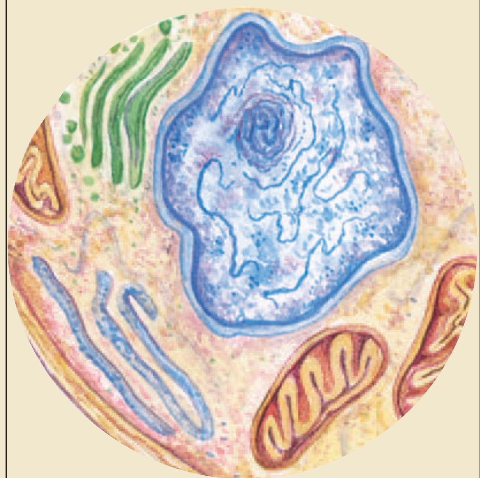
22 The Origin of Life and Evolution of Cells



CHAPTER 22

Chapter Outline

Key Concepts	Applications
Know the history of the scientific interest in the origin of life.	• Understand how scientists have studied how life began. • Understand the predictive differences between the theory of spontaneous generation and the theory of biogenesis. • Explain how these two theories have been tested.
Describe the most probable physical conditions on early Earth and the changes thought to have happened before life could exist.	• Describe what experimental evidence exists for the origin of life from inorganic material. • Describe what conditions on Earth were like billions of years ago.
Know what conditions were like on Earth billions of years ago.	• Describe what the first living thing might have been like.
Understand how conditions on Earth probably changed over billions of year.	• Know how the first living things might have given rise to the variety we see today. • Describe how living organisms can impact the global environment.

22.1 Spontaneous Generation Versus Biogenesis

For centuries humans have studied the basic nature of their environment. The vast amount of information presented in previous chapters is evidence of our ability to gather and analyze information. These efforts have resulted in solutions to many problems and have simultaneously revealed new and more challenging topics to study. Despite the growth in scientific knowledge, two questions have continued to be subjects of speculation: What is the nature of life? How did life originate?

In earlier times, no one ever doubted that life originated from nonliving things. The Greeks, Romans, Chinese, and many other ancient peoples believed that maggots arose from decaying meat; mice developed from wheat stored in dark, damp places; lice formed from sweat; and frogs originated from damp mud. The concept of **spontaneous generation**—the theory that living organisms arise from nonliving material—was proposed by Aristotle (384–322 B.C.) and became widely accepted until the seventeenth century (figure 22.1). However, there were some who doubted this theory. These people subscribed to an opposing theory, called *biogenesis*. **Biogenesis** is the concept that life originates only from preexisting life. (While the term "theory" is (and continues to be) used, the limited amount of scientific information available during that historical period only justified using the term "hypothesis" to refer to biogenesis and spontaneous generation.)

One of the earliest challenges to the theory of spontaneous generation came in 1668. Francesco Redi, an Italian physician, set up a controlled experiment designed to disprove the theory of spontaneous generation (figure 22.2). He used two sets of jars that were identical except for one aspect. Both sets of jars contained decaying meat, and both were exposed to the atmosphere; however, one set of jars was covered by gauze, and the other was uncovered. Redi observed that flies settled on the meat in the open jar, but the gauze blocked their access to the covered jars. When maggots appeared on the meat in the uncovered jars but not on the meat in the covered ones, Redi concluded that the maggots arose from the eggs of the flies and not from spontaneous generation in the meat.

Even after Redi's experiment, some people still supported the theory of spontaneous generation. After all, a belief that has been prevalent for over 2,000 years does not die a quick death. In 1748 John T. Needham, an English priest, placed a solution of boiled mutton broth in containers

Figure 22.1

Life from Nonlife
Many works of art explore the idea that living things could originate from very different types of organisms or even from nonliving matter. M. C. Escher's work entitled "The Reptiles, 1943" shows the life cycle of a little alligator. Amid all kinds of objects, a drawing book lies open at a drawing of a mosaic of reptilian figures in three contrasting shades. Evidently, one of them is tired of lying flat and rigid among its fellows, so it puts one plastic-looking leg over the edge of the book, wrenches itself free, and launches out into "real" life. It climbs up the back of the zoology book and works its way laboriously up the slippery slope of the set square to the highest point of its existence. Then after a quick snort, tired but fulfilled, it goes downhill again, via an ashtray, to the level surface, to that flat drawing paper, and meekly rejoins its erstwhile friends, taking up once more its function as one element of surface division.

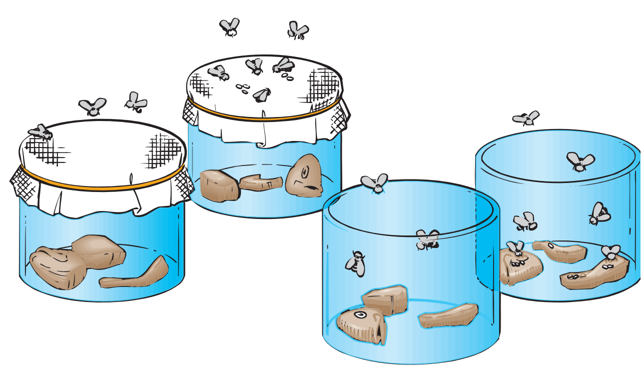


Figure 22.2

Redi's Experiment
The two sets of jars here are identical in every way except one–the gauze covering. The set on the left is called the control group; the set on the right is the experimental group. Any differences seen between the control and the experimental groups are the result of a single variable. In this manner, Redi concluded that the presence of maggots in meat was due to flies laying their eggs on the meat and not spontaneous generation.

that he sealed with corks. Within several days, the broth became cloudy and contained a large population of microorganisms. Needham reasoned that boiling killed all the organisms and that the corks prevented any microorganisms from entering the broth. He concluded that life in the broth was the result of spontaneous generation.

In 1767 another Italian scientist, Abbe Lazzaro Spallanzani, challenged Needham's findings. Spallanzani boiled a meat and vegetable broth, placed this medium in clean glass containers, and sealed the openings by melting the glass over a flame. He placed the sealed containers in boiling water to make certain all microorganisms were destroyed. As a control, he set up the same conditions but did not seal the necks, allowing air to enter the flasks (figure 22.3). Two days later, the open containers had a large population of microorganisms, but there were none in the sealed containers.

Spallanzani's experiment did not completely disprove the theory of spontaneous generation to everyone's satisfaction. The supporters of the theory attacked Spallanzani by stating that he excluded air, a factor believed necessary for spontaneous generation. Supporters also argued that boiling had destroyed a "vital element." When Joseph Priestly discovered oxygen in 1774, the proponents of spontaneous generation claimed that oxygen was the "vital element" that Spallanzani had excluded in his sealed containers.

In 1861 the French chemist Louis Pasteur convinced most scientists that spontaneous generation could not occur. He placed a fermentable sugar solution and yeast mixture in a flask that had a long swan neck. The mixture and the flask were boiled for a long time. The flask was left open to allow oxygen, the "vital element," to enter, but no organisms developed in the mixture. The organisms that did enter the flask settled on the bottom of the curved portion of the neck and could not reach the sugar-water mixture. As a control, he cut off the swan neck (figure 22.4). This allowed microorganisms from the air to fall into the flask, and within two days the fermentable solution was supporting a population of microorganisms. In his address to the French Academy, Pasteur stated, "Never will the doctrine of spontaneous generation arise from this mortal blow."

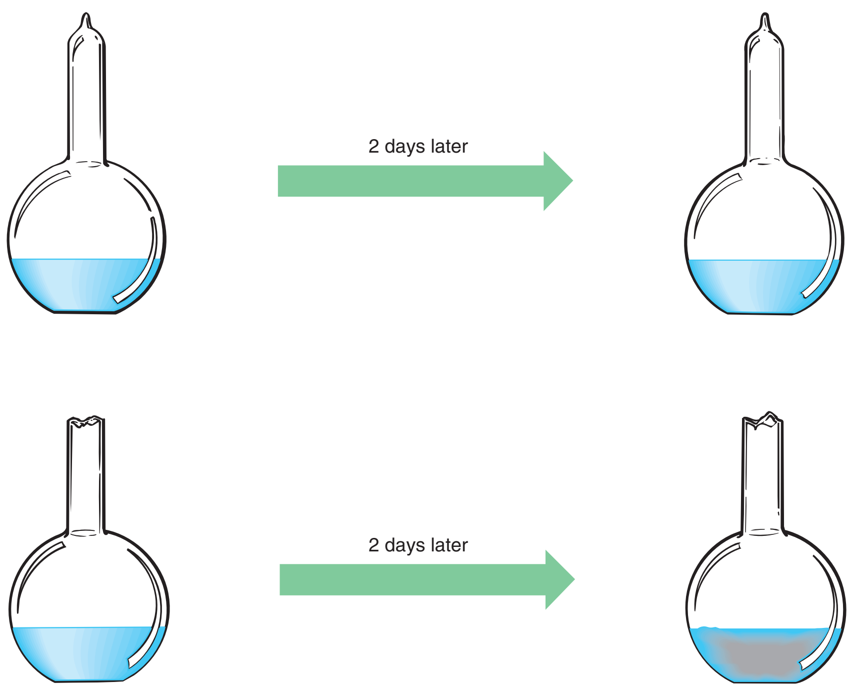


Figure 22.3

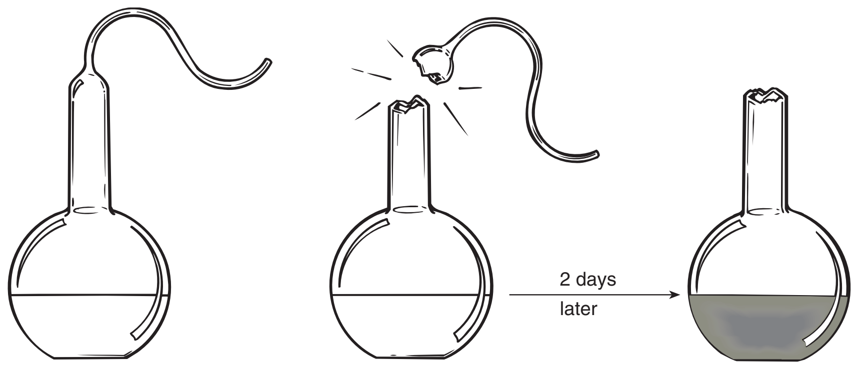
Spallanzani's Experiment
Spallanzani carried the experimental method of Redi one step further. He boiled a meat and vegetable broth and placed this medium into clean flasks. He sealed one and put it in boiling water. As a control, he subjected another flask to the same conditions, except he left it open. Within two days, the open flask had a population of microorganisms. Spallanzani demonstrated that spontaneous generation could not occur unless the broth was exposed to the "germs" in the air.

22.2 Current Thinking About the Origin of Life

Although Pasteur thought that he had defeated those that believed in spontaneous generation and strongly supported biogenesis, we still have modifications of these two major scientific theories regarding the origin of life today. One holds that life arrived on Earth from some extraterrestrial source (biogenesis) and the other maintains that life was created on Earth from nonliving material (spontaneous generation). Early in the 1900s, Svante Arrhenius proposed a different twist on biogenesis. His concept, called **panspermia,** hypothesized that life arose outside the Earth and that living things were transported to Earth serving to seed the planet with life. While his ideas had little scientific support at that time, his basic idea has since been revived and modified as a result of new evidence gained from space explorations, as you will see later in the chapter. However, panspermia does not explain *how* life arose originally. Explanations of how life might have originated are now focused on chemical theories. The chemical theories suggest that life arose from natural processes and that these processes can be observed and evaluated by scientific experimentation. These hypotheses proposed that inorganic matter changed into organic matter composed of complex carbon-containing molecules and that these in turn combined to

Figure 22.4

Pasteur's Experiment
Pasteur used the swan-neck flask that allowed oxygen, but not airborne organisms, to enter the flask. He broke the neck off another flask. Within two days, there was growth in this second flask. Pasteur demonstrated that air which contains oxygen but is free of germs does not cause spontaneous generation.



form the first living cell. It is important to recognize that we will probably never know for sure how life on Earth came to be, but it is interesting to speculate and examine the evidence related to this fundamental question.

The biogenesis concept (referred to as "directed panspermia") received renewed support when in 1969 in Murchison, Australia, a meteorite was found to contain amino acids and other complex organic molecules. In 1996 a meteorite from Antarctica was also analyzed. It has been known for many years that meteorites often contain organic molecules and this suggested that life may have existed elsewhere in the solar system. The chemical makeup of the Antarctic meteorite suggests that it was a portion of the planet Mars, which was ejected from Mars as a result of a collision between the planet and an asteroid. Analysis of the meteorite shows the presence of complex organic molecules and small globules that resemble those found on Earth that are thought to be the result of the activity of ancient microorganisms. Because Mars currently has some water as ice and shows features that resemble dried up river systems, Mars may have had much more water in the past. For these reasons many believe it is reasonable to consider that life of a nature similar to that presently found on Earth could have existed on Mars.

The alternative view that life originated on the Earth has also received support. Let us look at several lines of evidence.

1. The Earth is the only planet in our solar system with a temperature range that allows for water to exist as a liquid on its surface, and water is the most common compound in most kinds of living things.
2. Analysis of the atmospheres of other planets shows that they all lack oxygen. The oxygen in the Earth's atmosphere is the result of current biological activity. Therefore, before life on Earth the atmosphere probably lacked oxygen.
3. Experiments demonstrate that organic molecules can be generated in an atmosphere that lacks oxygen.
4. Because it is assumed that all of the planets have been cooling off as they age, it is very likely that the Earth was much hotter in the past. The large portions of the Earth's surface that are of volcanic origin strongly suggest a hotter past. There is also the likelihood that various large bodies collided with the Earth early in its history and that they could have led to increased temperatures at least in the site of the collision.
5. Recognition that there are distinct prokaryotic organisms that live in extreme environments of high temperature, high salinity, low pH, or the absence of oxygen suggests that they may have been adapted to life in a world that is very different from today's Earth. These kinds of organisms are found today in unusual locations such as hot springs and around thermal vents in the ocean floor and may be descendants of the first organisms formed on the primitive Earth.

22.3 The "Big Bang" and the Origin of the Earth

As astronomers and others look at the current stars and galaxies it can be observed that they are moving apart from one another. This and other evidence has led to the concept that our current universe began as a very dense mass of matter that had a great deal of energy. This dense mass of matter exploded in a "big bang" that resulted in the formation of atoms. According to this scientific theory the original universe consisted primarily of atoms of hydrogen and helium. The *solar nebula theory* proposes that the solar system was formed from a large cloud of gases that developed some 10 to 20 billion years ago (Ba) (figure 22.5). The simplest and most abundant gases would have been hydrogen and helium. A gravitational force was created by the collection of particles within this cloud that caused other particles to be pulled from the outer edges to the center. As particles collected into larger bodies, gravity increased and more particles were attracted to the bodies. Ultimately a central body (the Sun) was formed and several other bodies (planets) formed that moved around it (How Science Works 22.1). The Sun consists primarily of hydrogen and helium atoms, which are being fused together to form larger atoms with the

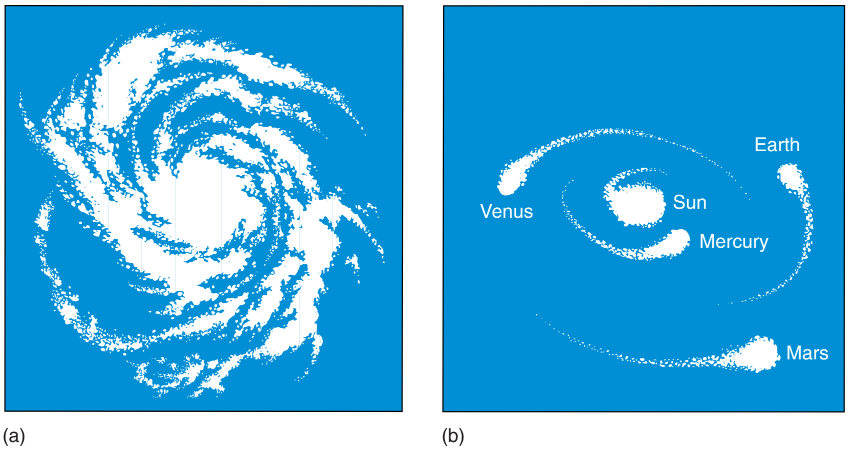


Figure 22.5

Formation of Our Solar System
As gravity pulled the gas particles into the center, the Sun developed *(a).* In other regions, smaller gravitational forces caused the formation of the Sun's planets *(b).*

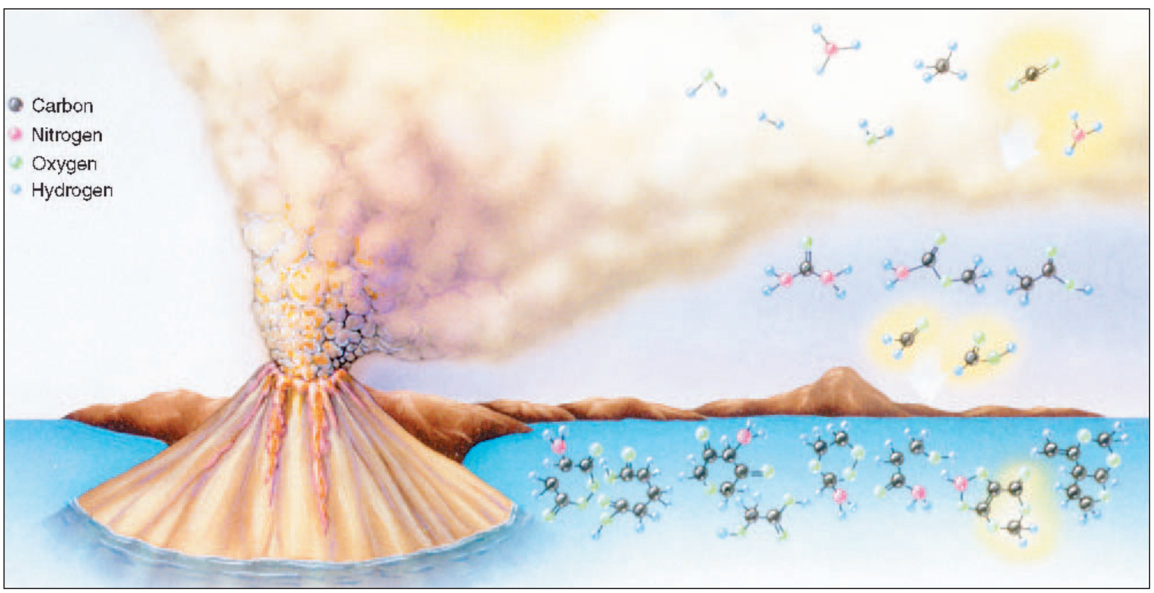


Figure 22.6

Formation of Organic Molecules in the Atmosphere
The environment of the primitive Earth was harsh and lifeless. But many scientists believe that it contained the necessary molecules to fashion the first living cell. The energy furnished by volcanoes, lightning, and ultraviolet light broke the bonds in the simple inorganic molecules in the atmosphere. New bonds formed as the atoms from the smaller molecules were rearranged and bonded to form simple organic compounds in the atmosphere. The rain carried these chemicals into the oceans. Here they reacted with each other to form more complex organic molecules.

release of large amounts of thermonuclear energy. Many scientists believe that Earth—along with other planets, meteors, asteroids, and comets—was formed at least 4.6 Ba. A large amount of heat was generated as the particles became concentrated to form Earth. Geologically, this is called the "Hadean Era." The term Hadean means "hellish." Although not as hot as the Sun, the material of Earth formed a molten core that became encased by a thin outer crust as it cooled. In its early stages of formation, about 4 Ba, there may have been a considerable amount of volcanic activity on Earth (figure 22.6).

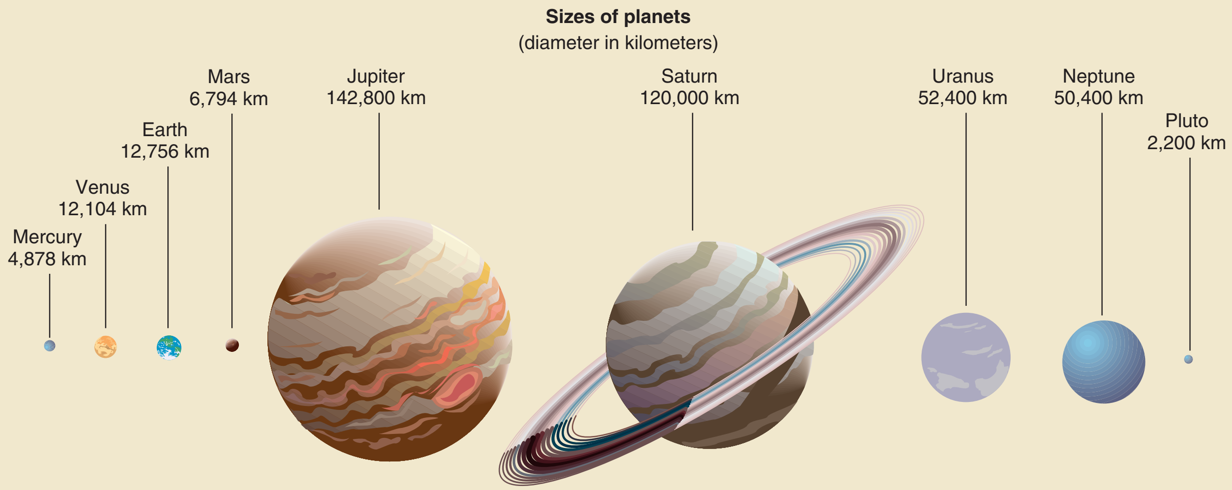
Physically, Earth was probably much different than it is today. Because the surface was hot, there was no water on the surface or in the atmosphere. In fact, the tremendous amount of heat probably prevented any atmosphere from forming. The gases associated with our present atmosphere (nitrogen, oxygen, carbon dioxide, and water vapor) were contained in the planet's molten core. These hostile

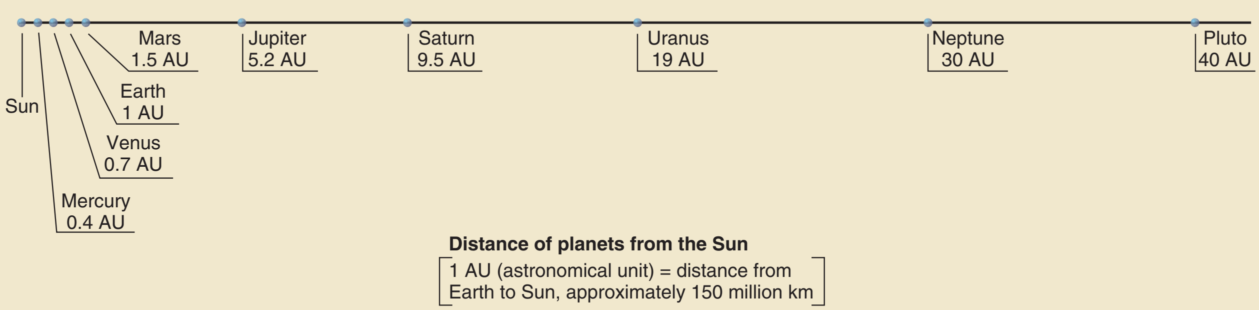
HOW SCIENCE WORKS 22.1

Gathering Information About the Planets

Our exploration of our solar system has become quite sophisticated with the development of space travel. Only the planet Pluto has not been visited by a spacecraft. Spacecraft that took close-up pictures of the planets as they traveled past them on their way to other solar systems have visited the distant planets of Jupiter, Saturn, and Neptune. The *Galileo* spacecraft released a probe that entered the atmosphere of Jupiter in 1996. In addition to the Earth's Moon, Mars and Venus have had spacecraft land on their surfaces and send back pictures and data about temperature, atmospheric composition, and the geologic nature of their surfaces.

Several characteristics of planets affect how likely it is that life could be found or might have been present on a planet. The distance from the Sun determines the amount of energy received from the Sun. Planets that are near the Sun receive more solar energy and distant planets receive less. The larger the mass of a planet the greater its force of gravity. The force of gravity will influence how many other bodies it can capture (moons) and how much atmosphere it can hold. Some of the planets are gases, whereas others have solid surfaces. In order for life as we know it on Earth to exist a planet must have liquid water, an appropriate atmosphere, and a solid surface. The only planet that may have had these conditions at one time is Mars.





conditions (high temperature, lack of water, lack of atmosphere) on early Earth could not have supported any form of life similar to what we see today.

Over hundreds of millions of years, Earth is thought to have slowly changed. As it cooled, volcanic activity probably caused the release of water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and hydrogen (H_2), and the early atmosphere was formed. These gases formed a **reducing atmosphere**—an atmosphere that did not contain molecules of oxygen (O_2). Any oxygen would have quickly combined with other atoms to form compounds, so a significant quantity of molecular oxygen would have been highly unlikely. Further cooling enabled the water vapor in the atmosphere to condense into droplets of rain. The water ran over the land and collected to form the oceans we see today.

22.4 Steps Needed to Produce Life from Inorganic Materials

When we consider the nature of the simplest forms of life today, we find that living things consist of an outer membrane that separates the cell from its surroundings, genetic material in the form of nucleic acids, and many kinds of enzymes that control the activities of the cell. Therefore, when we speculate about the origin of life from inorganic material it seems logical that several events or steps were necessary:

1. Organic molecules must first be formed from inorganic molecules.
2. Basic organic molecules form RNA that can serve as the genetic material and to catalyze other reactions.
3. RNA becomes self-replicating.
4. The organic RNA molecules must be collected together and segregated from other molecules by a membrane.
5. The control of protein synthesis must be taken over by RNA.
6. Proteins become the catalysts (enzymes) of the cell.
7. DNA replaces RNA as the self-replicating genetic material of the cell.
8. Ultimately these first cellular units must be able to reproduce more of themselves.

Formation of the First Organic Molecules

In the 1920s, a Russian biochemist, Alexander I. Oparin, and a British biologist, J. B. S. Haldane, working independently, proposed that the first organic molecules were formed spontaneously in the reducing atmosphere thought to be present on the early Earth. The molecules of water vapor, ammonia, methane, carbon dioxide, and hydrogen supplied the atoms of carbon, hydrogen, oxygen, and nitrogen, and lightning, heat from volcanoes, and ultraviolet radiation furnished the energy needed for the synthesis of simple organic molecules. It is important to understand the significance of a reducing atmosphere to this theory. The absence of oxygen in the atmosphere would have allowed these organic molecules to remain and combine with one another. This does not happen today because organic molecules are either consumed by organisms or oxidized to simpler inorganic compounds in the atmosphere. Many kinds of air pollutants are organic molecules called hydrocarbons that eventually degrade into smaller molecules in the atmosphere. Unfortunately they participate in the formation of smog as they are broken down.

After these simple organic molecules were formed in the atmosphere, they probably would have been washed from the air and carried into the newly formed oceans by the rain. Here, the molecules could have reacted with one another to form the more complex molecules of simple sugars, amino acids, and nucleic acids. This accumulation is thought to have occurred over half a billion years, resulting in oceans that were a dilute organic soup. These simple organic molecules in the ocean served as the building materials for more complex organic macromolecules, such as complex carbohydrates, proteins, lipids, and nucleic acids. Recognize that all the ideas presented so far cannot be confirmed by direct observation because we cannot go back in time. However, several of these assumptions central to this theory of the origin of life have been laboratory tested.

In 1953 Stanley L. Miller conducted an experiment to test the idea that organic molecules could be synthesized in a reducing environment. Miller constructed a simple model of the early Earth's atmosphere (figure 22.7). In a glass apparatus he placed distilled water to represent the early oceans. Adding hydrogen, methane, and ammonia to the water simulated the reducing atmosphere. Electrical sparks provided the energy needed to produce organic compounds. By heating parts of the apparatus and cooling others, he simulated the rains that are thought to have fallen into the early oceans. After a week of operation, he removed some of the water from the apparatus. When this water was analyzed, it was found to contain many simple organic compounds. Although Miller demonstrated nonbiological synthesis of simple organic molecules like amino acids and simple sugars, his results did not account for complex organic molecules like proteins and nucleic acids (e.g., DNA). However, other researchers produced some of the components of nucleic acid under similar primitive conditions.

Several ideas have been proposed for the concentration of simple organic molecules and their combination into macromolecules. The first hypothesis suggests that a portion of the early ocean could have been separated from the main ocean by geologic changes. The evaporation of water from this pool could have concentrated the molecules, which might have led to the manufacture of macromolecules by dehydration synthesis. Second, it has been proposed that freezing may have been the means of concentration. When a mixture of alcohol and water is placed in a freezer, the water freezes solid and the alcohol becomes concentrated into a

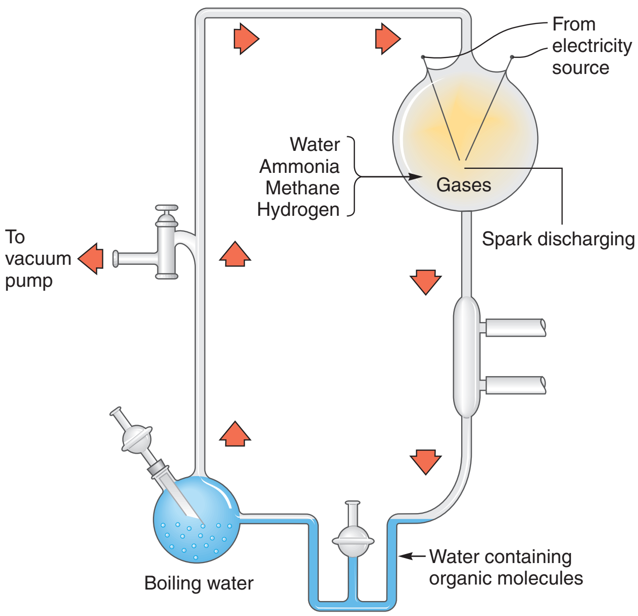


Figure 22.7

Miller's Apparatus
Stanley Miller developed this apparatus to demonstrate that the spontaneous formation of complex organic molecules could take place in a reducing atmosphere.

Figure 22.8

Stromatolites in Australia
This photo of stromatolites was taken at Hamelin Pool, Western Australia, a marine nature reserve. By taking samples from fossils of similar structures and cutting them into slices or sections, microscopic images can be produced that display the world's oldest cells. The dome-shaped structures shown in the photograph are composed of cyanobacteria and materials they secrete, and grow up to 60 centimeters tall.

small portion of liquid. A similar process could have occurred on Earth's early surface, resulting in the concentration of simple organic molecules. In this concentrated solution, dehydration synthesis in a reducing atmosphere could have occurred, resulting in the formation of macromolecules. A third theory proposes that clay particles may have been a factor in concentrating simple organic molecules. Small particles of clay have electrical charges that can attract and concentrate organic molecules like protein from a watery solution. Once the molecules became concentrated, it would have been easier for them to interact to form larger macromolecules.

Isolating Organic Molecules—Coacervates and Microspheres

Geologists and biologists typically measure the history of life by looking back from the present. Therefore, time scales are given in "years ago." It has been estimated that the formation of simple organic molecules in the atmosphere began about 4 Ba and lasted approximately 1.5 billion years. The oldest known fossils of living cells are thought to have formed 3.5 Ba. Fossilized, photosynthetic bacteria have been found in geological formations called *stromatolites* on the coasts of South Africa and Western Australia (figure 22.8). The question is, How do you get from the spontaneous formation of macromolecules to primitive cells in half a billion years?

Two hypotheses are proposed for the formation of **prebionts,** nonliving structures that led to the formation of the first living cells from which the more complex cells have today evolved. Oparin speculated that a prebiont consisted of carbohydrates, proteins, lipids, and nucleic acids that accumulated to form a **coacervate.** Such a structure could have consisted of a collection of organic macromolecules surrounded by a film of water molecules. This arrangement of water molecules, although not a membrane, could have functioned as a physical barrier between the organic molecules and their surroundings. They could selectively take in materials from their surroundings and incorporate them into their structure.

Coacervates have been synthesized in the laboratory (figure 22.9). They can selectively absorb chemicals from the surrounding water and incorporate them into their structure. Also, the chemicals within coacervates have a specific arrangement—they are not random collections of molecules. Some coacervates contain enzymes that direct a specific type of chemical reaction. Because they lack a definite membrane, no one claims coacervates are alive, but they do exhibit some lifelike traits: They are able to grow and divide if the environment is favorable.

An alternative hypothesis is that this early prebiotic cell structure could have been a *microsphere* or *protocell.* A **microsphere** is a nonliving collection of organic macromolecules with a double-layered outer boundary. Sidney Fox

Figure 22.9

Coacervates
One hypothesis proposes that a film of water that acted as a primitive cell membrane could have surrounded organic molecules forming a structure that resembles a living cell. Such structure can easily be produced in the lab.

demonstrated the ability to build microspheres from *proteinoids*. **Proteinoids** are proteinlike structures consisting of branched chains of amino acids. Proteinoids are formed by the dehydration synthesis of amino acids at a temperature of 180°C. Fox, from the University of Miami, showed that it is feasible to combine single amino acids into polymers of proteinoids. He also demonstrated the ability to build microspheres from these proteinoids.

Microspheres can be formed when proteinoids are placed in boiling water and slowly allowed to cool. Some of the proteinoid material produces a double-boundary structure that encloses the microsphere. Although these walls do not contain lipids, they do exhibit some membranelike characteristics and suggest the structure of a cellular membrane. Microspheres swell or shrink depending on the osmotic potential in the surrounding solution. They also display a type of internal movement (streaming) similar to that exhibited by cells and contain some proteinoids that function as enzymes. Using ATP as a source of energy, microspheres can direct the formation of polypeptides and nucleic acids. They can absorb material from the surrounding medium and form buds, which results in a second generation of microspheres. Given these characteristics, some investigators believe that microspheres can be considered **protocells,** the first living cells.

The laboratory synthesis of coacervates and microspheres helps us understand how the first primitive living cells might have developed. However, it leaves a large gap in our understanding because it does not explain how these first cells might have become the highly complex living cells we see today.

Meeting Metabolic Needs—Heterotrophs or Autotrophs

Fossil evidence indicates that there were primitive forms of life on Earth about 3.5 Ba. Regardless of how they developed, these first primitive cells would have needed a way to add new organic molecules to their structures as previously existing molecules were lost or destroyed. There are two ways to accomplish this. **Heterotrophs** capture organic molecules such as sugars, amino acids, or organic acids from their surroundings, which they use to make new molecules and provide themselves with a source of energy. **Autotrophs** use some external energy source such as sunlight or the energy from inorganic chemical reactions to allow them to combine simple inorganic molecules like water and carbon dioxide to make new organic molecules. These new organic molecules can then be used as building materials for new cells or can be broken down at a later date to provide a source of energy.

Many scientists support the idea that the first living things produced on Earth were heterotrophs that lived off the organic molecules that would have been found in the oceans. Because the early heterotrophs are thought to have developed in a reducing atmosphere that lacked oxygen, they would have been of necessity anaerobic organisms; therefore they did not obtain the maximum amount of energy from the organic molecules they obtained from their environment. At first, this would not have been a problem. The organic molecules that had been accumulating in the ocean for millions of years served as an ample source of organic material for the heterotrophs. However, as the population of heterotrophs increased through reproduction, the supply of organic material would have been consumed faster than it was being spontaneously produced in the atmosphere. If there was no other source of organic compounds, the heterotrophs would have eventually exhausted their nutrient supply, and they would have become extinct.

Even though the early heterotrophs probably contained nucleic acids and were capable of producing enzymes that could regulate chemical reactions, they probably carried out a minimum of biochemical activity. There is evidence to suggest that a wide variety of compounds were present in the early oceans, some of which could have been used unchanged by the heterotrophs. There was no need for the heterotrophs to modify the compounds to meet their needs.

Those compounds that could be easily used by heterotrophs would have been the first to become depleted from the early environment. However, some of the heterotrophs may have contained a mutated form of nucleic acid, which allowed them to convert material that was not directly usable into a compound that could be used. Mutations may have been common because the amount of ultraviolet light, one cause of mutations, would have been high. The absence of ozone in the upper atmosphere of the early Earth would have allowed high amounts of ultraviolet light to reach the Earth's surface. Heterotrophs with such mutations could have survived, whereas those without it would have become extinct as the compounds they used for food became scarce. It has been suggested that through a series of mutations in the early heterotrophs, a more complex series of biochemical reactions originated within some of the cells. Such cells could use chemical reactions to convert ingestible chemicals into usable organic compounds.

As with many areas of science there are often differences of opinion. Although this heterotroph hypothesis for the origin of living things was the prevailing theory for many years, recent discoveries have caused many scientists to consider an alternative—that the first organism was an autotroph. Several kinds of information support this theory. Many kinds of very primitive prokaryotic organisms, members of the Domain Archaea, were autotrophic and lived in extremely hostile environments. For this reason, they are referred to as "extremophiles" (lovers of extremes). The nutrients they utilized were most likely CO_2, CO, H_2, H_2S, N_2, and S. The end products of their metabolism were probably such compounds as H_2SO_4, CH_4, and H_2O. These organisms are found in hot springs like those found in Yellowstone National Park, Kamchatka, Russia (Siberia), or near hot thermal vents—areas where hot mineral-rich water enters seawater from the deep ocean floor. They use inorganic chemical reactions as a source of energy to allow them to synthesize organic molecules from inorganic components. The fact that many of these organisms live in very hot environments suggests that they may have originated on an Earth that was much hotter than it is currently. There is much evidence that the Earth was a much hotter place in the past. If the first organisms were autotrophs there could have been subsequent evolution of a variety of kinds of cells, both autotrophic and heterotrophic, that could have led to the diversity of different prokaryotic cells seen today in the Domains Eubacteria and Archaea (see chapter 4).

Reproduction and the Origin of Genetic Material

The reproduction of most current organisms involves the replication of DNA and the distribution of the copied DNA to subsequent cells. (Those that do not use DNA use RNA as their genetic material.) DNA is responsible for the manufacture of RNA, which subsequently leads to the manufacture of proteins. This is the central dogma of modern molecular biology. However, it is difficult to see how this complicated sequence of events, which involves many steps and the assistance of several enzymes, could have been generated spontaneously, so scientists have looked for simpler systems that could have led to the DNA system we see today.

Science works simultaneously on several fronts. Scientists involved in studying the structure and function of viruses discovered that many viruses do not contain DNA but store their genetic information in the structure of RNA. In order for these RNA-viruses to reproduce, they must enter a cell and have their RNA reverse-transcribed into DNA, which the host cell translates to manufacture new virus protein and RNA.

Other scientists who study viral diseases find that it is difficult to develop vaccines for many viral diseases because their genetic material easily mutates. Because of this, researchers have been studying the nature of viral DNA or RNA to see what causes the high rate of mutation. This has led others to explore the RNA viruses and ask the question: Can RNA replicate itself without DNA? This is an important question, because if RNA can replicate itself it would have all of the properties necessary to serve as genetic material. It could store information, translate information into protein structure, mutate, and make copies of itself.

Other research about the nature of RNA provides interesting food for thought. RNA can be assembled from simpler subunits that could have been present on the early Earth. Scientists have also shown that RNA molecules are able to make copies of themselves without the need for enzymes, and they can do so without being inside cells. These molecules have been called *ribozymes*. This new evidence suggests that RNA may have been the first genetic material and helps solve one of the problems associated with the origin of life: How genetic information was stored in these primitive life-forms. Because RNA is a much simpler molecule than DNA and can make copies of itself without the aid of enzymes, perhaps it was the first genetic material. Once a primitive life-form had the ability to copy its genetic material it would be able to reproduce. Reproduction is one of the most fundamental characteristics of living things.

As a result of this discussion you should understand that we do not know how life on Earth originated. Scientists look at many kinds of evidence and continue to explore new avenues of research. So we currently have three competing theories for the origin of life on Earth:

1. Life arrived from some extraterrestrial source (directed panspermia/biogenesis).
2. Life originated on Earth as a heterotroph (spontaneous generation).
3. Life originated on Earth as an autotroph (spontaneous generation).

22.5 Major Evolutionary Changes in the Nature of Living Things

Once living things existed and had a genetic material that stored information but was changeable (mutational), living things could have proliferated into a variety of kinds that were adapted to specific environmental conditions.

Remember that the Earth has not been static but has been changing as a result of its cooling, volcanic activity, and encounters with asteroids. In addition, the organisms have had an impact on the way in which the Earth has developed. Regardless of the way in which life originated on Earth, there have been several major events in the subsequent evolution of living things.

The Development of an Oxidizing Atmosphere

Ever since its formation, Earth has undergone constant change. In the beginning, it was too hot to support an atmosphere. Later, as it cooled and as gases escaped from volcanoes, a reducing atmosphere (lacking oxygen) was likely to have been formed. The early life-forms would have lived in this reducing atmosphere. However, today we have an oxidizing atmosphere and most organisms use this oxygen as a way to extract energy from organic molecules through a process of aerobic respiration. But what caused the atmosphere to change? Today it is clear that the oxygen in our atmosphere is the result of the process of photosynthesis. Prokaryotic cyanobacteria are the simplest organisms that are able to photosynthesize so it seems logical that the first organisms could have accumulated many mutations over time that could have resulted in photosynthetic autotrophs. One of the waste products of the process of photosynthesis is molecular oxygen (O_2). This would have been a significant change because it would have led to the development of an **oxidizing atmosphere,** which contains molecular oxygen. The development of an oxidizing atmosphere created an environment unsuitable for the formation of organic molecules. Organic molecules tend to break down (oxidize) when oxygen is present. The presence of oxygen in the atmosphere would make it impossible for life to spontaneously originate in the manner described earlier in this chapter because an oxidizing atmosphere would not allow the accumulation of organic molecules in the seas. However, new life is generated through reproduction, and new *kinds* of life are generated through mutation and evolution. The presence of oxygen in the atmosphere had one other important outcome: It opened the door for the evolution of aerobic organisms.

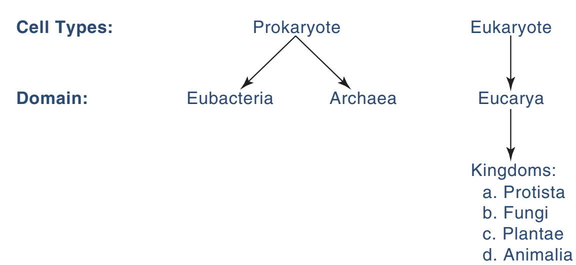
It appears that an oxidizing atmosphere began to develop about 2 Ba. Although various chemical reactions released small amounts of molecular oxygen into the atmosphere, it was photosynthesis that generated most of the oxygen. The oxygen molecules also reacted with one another to form ozone (O_3). Ozone collected in the upper atmosphere and acted as a screen to prevent most of the ultraviolet light from reaching Earth's surface. The reduction of ultraviolet light diminished the spontaneous formation of complex organic molecules. It also reduced the number of mutations in cells. In an oxidizing atmosphere, it was no longer possible for organic molecules to accumulate over millions of years to be later incorporated into living material.

The appearance of oxygen in the atmosphere also allowed for the evolution of aerobic respiration. Because the first heterotrophs were of necessity anaerobic organisms, they did not derive large amounts of energy from the organic materials available as food. With the evolution of aerobic heterotrophs, there could be a much more efficient conversion of food into usable energy. Aerobic organisms would have a significant advantage over anaerobic organisms: They could use the newly generated oxygen as a final hydrogen acceptor and, therefore, generate many more ATPs (adenosine triphosphates) from the food molecules they consumed.

The Establishment of Three Major Domains of Life

In 1977 Carl Woese published the idea that the "bacteria" (organisms that lack a nucleus), which had been considered a group of similar organisms, were really made up of two very different kinds of organisms: the Eubacteria and Archaea. Furthermore the Archaea shared some characteristics with eukaryotic organisms. Subsequent investigations have supported these ideas and led to an entirely different way of looking at the classification and evolution of living things. Although biologists have traditionally divided organisms into kingdoms based on their structure and function, it was very difficult to do this with microscopic organisms. With the newly developed ability to decode the sequence of nucleic acids, it became possible to look at the genetic nature of organisms without being confused by their external structures. Woese studied the sequences of ribosomal RNA and compared similarities and differences. As a result of his studies and those of many others a new concept of the relationships between various kinds of organisms has emerged.

The three main kinds of living things, Eubacteria, Archaea, and Eucarya, have been labeled "domains." Within each domain there are several kingdoms. In the Eucarya there are four kingdoms that we already recognize: Animalia, Plantae, Fungi, Protista. However, previously all of the Eubacteria and Archaea have been lumped into the same kingdom: Prokaryote. It has become clear that there are great differences between the Eubacteria and Archaea, and within each of these groups there are greater differences than are found among the other four kingdoms (Animalia, Plantae, Fungi, and Protista).



This new picture of living things requires us to reorganize our thinking. It appears that the oldest organisms may have been bacteria that were able to live in hot situations

Table 22.1

MAJOR DOMAINS OF LIFE

Eubacteria	Archaea	Eucarya
No nuclear membrane.	No nuclear membrane.	Nuclear membrane present.
Chlorophyll-based photosynthesis is a bacterial invention but most can function anaerobically.	None have been identified as pathogenic.	Many kinds of membranous organelles present in cells.
Oxygen-generating photosynthesis was an invention of the cyanobacteria.	Probably have a common ancestor with Eucarya.	Chloroplasts are probably derived from cyanobacteria.
Large number of heterotrophs oxidize organic molecules for energy.	Many obtain energy from inorganic reactions to make organic matter.	Mitochondria probably derived from certain aerobic bacteria.
Some use energy from inorganic chemical reactions to produce organic molecules.	Typically found in extreme environments.	Probably have a common ancestor with Archaea.
Some live at high temperatures and may be ancestral to Archaea.	Few heterotrophs.	Common evolutionary theme is the development of complex cells through symbiosis with other organisms.
Much metabolic diversity among closely related organisms.	Example: *Pyrolobus fumarii,* deep-sea hydrothermal vents, hot springs, volcanic areas, growth to 113°C	Example: *Homo sapiens,* all cells of the human body
Example: *Streptococcus pneumoniae,* one cause of pneumonia		

and that they gave rise to the Archaea, many of whom still require extreme environments. Perhaps most startling is the idea that the Archaea and Eucarya share many characteristics suggesting that they are more closely related to each other than either is to the Eubacteria.

It appears that each domain developed specific abilities. The Archaea are primarily organisms that use inorganic chemical reactions to generate the energy they need to make organic matter. Often these reactions result in the production of methane (CH_4). These organisms are known as methanogens. Others use sulfur and produce hydrogen sulfide (H_2S). Most of these organisms are found in extreme environments such as hot springs or in extremely salty or acid environments.

The Eubacteria developed many different metabolic abilities. Today many are able to use organic molecules as a source of energy, some are able to carry on photosynthesis, and still others are able to get energy from inorganic chemical reactions similar to Archaea.

The Eucarya are the most familiar and appear to have exploited the metabolic abilities of other organisms by incorporating them into their own structure. Chloroplasts and mitochondria are both bacterialike structures found inside eukaryotic cells. Table 22.1 summarizes the major characteristics of these three domains.

The Origin of Eukaryotic Cells

The earliest fossils appear to be similar in structure to that of present-day bacteria. Therefore it is likely that the early heterotrophs and autotrophs were probably simple one-celled organisms like bacteria. They were **prokaryotes** that lacked nuclear membranes and other membranous organelles, such as mitochondria, an endoplasmic reticulum, chloroplasts, and a Golgi apparatus. Present-day bacteria and archaea are prokaryotes. All other forms of life are **eukaryotes,** which possess a nuclear membrane and other membranous organelles.

Biologists generally believe that the eukaryotes evolved from the prokaryotes. The **endosymbiotic theory** attempts to explain this evolution. This theory suggests that present-day eukaryotic cells evolved from the combining of several different types of primitive prokaryotic cells. It is thought that some organelles found in eukaryotic cells may have originated as free-living prokaryotes. For example, because mitochondria and chloroplasts contain bacteria-like DNA and ribsomes, control their own reproduction, and synthesize their own enzymes, it has been suggested that they were once free-living prokaryotes. These bacterial cells could have established a symbiotic relationship with another primitive nuclear membrane-containing cell type (figure 22.10). When this theory was first suggested it met with a great deal of

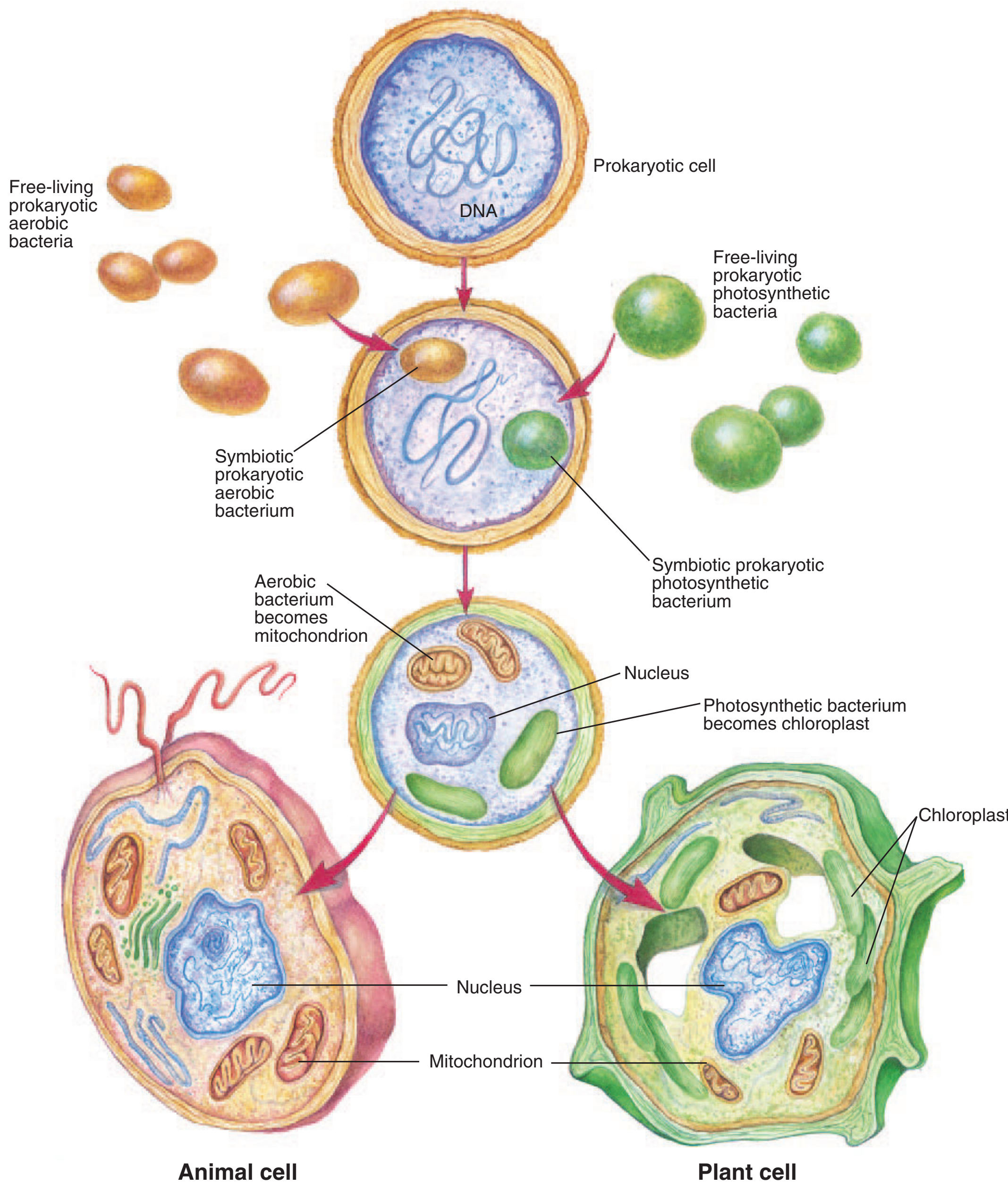


Figure 22.10

The Endosymbiotic Theory
This theory proposes that some free-living prokaryotic bacteria developed symbiotic relationships with a host cell. When some aerobic bacteria developed into mitochondria and photosynthetic bacteria developed into chloroplasts, a eukaryotic cell evolved. These cells evolved into eukaryotic plant and animal cells.

criticism. However, continuing research has uncovered several other instances of the probable joining of two different prokaryotic cells to form one.

If these cells adapted to one another and were able to survive and reproduce better as a team, it is possible that this relationship may have evolved into present-day eukaryotic cells. If this relationship had included only a nuclear membrane-containing cell and aerobic bacteria, the newly evolved cell would have been similar to present-day heterotrophic protozoa, fungi, and animal cells. If this relationship

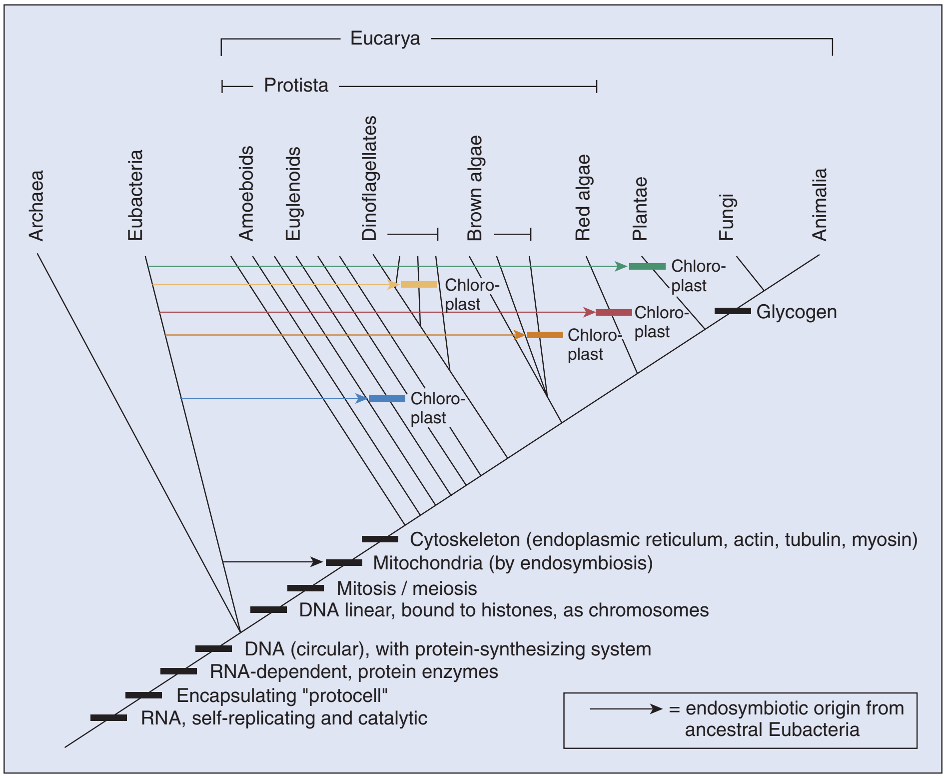


Figure 22.11

From Archaea to Eucarya
This graph proposes the changes that are hypothesized to have occurred during the evolution of cells leading to the various cell and organism types we see on Earth today.

Source: http://www.scibridge.sdsu.edu

had included both aerobic bacteria and photosynthetic bacteria, the newly formed cell would have been similar to present-day autotrophic algae and plant cells. In addition it is likely that endosymbiosis occurred among eukaryotic organisms as well. Several kinds of eukaryotic red and brown algae contain chloroplastlike structures that appear to have originated as free-living eukaryotic cells (figure 22.11).

Regardless of the type of cell (prokaryotic or eukaryotic), or whether the organisms are heterotrophic or autotrophic, all organisms have a common basis. DNA is the universal genetic material; protein serves as structural material and enzymes; and ATP is the source of energy. Although there is a wide variety of organisms, they all are built from the same basic molecular building blocks. Therefore, it is probable that all life derived from a single origin and that the variety of living things seen today evolved from the first protocells.

Let us return for a moment to the question that perplexed early scientists and caused the controversies surrounding the opposing theories of spontaneous generation and biogenesis. From our modern perspective we can see that all life we experience comes into being as a result of reproduction. Life is generated from other living things, the process of biogenesis. However, reproduction does not answer the question: Where did life come from in the first place? We can speculate, test hypotheses, and discuss various possibilities, but we will probably never know for sure. Life either always was or it started at some point in the past. If it started, then spontaneous generation of some type had to occur at least once, but it is not happening today.

In this chapter we have discussed several ideas about how cells may have originated. It is thought that from these cells evolved the great diversity we see in living organisms today.

22.6 Evolutionary Time Line

A geological time chart shows a chronological history of living organisms based on the fossil record. The largest geological time units are called *eons*. From earliest to most recent, the geological eras of the Precambrian Eon are the Hadean, Archaean, and Proterozoic. The Phanerozoic Eon is divided

Era	Period	Epoch	Millions of Years Ago	Important Events
Cenozoic (Age of Mammals)	Quaternary	Recent	Present	Modern humans
		Pleistocene	1.8	Early humans
	Tertiary	Pliocene	6	Ape radiation
		Miocene	23	Abundant grazing mammals
		Oligocene	38	Angiosperms dominant
		Eocene	54	Mammalian radiation
		Paleocene	65	First placental mammals
Mesozoic (Age of Reptiles)	Cretaceous		144–65	Climax of reptiles; first angiosperms; extinction of ammonoids
	Jurassic		208–144	Reptiles dominant; first birds; first mammals
	Triassic		245–208	First dinosaurs; cycads and conifers dominant
Paleozoic	Permian		286–245	Widespread extinction of marine invertebrates; expansion of primitive reptiles
	Pennsylvanian		320–286	Great swamp trees (coal forests); amphibians prominent
	Mississipian		360–320	
	Devonian		408–360	Age of fishes; first amphibians
	Silurian		436–408	First land plants; eurypterids prominent
	Ordovician		505–436	Earliest known fishes
	Cambrian		540–505	Abundant marine invertebrates; trilobites and brachiopods dominant; algae prominent
Proterozoic			2500–540	Soft-bodied primitive life
Archaean			3800–2500	
Hadean			4600–3800	

Figure 22.12

Geological Time Chart

into the eras Paleozoic, Mesozoic, and Cenozoic. Each of these *eras* is subdivided into smaller time units called *periods*. For example, Jurassic is a period of the Mesozoic Era that began 180 million years ago (figure 22.12).

Recent evidence suggests that prokaryotic cell types (Domain Eubacteria) most likely came in to existence approximately 3800 to 3700 million years ago (Ma) during the Archaean Era of the Precambrian Eon. This was just prior to the development of the prokaryotic life-forms that are members of the Domain Archaea. The photosynthetic eubacterial cyanobacteria are thought to have been responsible for the production of molecular oxygen (O_2) that began to accumulate in the atmosphere and make conditions favorable for the evolution of other types of cells. Members of the Archaea are often referred to as extremophiles since they live in extreme environments. This includes environments that are extremely acid, hot, or otherwise chemically inhospitable to other life-forms. To date, the bacterium, *Pyrolobus fumarii*, has been identified as the most extreme thermophile (heat loving) growing at 113°C (under pressure) at sea bottom! The first members of the Domain Eucarya, the eukaryotic organisms, appeared approximately 1.8 billion years ago (Ba).

Figure 22.13

The Age of the Dinosaurs
Dinosaurs were the dominant vertebrates for millions of years.

The part of the Earth's history dominated by unicellular organisms (the Age of Bacteria) is generally referred to as the Precambrian Eon. There is little fossil record of Precambrian unicellular life, although it comprises a span of time much greater than the entire history of multicellular plants and animals. The first multicellular organisms appeared 700 million years ago at the end of the Precambrian Eon. During the Cambrian Period of the Paleozoic Era, an explosion of multicellular organisms occurred. Marine invertebrates were abundant, with individuals from most present-day phyla existing at that time.

Several other "explosions," or *adaptive radiations,* followed. Note on the geological time chart that a different major form of vegetation dominated each era. The Paleozoic Era was dominated by nonvascular and primitive vascular plants; the Mesozoic Era by cone-bearing evergreens; and the Cenozoic by the flowering plants with which we are most familiar dominated the Paleozoic Era. Likewise, many periods are associated with specific animal groups. Among vertebrates, the Devonian Period is considered the Age of Fishes and the Pennsylvanian Period the Age of Amphibians. The Mesozoic Era is considered the Age of Reptiles and the Cenozoic Era is considered the Age of Mammals. In each instance, dominance of a particular animal group resulted from adaptive radiation events.

Amphibians, for example, most likely evolved from a lobe-finned fish of the Devonian Period. This organism possessed two important adaptations: lungs and paired lobed fins that allowed the organism to pull itself onto land and travel to new water holes during times of drought. Selective pressures resulted in fins evolving into legs and the first amphibian came into being. During this lengthy time, landmasses were colonized by vegetation but only a few types of animals moved onto the land. The first vertebrates to spend part of their lives on land found a variety of unexploited niches resulting in the rapid evolution of new amphibian species and their dominance during the Pennsylvanian Period.

For 40 million years, amphibians were the only vertebrate animals on land. During this time, mutations continued to occur, and valuable modifications were passed on to future generations that eventually led to the development of reptiles. One change allowed the male to deposit sperm directly within the female. Because the sperm could directly enter the female and remain in a moist interior, it was no longer necessary for the animals to return to the water to mate, as amphibians still must do. However, developing young still required a moist environment for early growth. A second modification, the amniotic egg, solved this problem. An amniotic egg, like a chicken egg, protects the developing young from injury and dehydration while allowing for the exchange of gases with the external environment. A third adaptation, the development of protective scales and relatively impermeable skin, protected reptiles from dehydration. With these adaptations, reptiles were able to outcompete amphibians in most terrestrial environments. Amphibians that did survive were the ancestors of present-day frogs, toads, and salamanders. With extensive adaptive radiation, reptiles took to the land, sea, and air. A particularly successful group of reptiles was the dinosaurs (figure 22.13). The length of time that dinosaurs dominated the

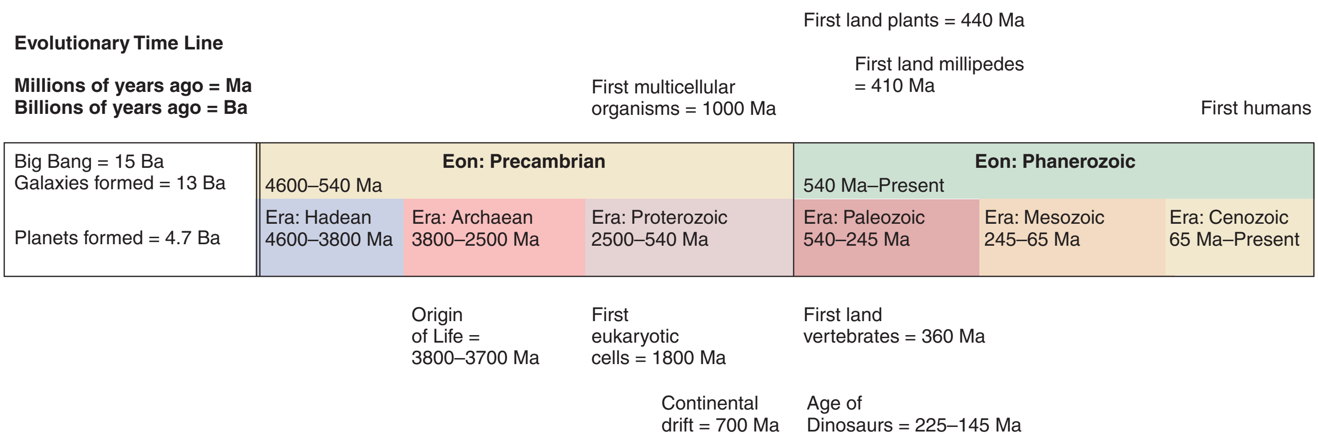


Figure 22.14

Evolutionary Time Line
This chart displays how science sees the probable events that occurred beginning with the "Big Bang" to present day.

Earth, more than 100 million years, was greater than the length of time from their extinction to the present.

As reptiles diversified, some developed characteristics common to other classes of vertebrates found today, such as warm-bloodedness, feathers, and hair. Warm-blooded reptiles with scales modified as feathers for insulation eventually evolved into organisms capable of flight. Through natural selection, reptilian characteristics were slowly eliminated and characteristics typical of today's modern birds (multiple adaptations to flight, keen senses, and complex behavioral instincts) developed. Archaeopteryx, the first bird, had characteristics typical of both birds and reptiles.

Also evolving from reptiles were the mammals. The first reptiles with mammalian characteristics appeared in the Permian Period, although the first true mammals did not appear until the Triassic Period. These organisms remained relatively small in number and size until after the mass extinction of the reptiles. Extinctions opened many niches and allowed for the subsequent adaptive radiation of mammals. As with the other adaptive radiations, mammals possessed unique characteristics that made them better adapted to the changing environment; the characteristics include insulating hair, constant body temperature, internal development of young. Figure 22.14 summarizes the hypothetical evolutionary time line.

SUMMARY

The centuries of research outlined in this chapter illustrate the development of our attempts to understand the origin of life. Current theories speculate that either the primitive Earth's environment led to the spontaneous organization of organic chemicals into primitive cells or primitive forms of life arrived on Earth from space. Regardless of how the first living things came to be on Earth, these basic units of life were probably similar to present-day prokaryotes. These primitive cells could have changed through time as a result of mutation and in response to a changing environment. The recognition that many prokaryotic organisms have characteristics that clearly differentiate them from the rest of the bacteria has led to the development of the concept that there are three major domains of life: the Eubacteria, the Archaea, and the Eucarya. The Eubacteria and Archaea are similar in structure but the Archaea have distinctly different metabolic processes from the Eubacteria. Some people consider the Archaea, many of which can live in very extreme environments, good candidates for the first organisms to inhabit Earth. The origin of the Eucarya is less contentious. Similarities between cyanobacteria and chloroplasts and between aerobic bacteria and mitochondria suggest that eukaryotic cells may really be a combination of ancient cell ancestors that lived together symbiotically. The likelihood of these occurrences is supported by experiments that have simulated primitive Earth environments and investigations of the cellular structure of simple organisms. Despite volumes of information, the question of how life began remains unanswered.

THINKING CRITICALLY

It has been postulated that there is "life" on another planet in our galaxy. The following data concerning the nature of this life have been obtained from "reliable" sources. Using these data, what additional information is necessary, and how would you go about verifying these data in developing a theory of the origin of life on planet X?

1. The age of the planet is 10 billion years.
2. Water is present in the atmosphere.
3. The planet is farther from the Sun than our Earth is from our Sun.
4. The molecules of various gases in the atmosphere are constantly being removed.
5. Chemical reactions on this planet occur at approximately half the rate at which they occur on Earth.

CONCEPT MAP TERMINOLOGY

Construct a concept map to show relationships among the following concepts.

autotroph
biogenesis
endosymbiotic theory
eukaryote
heterotroph
oxidizing atmosphere
prokaryotes
reducing atmosphere
spontaneous generation

KEY TERMS

autotrophs
biogenesis
coacervate
endosymbiotic theory
eukaryote
heterotroph
microsphere
oxidizing atmosphere
panspermia
prebionts
prokaryote
proteinoid
protocell
reducing atmosphere
spontaneous generation

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Topics	Questions	Media Resources
22.1 Spontaneous Generation Versus Biogenesis	1. What is meant by spontaneous generation? What is meant by biogenesis? 2. Of the following scientists, name those who supplied evidence that supported the theory of spontaneous generation and those who supported biogenesis: Spallanzani, Needham, Pasteur, Fox, Miller, Oparin.	**Quick Overview** • Two different views **Key Points** • Spontaneous generation versus biogenesis **Interactive Concept Maps** • Origin of life **Experience This!** • Spontaneous generation or biogenesis?
22.2 Current Thinking About the Origin of Life		**Quick Overview** • Information from other sciences **Key Points** • Current thinking about the origin of life **Animations and Review** • Fossils • Origin of life
22.3 The "Big Bang" and the Origin of the Earth	3. Why do scientists believe life originated in the seas? 4. The current theory of the origin of life as a result of nonbiological manufacture of organic molecules depends on our knowing something of Earth's history. Why is this so?	**Quick Overview** • Formation of the solar system **Key Points** • The "Big Bang" and the origin of the Earth
22.4 Steps Needed to Produce Life from Inorganic Materials	5. In what sequence did the following things happen: living cell, oxidizing atmosphere, autotrophy, heterotrophy, reducing atmosphere, first organic molecule? 6. Can spontaneous generation occur today? Explain. 7. What were the circumstances on primitive Earth that favored the survival of anaerobic heterotrophs?	**Quick Overview** • Logical steps **Key Points** • Steps needed to produce life from inorganic materials **Animations and Review** • Key events **Interactive Concept Maps** • Formation of organic molecules

Topics	Questions	Media Resources
22.5 Major Evolutionary Changes in the Nature of Living Things	8. List two important effects caused by the increase of oxygen in the atmosphere. 9. What evidence supports the theory that eukaryotic cells arose from the development of a symbiotic relationship between primitive prokaryotic cells?	**Quick Overview** • Benchmark changes in living organisms **Key Points** • Major evolutionary changes in the nature of living things **Animations and Review** • Continental drift • Extinctions • Evolutionary trends • Concept quiz **Interactive Concept Maps** • Text concept map
22.6 Evolutionary Time Line		**Quick Overview** • Summary of events **Key Points** • Evolutionary time line **Review Questions** • The origin of life and evolution of cells