choose the letter that best answers the question or completes the statement.

1. Which of the following is characteristic of an index fossil? **BI 8.e**
   I. Distinctive species
   II. Lived in a wide geographic range
   III. Lived for a long period of time
   A I only
   B II only
   C I and II only
   D II and III only

2. In which geologic era do you live?
   A Cenozoic
   B Mesozoic
   C Cambrian
   D Precambrian

3. The endosymbiotic theory includes all of the following EXCEPT
   A Photosynthetic prokaryotes evolved into chloroplasts.
   B Aerobic prokaryotes evolved into mitochondria.
   C Eukaryotic cells arose from the merging of different prokaryotic organisms.
   D All organelles evolved from specialized enfoldings of the plasma membrane.

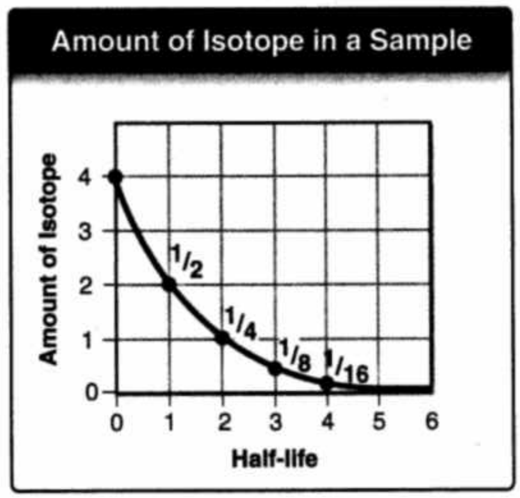
4. Which of the following is evidence for the endosymbiotic theory?
   I. Mitochondria and chloroplasts contain DNA similar to bacterial DNA.
   II. Mitochondria and chloroplasts contain ribosomes that differ from bacterial ribosomes.
   III. Mitochondria and chloroplasts reproduce by binary fission.
   A I only
   B II only
   C I and III only
   D II and III only

5. Potassium-40 is useful for dating very old fossils because **BI 8.e**
   A it has a very long half-life.
   B it has a very short half-life.
   C most organisms contain more potassium than carbon.
   D it does not undergo radioactive decay.

6. The Cambrian Period is also called the
   A Age of Humans.
   B Age of Fishes.
   C Age of Dinosaurs.
   D Age of Invertebrates.

Questions 7 and 8

The graph shows the radioactive decay of an isotope. Use the information in the graph to answer the questions that follow.



7. The half-life of thorium-230 is 75,000 years. How long will it take for 7/8 of the original amount of thorium-230 in a sample to decay?
   A 75,000 years
   B 225,000 years
   C 25,000 years
   D 70,000 years

8. The half-life of potassium-40 is about 1300 million years. After four half-lives have passed, how much of the original sample will be left?
   A $\frac{1}{16}$
   B $\frac{1}{16} \times 1300$ million grams
   C $\frac{1}{4}$
   D $\frac{1}{4} \times 1300$ million grams