

4

The Origin and Early History of Life

Concept Outline

4.1 All living things share key characteristics.

What Is Life? All known organisms share certain general properties, and to a large degree these properties define what we mean by life.

4.2 There are many ideas about the origin of life.

Theories about the Origin of Life. There are both religious and scientific views about the origin of life. This text treats only the latter—only the scientifically testable.

Scientists Disagree about Where Life Started. The atmosphere of the early earth was rich in hydrogen, providing a ready supply of energetic electrons with which to build organic molecules.

The Miller-Urey Experiment. Experiments attempting to duplicate the conditions of early earth produce many of the key molecules of living organisms.

4.3 The first cells had little internal structure.

Theories about the Origin of Cells. The first cells are thought to have arisen spontaneously, but there is little agreement as to the mechanism.

The Earliest Cells. The earliest fossils are of bacteria too small to see with the unaided eye.

4.4 The first eukaryotic cells were larger and more complex than bacteria.

The First Eukaryotic Cells. Fossils of the first eukaryotic cells do not appear in rocks until 1.5 billion years ago, over 2 billion years after bacteria. Multicellular life is restricted to the four eukaryotic kingdoms of life.

Has Life Evolved Elsewhere? It seems probable that life has evolved on other worlds besides our own. The possible presence of life in the warm waters beneath the surface of Europa, a moon of Jupiter, is a source of current speculation.



FIGURE 4.1

The origin of life. The fortuitous mix of physical events and chemical elements at the right place and time created the first living cells on earth.

There are a great many scientists with intriguing ideas that explain how life may have originated on earth, but there is very little that we know for sure. New hypotheses are being proposed constantly, and old ones reevaluated. By the time this text is published, some of the ideas presented here about the origin of life will surely be obsolete. Thus, the contesting ideas are presented in this chapter in an open-ended format, attempting to make clear that there is as yet no one answer to the question of how life originated on earth. Although recent photographs taken by the Hubble Space Telescope have revived controversy about the age of the universe, it seems clear the earth itself was formed about 4.6 billion years ago. The oldest clear evidence of life—microfossils in ancient rock—are 3.5 billion years old. The origin of life seems to have taken just the right combination of physical events and chemical processes (figure 4.1).

4.1 All living things share key characteristics.

The earth formed as a hot mass of molten rock about 4.6 billion years ago. As the earth cooled, much of the water vapor present in its atmosphere condensed into liquid water, which accumulated on the surface in chemically rich oceans. One scenario for the origin of life is that it originated in this dilute, hot smelly soup of ammonia, formaldehyde, formic acid, cyanide, methane, hydrogen sulfide, and organic hydrocarbons. Whether at the oceans' edge, in hydrothermal deep-sea vents, or elsewhere, the consensus among researchers is that life arose spontaneously from these early waters less than 4 billion years ago. While the way in which this happened remains a puzzle, one cannot escape a certain curiosity about the earliest steps that eventually led to the origin of all living things on earth, including ourselves. How did organisms evolve from the complex molecules that swirled in the early oceans?

What Is Life?

Before we can address this question, we must first consider what qualifies something as “living.” What *is* life? This is a difficult question to answer, largely because life itself is not a simple concept. If you try to write a definition of “life,” you will find that it is not an easy task, because of the loose manner in which the term is used.

Imagine a situation in which two astronauts encounter a large, amorphous blob on the surface of a planet. How would they determine whether it is alive?

Movement. One of the first things the astronauts might do is observe the blob to see if it moves. Most animals move about (figure 4.2), but movement from one place to another in itself is not diagnostic of life. Most plants and even some animals do not move about, while numerous nonliving objects, such as clouds, do move. The criterion of movement is thus neither *necessary* (possessed by all life) nor *sufficient* (possessed only by life).

Sensitivity. The astronauts might prod the blob to see if it responds. Almost all living things respond to stimuli (figure 4.3). Plants grow toward light, and animals retreat from fire. Not all stimuli produce responses, however. Imagine kicking a redwood tree or singing to a hibernating bear. This criterion, although superior to the first, is still inadequate to define life.

Death. The astronauts might attempt to kill the blob. All living things die, while inanimate objects do not. Death is not easily distinguished from disorder, however; a car that breaks down has not died because it was never alive. Death is simply the loss of life, so this is a circular definition at best. Unless one can detect life, death is a meaningless concept, and hence a very inadequate criterion for defining life.

Complexity. Finally, the astronauts might cut up the blob, to see if it is complexly organized. All living things are complex. Even the simplest bacteria

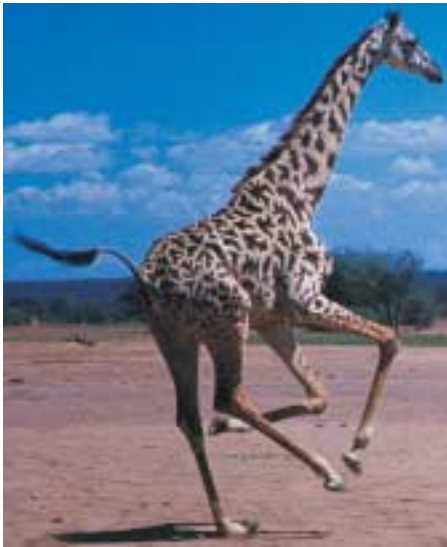


FIGURE 4.2

Movement. Animals have evolved mechanisms that allow them to move about in their environment. While some animals, like this giraffe, move on land, others move through water or air.



FIGURE 4.3

Sensitivity. This father lion is responding to a stimulus: he has just been bitten on the rump by his cub. As far as we know, all organisms respond to stimuli, although not always to the same ones or in the same way. Had the cub bitten a tree instead of its father, the response would not have been as dramatic.

contain a bewildering array of molecules, organized into many complex structures. However a computer is also complex, but not alive. Complexity is a *necessary* criterion of life, but it is not *sufficient* in itself to identify living things because many complex things are not alive.

To determine whether the blob is alive, the astronauts would have to learn more about it. Probably the best thing they could do would be to examine it more carefully and determine whether it resembles the organisms we are familiar with, and if so, how.

Fundamental Properties of Life

As we discussed in chapter 1, all known organisms share certain general properties. To a large degree, these properties define what we mean by life. The following fundamental properties are shared by all organisms on earth.

Cellular organization. All organisms consist of one or more *cells*—complex, organized assemblages of molecules enclosed within membranes (figure 4.4).

Sensitivity. All organisms respond to stimuli—though not always to the same stimuli in the same ways.

Growth. All living things assimilate energy and use it to grow, a process called *metabolism*. Plants, algae, and some bacteria use sunlight to create covalent carbon-carbon bonds from CO₂ and H₂O through photosynthesis. This transfer of the energy in covalent bonds is essential to all life on earth.

Development. Multicellular organisms undergo systematic gene-directed changes as they grow and mature.

Reproduction. All living things reproduce, passing on traits from one generation to the next. Although some organisms live for a very long time, no organism lives forever, as far as we know. Because all organisms die, ongoing life is impossible without *reproduction*.

Regulation. All organisms have regulatory mechanisms that coordinate internal processes.

Homeostasis. All living things maintain relatively constant internal conditions, different from their environment.

The Key Role of Heredity

Are these properties adequate to define life? Is a membrane-enclosed entity that grows and reproduces alive? Not necessarily. Soap bubbles and proteinoid microspheres spontaneously form hollow bubbles that enclose a small volume of water. These spheres can enclose energy-processing molecules, and they may also grow and subdivide. Despite these features, they are certainly not alive. Therefore, the criteria just listed,

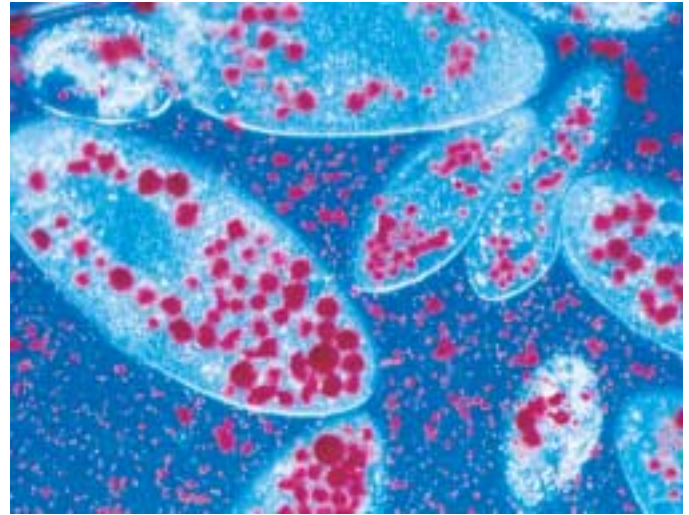


FIGURE 4.4
Cellular organization (150 \times). These *Paramecia*, which are complex, single-celled organisms called protists, have just ingested several yeast cells. The yeasts, stained *red* in this photograph, are enclosed within membrane-bounded sacs called digestive vacuoles. A variety of other organelles are also visible.

although necessary for life, are not sufficient to define life. One ingredient is missing—a mechanism for the preservation of improvement.

Heredity. All organisms on earth possess a *genetic system* that is based on the replication of a long, complex molecule called DNA. This mechanism allows for adaptation and evolution over time, also distinguishing characteristics of living things.

To understand the role of heredity in our definition of life, let us return for a moment to proteinoid microspheres. When we examine an individual microsphere, we see it at that precise moment in time but learn nothing of its predecessors. It is likewise impossible to guess what future droplets will be like. The droplets are the passive prisoners of a changing environment, and it is in this sense that they are not alive. The essence of being alive is the ability to encompass change and to reproduce the results of change permanently. Heredity, therefore, provides the basis for the great division between the living and the nonliving. Change does not become evolution unless it is passed on to a new generation. A genetic system is the sufficient condition of life. Some changes are preserved because they increase the chances of survival in a hostile world, while others are lost. Not only did life evolve—evolution is the very essence of life.

All living things on earth are characterized by cellular organization, heredity, and a handful of other characteristics that serve to define the term life.

4.2 There are many ideas about the origin of life.

Theories about the Origin of Life

The question of how life originated is not easy to answer because it is impossible to go back in time and observe life's beginnings; nor are there any witnesses. There is testimony in the rocks of the earth, but it is not easily read, and often it is silent on issues crying out for answers. There are, in principle, at least three possibilities:

- 1. Special creation.** Life-forms may have been put on earth by supernatural or divine forces.
- 2. Extraterrestrial origin.** Life may not have originated on earth at all; instead, life may have infected earth from some other planet.
- 3. Spontaneous origin.** Life may have evolved from inanimate matter, as associations among molecules became more and more complex.

Special Creation. The theory of special creation, that a divine God created life is at the core of most major religions. The oldest hypothesis about life's origins, it is also the most widely accepted. Far more Americans, for example, believe that God created life on earth than believe in the other two hypotheses. Many take a more extreme position, accepting the biblical account of life's creation as factually correct. This viewpoint forms the basis for the very unscientific "scientific creationism" viewpoint discussed in chapter 21.

Extraterrestrial Origin. The theory of **panspermia** proposes that meteors or cosmic dust may have carried significant amounts of complex organic molecules to earth, kicking off the evolution of life. Hundreds of thousands of meteorites and comets are known to have slammed into the early earth, and recent findings suggest that at least some may have carried organic materials. Nor is life on other planets ruled out. For example, the discovery of liquid water under the surface of Jupiter's ice-shrouded moon Europa and suggestions of fossils in

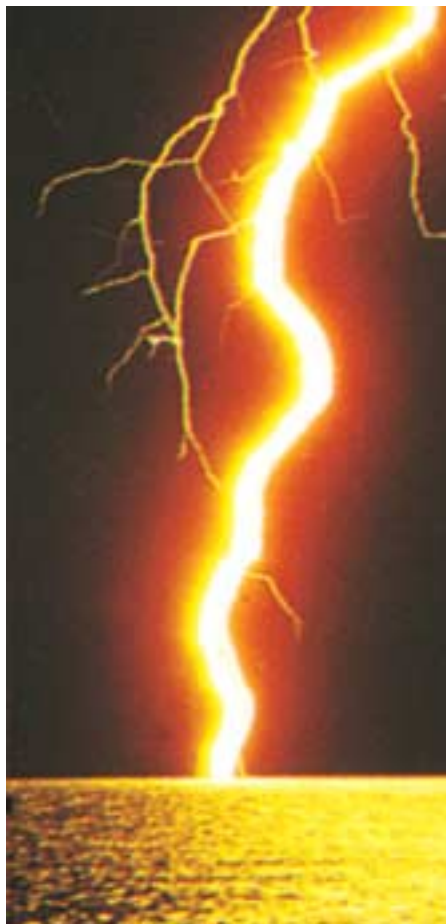


FIGURE 4.5
Lightning. Before life evolved, the simple molecules in the earth's atmosphere combined to form more complex molecules. The energy that drove these chemical reactions may have come from lightning and forms of geothermal energy.

rocks from Mars lend some credence to this idea. The hypothesis that an early source of carbonaceous material is extraterrestrial is testable, although it has not yet been proven. Indeed, NASA is planning to land on Europa, drill through the surface, and send a probe down to see if there is life.

Spontaneous Origin. Most scientists tentatively accept the theory of spontaneous origin, that life evolved from inanimate matter. In this view, the force leading to life was selection. As changes in molecules increased their stability and caused them to persist longer, these molecules could initiate more and more complex associations, culminating in the evolution of cells.

Taking a Scientific Viewpoint

In this book we will focus on the second and third possibilities, attempting to understand whether natural forces could have led to the origin of life and, if so, how the process might have occurred. This is not to say that the first possibility is definitely not the correct one. Any one of the three possibilities might be true. Nor do the second and third possibilities preclude religion (a divine agency might have acted via evolution, for example). However, we are limiting the scope of our inquiry to scientific matters, and only the second and third possibilities permit testable hypotheses to be constructed—that is, explanations that can be tested and potentially disproved.

In our search for understanding, we must look back to the early times. There are fossils of simple living things, bacteria, in rocks 3.5 billion years old. They tell us that life originated during the first billion years of the history of our planet. As we attempt to determine how this process took place, we will first focus on how organic molecules may have originated (figure 4.5), and then we will consider how those molecules might have become organized into living cells.

Panspermia and spontaneous origin are the only testable hypotheses of life's origin currently available.

Scientists Disagree about Where Life Started

While most researchers agree that life first appeared as the primitive earth cooled and its rocky crust formed, there is little agreement as to just where this occurred.

Did Life Originate at the Ocean's Edge?

The more we learn about earth's early history, the more likely it seems that earth's first organisms emerged and lived at very high temperatures. Rubble from the forming solar system slammed into early earth from 4.6 to 3.8 billion years ago, keeping the surface molten hot. As the bombardment slowed down, temperatures dropped. By about 3.8 billion years ago, ocean temperatures are thought to have dropped to a hot 49° to 88°C (120° to 190°F). Between 3.8 and 3.5 billion years ago, life first appeared, promptly after the earth was inhabitable. Thus, as intolerable as early earth's infernal temperatures seem to us today, they gave birth to life.

Very few geochemists agree on the exact composition of the early atmosphere. One popular view is that it contained principally carbon dioxide (CO₂) and nitrogen gas (N₂), along with significant amounts of water vapor (H₂O). It is possible that the early atmosphere also contained hydrogen gas (H₂) and compounds in which hydrogen atoms were bonded to the other light elements (sulfur, nitrogen, and carbon), producing hydrogen sulfide (H₂S), ammonia (NH₃), and methane (CH₄).

We refer to such an atmosphere as a reducing atmosphere because of the ample availability of hydrogen atoms and their electrons. In such a reducing atmosphere it would not take as much energy as it would today to form the carbon-rich molecules from which life evolved.

The key to this reducing atmosphere hypothesis is the assumption that there was very little oxygen around. In an atmosphere with oxygen, amino acids and sugars react spontaneously with the oxygen to form carbon dioxide and water. Therefore, the building blocks of life, the amino acids, would not last long and the spontaneous formation of complex carbon molecules could not occur. Our atmosphere changed once organisms began to carry out photosynthesis, harnessing the energy in sunlight to split water molecules and form complex carbon molecules, giving off gaseous oxygen molecules in the process. The earth's atmosphere is now approximately 21% oxygen.

Critics of the reducing atmosphere hypothesis point out that no carbonates have been found in rocks dating back to the early earth. This suggests that at that time carbon dioxide was locked up in the atmosphere, and if that was the case, then the prebiotic atmosphere would not have been reducing.

Another problem for the reducing atmosphere hypothesis is that because a prebiotic reducing atmosphere would have been oxygen free, there would have been no ozone. Without the protective ozone layer, any organic compounds

that might have formed would have been broken down quickly by ultraviolet radiation.

Other Suggestions

If life did not originate at the ocean's edge under the blanket of a reducing atmosphere, where did it originate?

Under frozen oceans. One hypothesis proposes that life originated under a frozen ocean, not unlike the one that covers Jupiter's moon Europa today. All evidence suggests, however, that the early earth was quite warm and frozen oceans quite unlikely.

Deep in the earth's crust. Another hypothesis is that life originated deep in the earth's crust. In 1988 Gunter Wächtershäuser proposed that life might have formed as a by-product of volcanic activity, with iron and nickel sulfide minerals acting as chemical catalysts to recombine gases spewing from eruptions into the building blocks of life. In later work he and coworkers were able to use this unusual chemistry to build precursors for amino acids (although they did not actually succeed in making amino acids), and to link amino acids together to form peptides. Critics of this hypothesis point out that the concentration of chemicals used in their experiments greatly exceed what is found in nature.

Within clay. Other researchers have proposed the unusual hypothesis that life is the result of silicate surface chemistry. The surface of clays have positive charges to attract organic molecules, and exclude water, providing a potential catalytic surface on which life's early chemistry might have occurred. While interesting conceptually, there is little evidence that this sort of process could actually occur.

At deep-sea vents. Becoming more popular is the hypothesis that life originated at deep-sea hydrothermal vents, with the necessary prebiotic molecules being synthesized on metal sulfides in the vents. The positive charge of the sulfides would have acted as a magnet for negatively charged organic molecules. In part, the current popularity of this hypothesis comes from the new science of genomics, which suggests that the ancestors of today's prokaryotes are most closely related to the bacteria that live on the deep-sea vents.

No one is sure whether life originated at the ocean's edge, under frozen ocean, deep in the earth's crust, within clay, or at deep-sea vents. Perhaps one of these hypotheses will be proven correct. Perhaps the correct theory has not yet been proposed.

When life first appeared on earth, the environment was very hot. All of the spontaneous origin hypotheses assume that the organic chemicals that were the building blocks of life arose spontaneously at that time. How is a matter of considerable disagreement.

The Miller-Urey Experiment

An early attempt to see what kinds of organic molecules might have been produced on the early earth was carried out in 1953 by Stanley L. Miller and Harold C. Urey. In what has become a classic experiment, they attempted to reproduce the conditions at ocean's edge under a reducing atmosphere. Even if this assumption proves incorrect—the jury is still out on this—their experiment is critically important, as it ushered in the whole new field of prebiotic chemistry.

To carry out their experiment, they (1) assembled a reducing atmosphere rich in hydrogen and excluding gaseous oxygen; (2) placed this atmosphere over liquid water, which would have been present at ocean's edge; (3) maintained this mixture at a temperature somewhat below 100°C ; and (4) simulated lightning by bombarding it with energy in the form of sparks (figure 4.6).

They found that within a week, 15% of the carbon originally present as methane gas (CH_4) had converted into other simple carbon compounds. Among these compounds were formaldehyde (CH_2O) and hydrogen cyanide (HCN ; figure 4.7). These compounds then combined to form simple molecules, such as formic acid (HCOOH) and urea (NH_2CONH_2), and more complex molecules containing carbon-carbon bonds, including the amino acids glycine and alanine.

As we saw in chapter 3, amino acids are the basic building blocks of proteins, and proteins are one of the major kinds of molecules of which organisms are composed. In similar experiments performed later by other scientists, more than 30 different carbon compounds were identified, including the amino acids glycine, alanine, glutamic acid, valine, proline, and aspartic acid. Other biologically important molecules were also formed in these experiments. For example, hydrogen cyanide contributed to the production of a complex ring-shaped molecule called adenine—one of the bases found in DNA and RNA. Thus, the key molecules of life could have formed in the atmosphere of the early earth.

The Path of Chemical Evolution

A raging debate among biologists who study the origin of life concerns which organic molecules came first, RNA or proteins. Scientists are divided into three camps, those that focus on RNA, protein, or a combination of the two. All three arguments have their strong points. Like the hypotheses that try to account for where life originated, these competing hypotheses are diverse and speculative.

An RNA World. The “RNA world” group feels that without a hereditary molecule, other molecules could not have formed consistently. The “RNA world” argument earned support when Thomas Cech at the University of Colorado discovered ribozymes, RNA molecules that can behave as enzymes, catalyzing their own assembly. Recent work has

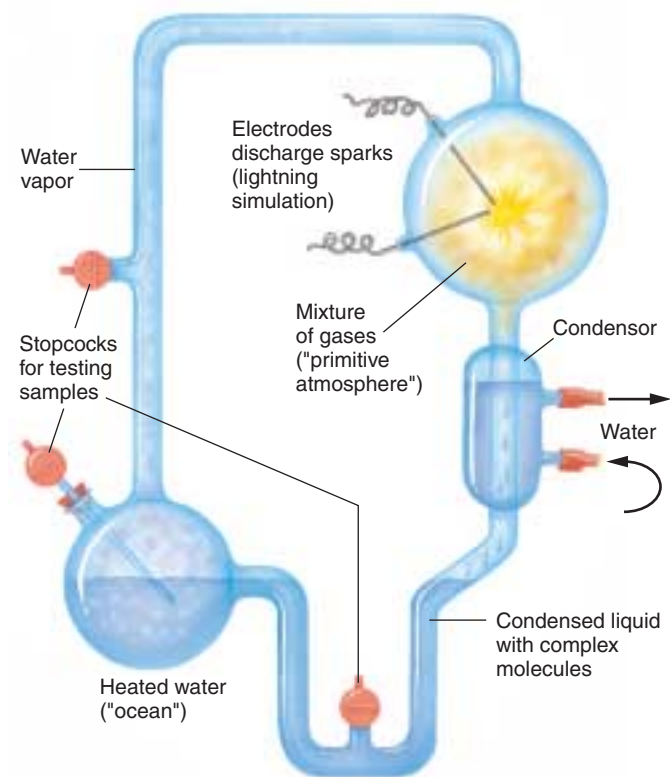


FIGURE 4.6

The Miller-Urey experiment. The apparatus consisted of a closed tube connecting two chambers. The upper chamber contained a mixture of gases thought to resemble the primitive earth's atmosphere. Electrodes discharged sparks through this mixture, simulating lightning. Condensers then cooled the gases, causing water droplets to form, which passed into the second heated chamber, the “ocean.” Any complex molecules formed in the atmosphere chamber would be dissolved in these droplets and carried to the ocean chamber, from which samples were withdrawn for analysis.

shown that the RNA contained in ribosomes (discussed in chapter 5) catalyzes the chemical reaction that links amino acids to form proteins. Therefore, the RNA in ribosomes also functions as an enzyme. If RNA has the ability to pass on inherited information and the capacity to act like an enzyme, were proteins really needed?

A Protein World. The “protein-first” group argues that without enzymes (which are proteins), nothing could replicate at all, heritable or not. The “protein-first” proponents argue that nucleotides, the individual units of nucleic acids such as RNA, are too complex to have formed spontaneously, and certainly too complex to form spontaneously again and again. While there is no doubt that simple proteins are easier to synthesize from abiotic components than nucleotides, both can form in the laboratory under the right conditions. Deciding which came first is a chicken-and-egg paradox. In an effort to shed light on this problem, Julius Rebek and a number of

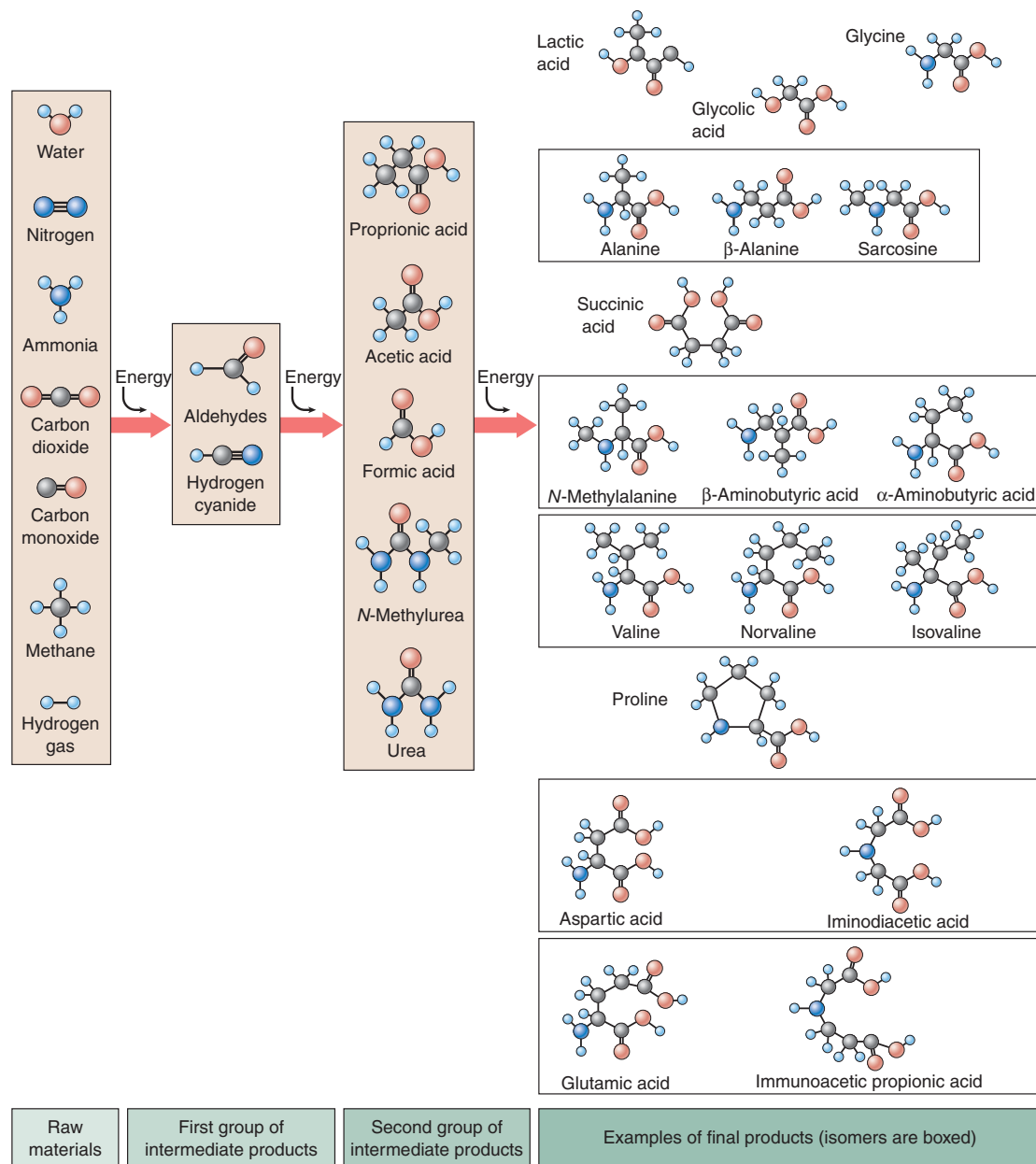


FIGURE 4.7

Results of the Miller-Urey experiment. Seven simple molecules, all gases, were included in the original mixture. Note that oxygen was not among them; instead, the atmosphere was rich in hydrogen. At each stage of the experiment, more complex molecules were formed: first aldehydes, then simple acids, then more complex acids. Among the final products, the molecules that are structural isomers of one another are grouped together in boxes. In most cases only one isomer of a compound is found in living systems today, although many may have been produced in the Miller-Urey experiment.

other chemists have created synthetic nucleotide-like molecules in the laboratory that are able to replicate. Moving even further, Rebek and his colleagues have created synthetic molecules that could replicate and “make mistakes.” This simulates mutation, a necessary ingredient for the process of evolution.

A Peptide-Nucleic Acid World. Another important and popular theory about the first organic molecules assumes key roles for both peptides and nucleic acids. Because RNA

is so complex and unstable, this theory assumes there must have been a pre-RNA world where the peptide-nucleic acid (PNA) was the basis for life. PNA is stable and simple enough to have formed spontaneously, and is also a self-replicator.

Molecules that are the building blocks of living organisms form spontaneously under conditions designed to simulate those of the primitive earth.

4.3 The first cells had little internal structure.

Theories about the Origin of Cells

The evolution of cells required early organic molecules to assemble into a functional, interdependent unit. Cells, discussed in the next chapter, are essentially little bags of fluid. What the fluid contains depends on the individual cell, but every cell's contents differ from the environment outside the cell. Therefore, an early cell may have floated along in a dilute "primordial soup," but its interior would have had a higher concentration of specific organic molecules.

Cell Origins: The Importance of Bubbles

How did these "bags of fluid" evolve from simple organic molecules? As you can imagine, the answer to this question is a matter for debate. Scientists favoring an "ocean's edge" scenario for the origin of life have proposed that bubbles may have played a key role in this evolutionary step. A bubble, such as those produced by soap solutions, is a hollow spherical structure. Certain molecules, particularly those with hydrophobic regions, will spontaneously form bubbles in water. The structure of the bubble shields the hydrophobic regions of the molecules from contact with water. If you have ever watched the ocean surge upon the shore, you may have noticed the foamy froth created by the agitated water. The edges of the primitive oceans were more than likely very frothy places bombarded by ultraviolet and other ionizing radiation, and exposed to an atmosphere that may have contained methane and other simple organic molecules.

Oparin's Bubble Theory

The first bubble theory is attributed to Alexander Oparin, a Russian chemist with extraordinary insight. In the mid-1930s, Oparin suggested that the present-day atmosphere was incompatible with the creation of life. He proposed that life must have arisen from nonliving matter under a set of very different environmental circumstances some time in the distant history of the earth. His was the theory of **primary abiogenesis** (primary because all living cells are now known to come from previously living cells, except in that first case). At the same time, J. B. S. Haldane, a British geneticist, was also independently espousing the same views. Oparin decided that in order for cells to evolve, they must have had some means of developing chemical complexity, separating their contents from their environment by means of a cell membrane, and concentrating materials within themselves. He termed these early, chemical-concentrating bubblelike structures **protobionts**.

Oparin's theories were published in English in 1938, and for awhile most scientists ignored them. However, Harold Urey, an astronomer at the University of Chicago, was quite taken with Oparin's ideas. He convinced one of his graduate students, Stanley Miller, to follow Oparin's rationale and see if he could "create" life. The Urey-Miller experiment has proven to be one of the most significant experiments in the history of science. As a result Oparin's ideas became better known and more widely accepted.

A Host of Bubble Theories

Different versions of "bubble theories" have been championed by numerous scientists since Oparin. The bubbles they propose go by a variety of names; they may be called *microspheres*, *protocells*, *protobionts*, *micelles*, *liposomes*, or *coacervates*, depending on the composition of the bubbles (lipid or protein) and how they form. In all cases, the bubbles are hollow spheres, and they exhibit a variety of cell-like properties. For example, the lipid bubbles called **coacervates** form an outer boundary with two layers that resembles a biological membrane. They grow by accumulating more subunit lipid molecules from the surrounding medium, and they can form budlike projections and divide by pinching in two, like bacteria. They also can contain amino acids and use them to facilitate various acid-base reactions, including the decomposition of glucose. Although they are not alive, they obviously have many of the characteristics of cells.

A Bubble Scenario

It is not difficult to imagine that a process of chemical evolution involving bubbles or microdrops preceded the origin of life (figure 4.8). The early oceans must have contained untold numbers of these microdrops, billions in a spoonful, each one forming spontaneously, persisting for a while, and then dispersing. Some would, by chance, have contained amino acids with side groups able to catalyze growth-promoting reactions. Those microdrops would have survived longer than ones that lacked those amino acids, because the persistence of both proteinoid microspheres and lipid coacervates is greatly increased when they carry out metabolic reactions such as glucose degradation and when they are actively growing.

Over millions of years, then, the complex bubbles that were better able to incorporate molecules and energy from the lifeless oceans of the early earth would have tended to persist longer than the others. Also favored would have been the microdrops that could use these molecules to expand in size, growing large enough to divide into "daughter"

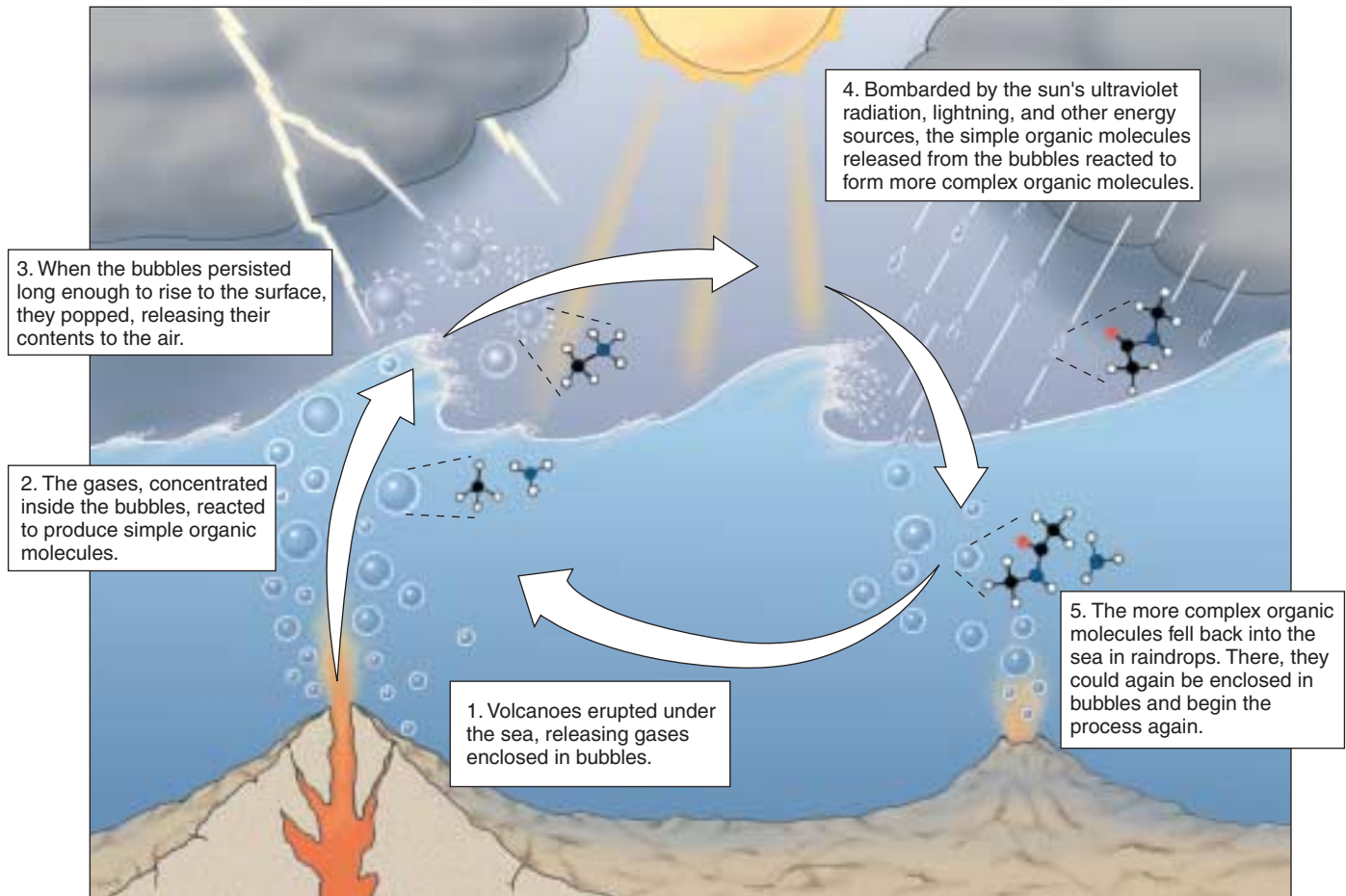


FIGURE 4.8

A current bubble hypothesis. In 1986 geophysicist Louis Lerman proposed that the chemical processes leading to the evolution of life took place within bubbles on the ocean's surface.

microdrops with features similar to those of their “parent” microdrop. The daughter microdrops have the same favorable combination of characteristics as their parent, and would have grown and divided, too. When a way to facilitate the reliable transfer of new ability from parent to offspring developed, heredity—and life—began.

Current Thinking

Whether the early bubbles that gave rise to cells were lipid or protein remains an unresolved argument. While it is true that lipid microspheres (coacervates) will form readily in water, there appears to be no mechanism for their heritable replication. On the other hand, one *can* imagine a heritable mechanism for protein microspheres. Although protein microspheres do not form readily in water, Sidney Fox and his colleagues at the University of Miami have shown that they can form under dry conditions.

The discovery that RNA can act as an enzyme to assemble new RNA molecules on an RNA template has raised

the interesting possibility that neither coacervates nor protein microspheres were the first step in the evolution of life. Perhaps the first components were RNA molecules, and the initial steps on the evolutionary journey led to increasingly complex and stable RNA molecules. Later, stability might have improved further when a lipid (or possibly protein) microsphere surrounded the RNA. At present, those studying this problem have not arrived at a consensus about whether RNA evolved before or after a bubblelike structure that likely preceded cells.

Eventually, DNA took the place of RNA as the replicator in the cell and the storage molecule for genetic information. DNA, because it is a double helix, stores information in a more stable fashion than RNA, which is single-stranded.

Little is known about how the first cells originated. Current hypotheses involve chemical evolution within bubbles, but there is no general agreement about their composition, or about how the process occurred.

The Earliest Cells

What do we know about the earliest life-forms? The fossils found in ancient rocks show an obvious progression from simple to complex organisms, beginning about 3.5 billion years ago. Life may have been present earlier, but rocks of such great antiquity are rare, and fossils have not yet been found in them.

Microfossils

The earliest evidence of life appears in **microfossils**, fossilized forms of microscopic life (figure 4.9). Microfossils were small (1 to 2 micrometers in diameter) and single-celled, lacked external appendages, and had little evidence of internal structure. Thus, they physically resemble present-day **bacteria** (figure 4.10), although some ancient forms cannot be matched exactly. We call organisms with this simple body plan **prokaryotes**, from the Greek words meaning “before” and “kernel,” or “nucleus.” The name reflects their lack of a **nucleus**, a spherical organelle characteristic of the more complex cells of **eukaryotes**.

Judging from the fossil record, eukaryotes did not appear until about 1.5 billion years ago. Therefore, for at least 2 billion years—nearly a half of the age of the earth—bacteria were the only organisms that existed.

Ancient Bacteria: Archaeobacteria

Most organisms living today are adapted to the relatively mild conditions of present-day earth. However, if we look in unusual environments, we encounter organisms that are quite remarkable, differing in form and metabolism from other living things. Sheltered from evolutionary alteration in unchanging habitats that resemble earth’s early environment, these living relics are the surviving representatives of the first ages of life on earth. In places such as the oxygen-free depths of the Black Sea or the boiling waters of hot springs and deep-sea vents, we can find bacteria living at very high temperatures without oxygen.

These unusual bacteria are called **archaeobacteria**, from the Greek word for “ancient ones.” Among the first to be studied in detail have been the **methanogens**, or methane-producing bacteria, among the most primitive bacteria that exist today. These organisms are typically simple in form and are able to grow only in an oxygen-free environment; in fact, oxygen poisons them. For this reason they are said to grow “without air,” or **anaerobically** (Greek *an*, “without” + *aer*, “air” + *bios*, “life”). The methane-producing bacteria convert CO₂ and H₂ into methane gas (CH₄). Although primitive, they resemble all other bacteria in having DNA, a lipid cell membrane, an exterior cell wall, and a metabolism based on an energy-carrying molecule called ATP.

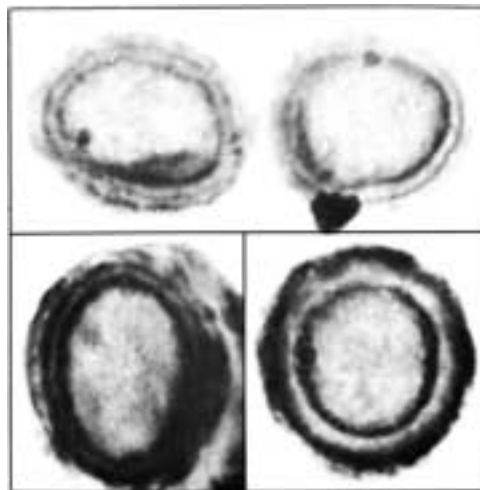


FIGURE 4.9
Cross-sections of fossil bacteria. These microfossils from the Bitter Springs formation of Australia are of ancient cyanobacteria, far too small to be seen with the unaided eye. In this electron micrograph, the cell walls are clearly evident.

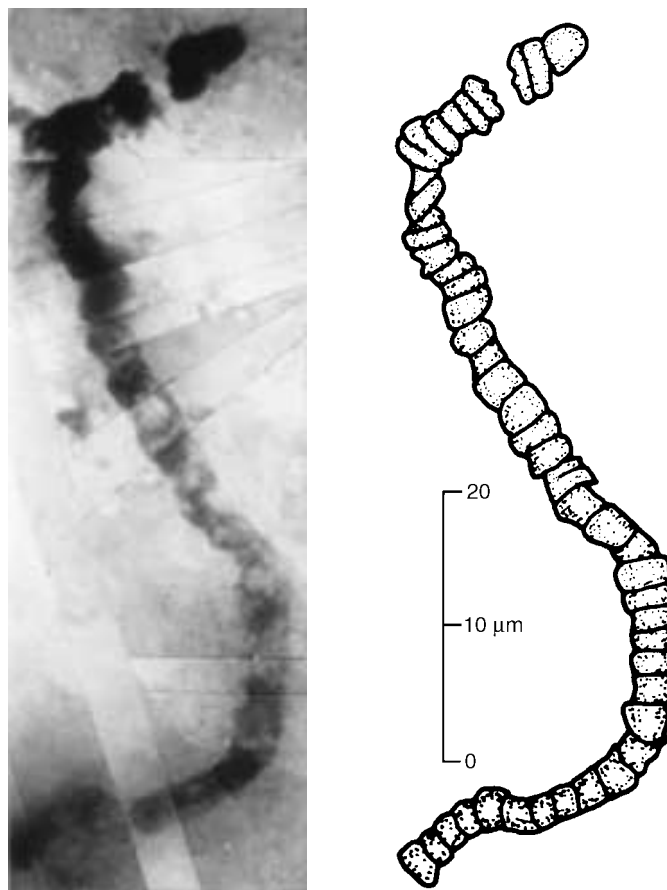


FIGURE 4.10
The oldest microfossil. This ancient bacterial fossil, discovered by J. William Schopf of UCLA in 3.5-billion-year-old rocks in western Australia, is similar to present-day cyanobacteria, as you can see by comparing it to figure 4.11.

Unusual Cell Structures

When the details of cell wall and membrane structure of the methane-producing bacteria were examined, they proved to be different from those of all other bacteria. Archaeobacteria are characterized by a conspicuous lack of a protein cross-linked carbohydrate material called **peptidoglycan** in their cell walls, a key compound in the cell walls of most modern bacteria. Archaeobacteria also have unusual lipids in their cell membranes that are not found in any other group of organisms. There are also major differences in some of the fundamental biochemical processes of metabolism, different from those of all other bacteria. The methane-producing bacteria are survivors from an earlier time when oxygen gas was absent.

Earth's First Organisms?

Other archaeobacteria that fall into this classification are some of those that live in very salty environments like the Dead Sea (**extreme halophiles**—"salt lovers") or very hot environments like hydrothermal volcanic vents under the ocean (**extreme thermophiles**—"heat lovers"). Thermophiles have been found living comfortably in boiling water. Indeed, many kinds of thermophilic archaeobacteria thrive at temperatures of 110°C (230°F). Because these thermophiles live at high temperatures similar to those that may have existed when life first evolved, microbiologists speculate that thermophilic archaeobacteria may be relics of earth's first organisms.

Just how different are extreme thermophiles from other organisms? A methane-producing archaeobacteria called *Methanococcus* isolated from deep-sea vents provides a startling picture. These bacteria thrive at temperatures of 88°C (185°F) and crushing pressures 245 times greater than at sea level. In 1996 molecular biologists announced that they had succeeded in determining the full nucleotide sequence of *Methanococcus*. This was possible because archaeobacterial DNA is relatively small—it has only 1700 genes, coded in a DNA molecule only 1,739,933 nucleotides long (a human cell has 2000 times more!). The thermophile nucleotide sequence proved to be astonishingly different from the DNA sequence of any other organism ever studied; fully two-thirds of its genes are unlike any ever known to science before! Clearly these archaeobacteria separated from other life on earth a long time ago. Preliminary comparisons to the gene sequences of other bacteria suggest that archaeobacteria split from other types of bacteria over 3 billion years ago, soon after life began.

Eubacteria

The second major group of bacteria, the **eubacteria**, have very strong cell walls and a simpler gene architecture. Most bacteria living today are eubacteria. Included in this group are bacteria that have evolved the ability to capture the energy of light and transform it into the energy of chemical



FIGURE 4.11

Living cyanobacteria. Although not multicellular, these bacteria often aggregate into chains such as those seen here.

bonds within cells. These organisms are *photosynthetic*, as are plants and algae.

One type of photosynthetic eubacteria that has been important in the history of life on earth is the cyanobacteria, sometimes called "blue-green algae" (figure 4.11). They have the same kind of chlorophyll pigment that is most abundant in plants and algae, as well as other pigments that are blue or red. Cyanobacteria produce oxygen as a result of their photosynthetic activities, and when they appeared at least 3 billion years ago, they played a decisive role in increasing the concentration of free oxygen in the earth's atmosphere from below 1% to the current level of 21%. As the concentration of oxygen increased, so did the amount of ozone in the upper layers of the atmosphere. The thickening ozone layer afforded protection from most of the ultraviolet radiation from the sun, radiation that is highly destructive to proteins and nucleic acids. Certain cyanobacteria are also responsible for the accumulation of massive limestone deposits.

All bacteria now living are members of either Archaeobacteria or Eubacteria.

4.4 The first eukaryotic cells were larger and more complex than bacteria.

All fossils more than 1.5 billion years old are generally similar to one another structurally. They are small, simple cells; most measure 0.5 to 2 micrometers in diameter, and none are more than about 6 micrometers in diameter. These simple cells eventually evolved into larger, more complex forms—the first eukaryotic cells.

The First Eukaryotic Cells

In rocks about 1.5 billion years old, we begin to see the first microfossils that are noticeably different in appearance from the earlier, simpler forms (figure 4.12). These cells are much larger than bacteria and have internal membranes and thicker walls. Cells more than 10 micrometers in diameter rapidly increased in abundance. Some fossilized cells 1.4 billion years old are as much as 60 micrometers in diameter; others, 1.5 billion years old, contain what appear to be small, membrane-bound structures. Indirect chemical traces hint that eukaryotes may go as far back as 2.7 billion years, although no fossils as yet support such an early appearance of eukaryotes.

These early fossils mark a major event in the evolution of life: a new kind of organism had appeared (figure 4.13). These new cells are called **eukaryotes**, from the Greek words for “true” and “nucleus,” because they possess an internal structure called a nucleus. All organisms other than the bacteria are eukaryotes.

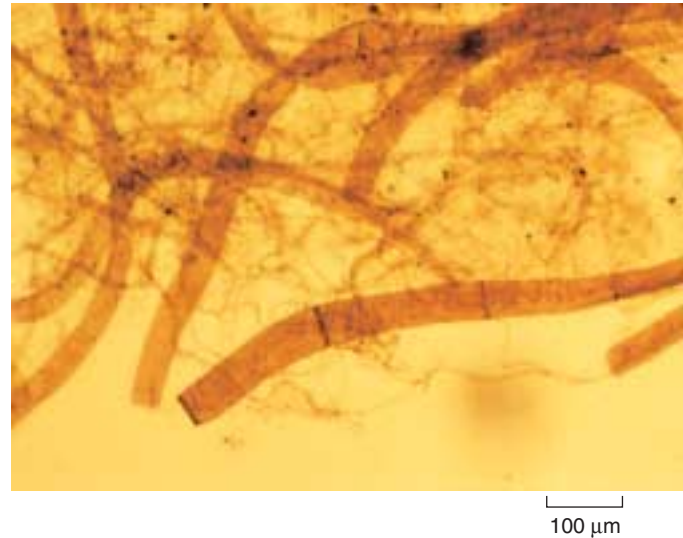


FIGURE 4.12
Microfossil of a primitive eukaryote. This multicellular alga is between 900 million and 1 billion years old.

Origin of the Nucleus and ER

Many bacteria have infoldings of their outer membranes extending into the cytoplasm and serving as passageways to the surface. The network of internal membranes in

CAMBRIAN	PHANEROZOIC	Geological evidence	Millions of years ago	Life forms
		Oldest multicellular fossils	570 600	Appearance of first multicellular organisms
PRECAMBRIAN	PROTEROZOIC	Oldest compartmentalized fossil cells	1500	Appearance of first eukaryotes Appearance of aerobic (oxygen-using) respiration
		Disappearance of iron from oceans and formation of iron oxides	2500	Appearance of oxygen-forming photosynthesis (cyanobacteria)
	ARCHEAN	Oldest definite fossils	3500	Appearance of chemoautotrophs (sulfate respiration) Appearance of life (prokaryotes): anaerobic (methane-producing) bacteria and anaerobic (hydrogen sulfide-forming) photosynthesis
		Oldest dated rocks	4500	Formation of the earth

FIGURE 4.13
The geological timescale. The periods refer to different stages in the evolution of life on earth. The timescale is calibrated by examining rocks containing particular kinds of fossils; the fossils are dated by determining the degree of spontaneous decay of radioactive isotopes locked within rock when it was formed.

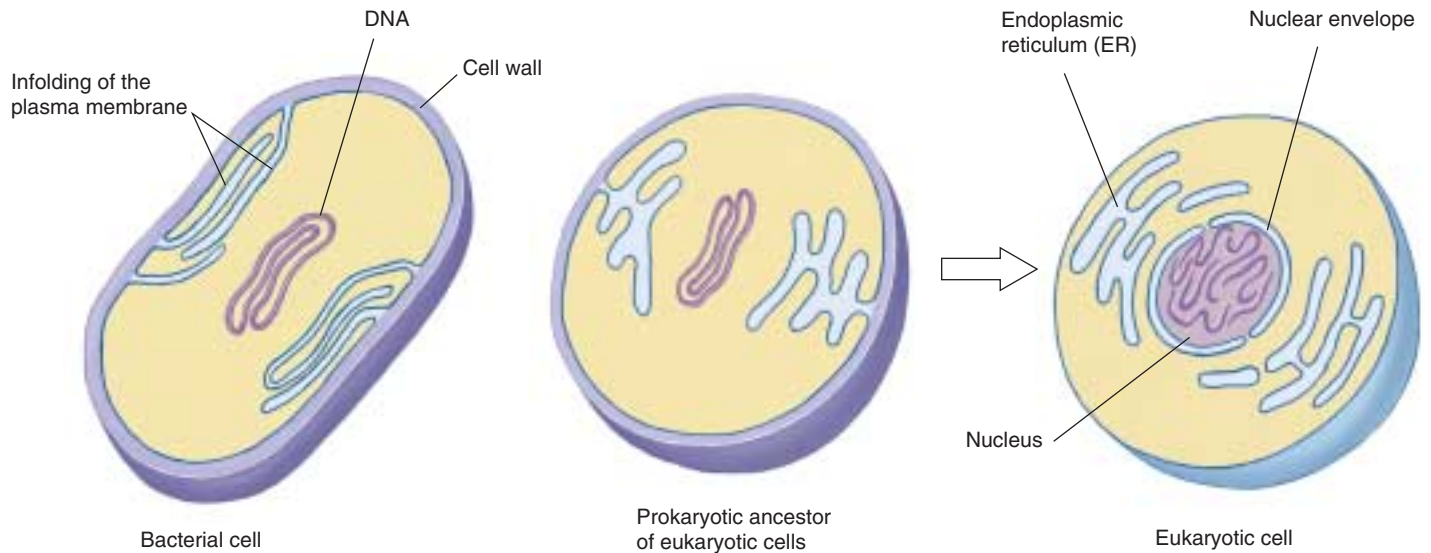


FIGURE 4.14

Origin of the nucleus and endoplasmic reticulum. Many bacteria today have infoldings of the plasma membrane (see also figure 34.7). The eukaryotic internal membrane system called the endoplasmic reticulum (ER) and the nuclear envelope may have evolved from such infoldings of the plasma membrane encasing prokaryotic cells that gave rise to eukaryotic cells.

eukaryotes called endoplasmic reticulum (ER) is thought to have evolved from such infoldings, as is the nuclear envelope, an extension of the ER network that isolates and protects the nucleus (figure 4.14).

Origin of Mitochondria and Chloroplasts

Bacteria that live within other cells and perform specific functions for their host cells are called *endosymbiotic bacteria*. Their widespread presence in nature led Lynn Margulis to champion the **endosymbiotic theory** in the early 1970s. This theory, now widely accepted, suggests that a critical stage in the evolution of eukaryotic cells involved endosymbiotic relationships with prokaryotic organisms. According to this theory, energy-producing bacteria may have come to reside within larger bacteria, eventually evolving into what we now know as mitochondria. Similarly, photosynthetic bacteria may have come to live within other larger bacteria, leading to the evolution of chloroplasts, the photosynthetic organelles of plants and algae. Bacteria with flagella, long whiplike cellular appendages used for propulsion, may have become symbiotically involved with nonflagellated bacteria to produce larger, motile cells. The fact that we now witness so many symbiotic relationships lends general support to this theory. Even stronger support comes from the observation that present-day organelles such as mitochondria, chloroplasts, and centrioles contain their own DNA, which is remarkably similar to the DNA of bacteria in size and character.

Sexual Reproduction

Eukaryotic cells also possess the ability to reproduce sexually, something prokaryotes cannot do effectively. **Sexual reproduction** is the process of producing offspring, with two copies of each chromosome, by fertilization, the union of two cells that each have one copy of each chromosome. The great advantage of sexual reproduction is that it allows for frequent genetic recombination, which generates the variation that is the raw material for evolution. Not all eukaryotes reproduce sexually, but most have the capacity to do so. The evolution of meiosis and sexual reproduction (discussed in chapter 12) led to the tremendous explosion of diversity among the eukaryotes.

Multicellularity

Diversity was also promoted by the development of **multicellularity**. Some single eukaryotic cells began living in association with others, in colonies. Eventually individual members of the colony began to assume different duties, and the colony began to take on the characteristics of a single individual. Multicellularity has arisen many times among the eukaryotes. Practically every organism big enough to see with the unaided eye is multicellular, including all animals and plants. The great advantage of multicellularity is that it fosters specialization; some cells devote all of their energies to one task, other cells to another. Few innovations have had as great an impact on the history of life as the specialization made possible by multicellularity.

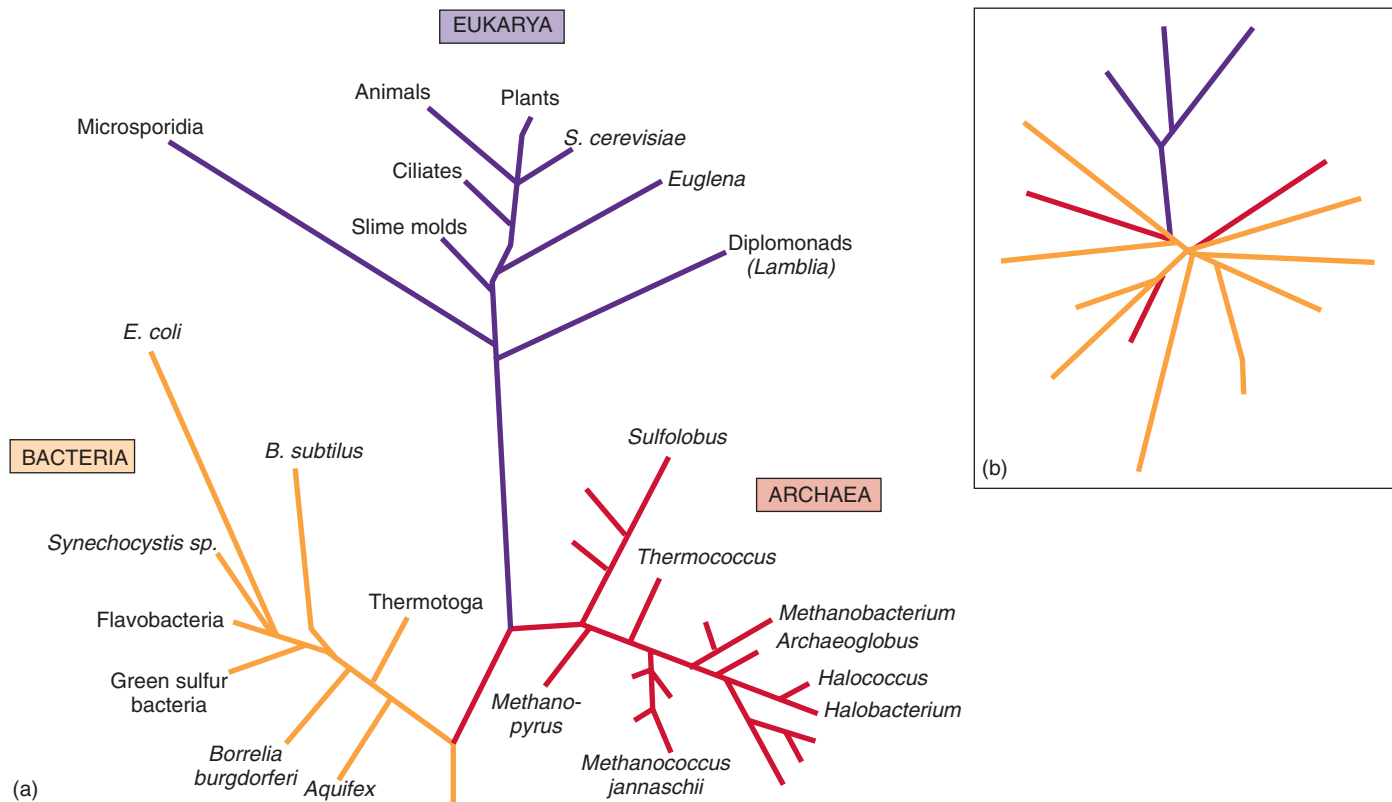


FIGURE 4.15

The three domains of life. The kingdoms Archaeobacteria and Eubacteria are as different from each other as from eukaryotes, so biologists have assigned them a higher category, a “domain.” (a) A three-domain tree of life based on ribosomal RNA consists of the Eukarya, Bacteria, and Archaea. (b) New analyses of complete genome sequences contradict the rRNA tree, and suggest other arrangements such as this one, which splits the Archaea. Apparently genes hopped from branch to branch as early organisms either stole genes from their food or swapped DNA with their neighbors, even distantly related ones.

The Kingdoms of Life

Confronted with the great diversity of life on earth today, biologists have attempted to categorize similar organisms in order to better understand them, giving rise to the science of taxonomy. In later chapters, we will discuss taxonomy and classification in detail, but for now we can generalize that all living things fall into one of three domains which include six kingdoms (figure 4.15):

Kingdom Archaeobacteria: Prokaryotes that lack a peptidoglycan cell wall, including the methanogens and extreme halophiles and thermophiles.

Kingdom Eubacteria: Prokaryotic organisms with a peptidoglycan cell wall, including cyanobacteria, soil bacteria, nitrogen-fixing bacteria, and pathogenic (disease-causing) bacteria.

Kingdom Protista: Eukaryotic, primarily unicellular (although algae are multicellular), photosynthetic or heterotrophic organisms, such as amoebas and paramecia.

Kingdom Fungi: Eukaryotic, mostly multicellular (although yeasts are unicellular), heterotrophic, usually nonmotile organisms, with cell walls of chitin, such as mushrooms.

Kingdom Plantae: Eukaryotic, multicellular, nonmotile, usually terrestrial, photosynthetic organisms, such as trees, grasses, and mosses.

Kingdom Animalia: Eukaryotic, multicellular, motile, heterotrophic organisms, such as sponges, spiders, newts, penguins, and humans.

As more is learned about living things, particularly from the newer evidence that DNA studies provide, scientists will continue to reevaluate the relationships among the kingdoms of life.

For at least the first 1 billion years of life on earth, all organisms were bacteria. About 1.5 billion years ago, the first eukaryotes appeared. Biologists place living organisms into six general categories called kingdoms.

Has Life Evolved Elsewhere?

We should not overlook the possibility that life processes might have evolved in different ways on other planets. A functional genetic system, capable of accumulating and replicating changes and thus of adaptation and evolution, could theoretically evolve from molecules other than carbon, hydrogen, nitrogen, and oxygen in a different environment. Silicon, like carbon, needs four electrons to fill its outer energy level, and ammonia is even more polar than water. Perhaps under radically different temperatures and pressures, these elements might form molecules as diverse and flexible as those carbon has formed on earth.

The universe has 10^{20} (100,000,000,000,000,000,000) stars similar to our sun. We don't know how many of these stars have planets, but it seems increasingly likely that many do. Since 1996, astronomers have been detecting planets orbiting distant stars. At least 10% of stars are thought to have planetary systems. If only 1 in 10,000 of these planets is the right size and at the right distance from its star to duplicate the conditions in which life originated on earth, the "life experiment" will have been repeated 10^{15} times (that is, a million billion times). It does not seem likely that we are alone.

Ancient Bacteria on Mars?

A dull gray chunk of rock collected in 1984 in Antarctica ignited an uproar about ancient life on Mars with the report that the rock contains evidence of possible life. Analysis of gases trapped within small pockets of the rock indicate it is a meteorite from Mars. It is, in fact, the oldest rock known to science—fully 4.5 billion years old. Back then, when this rock formed on Mars, that cold, arid planet was much warmer, flowed with water, and had a carbon dioxide atmosphere—conditions not too different from those that spawned life on earth.

When examined with powerful electron microscopes, carbonate patches within the meteorite exhibit what look like microfossils, some 20 to 100 nanometers in length. One hundred times smaller than any known bacteria, it is not clear they actually are fossils, but the resemblance to bacteria is striking.

Viewed as a whole, the evidence of bacterial life associated with the Mars meteorite is not compelling. Clearly, more painstaking research remains to be done before the discovery can claim a scientific consensus. However, while there is no conclusive evidence of bacterial life associated with this meteorite, it seems very possible that life has evolved on other worlds in addition to our own.

Deep-Sea Vents

The possibility that life on earth actually originated in the vicinity of deep-sea hydrothermal vents is gaining popularity. At the bottom of the ocean, where these vents spewed



FIGURE 4.16

Is there life elsewhere? Currently the most likely candidate for life elsewhere within the solar system is Europa, one of the many moons of the large planet Jupiter.

out a rich froth of molecules, the geological turbulence and radioactive energy battering the land was absent, and things were comparatively calm. The thermophilic archaeobacteria found near these vents today are the most ancient group of organisms living on earth. Perhaps the gentler environment of the ocean depths was the actual cradle of life.

Other Planets

Has life evolved on other worlds within our solar system? There are planets other than ancient Mars with conditions not unlike those on earth. Europa, a large moon of Jupiter, is a promising candidate (figure 4.16). Europa is covered with ice, and photos taken in close orbit in the winter of 1998 reveal seas of liquid water beneath a thin skin of ice. Additional satellite photos taken in 1999 suggest that a few miles under the ice lies a liquid ocean of water larger than earth's, warmed by the push and pull of the gravitational attraction of Jupiter's many large satellite moons. The conditions on Europa now are far less hostile to life than the conditions that existed in the oceans of the primitive earth. In coming decades satellite missions are scheduled to explore this ocean for life.

There are so many stars that life may have evolved many times. Although evidence for life on Mars is not compelling, the seas of Europa offer a promising candidate which scientists are eager to investigate.



Chapter 4

Summary

Questions

Media Resources

4.1 All living things share key characteristics.

- All living things are characterized by cellular organization, growth, reproduction, and heredity.
- Other properties commonly exhibited by living things include movement and sensitivity to stimuli.

1. What characteristics of living things are *necessary* characteristics (possessed by all living things), and which are *sufficient* characteristics (possessed only by living things)?

4.2 There are many ideas about the origin of life.

- Of the many explanations of how life might have originated, only the theories of spontaneous and extraterrestrial origins provide scientifically testable explanations.
- Experiments recreating the atmosphere of primitive earth, with the energy sources and temperatures thought to be prevalent at that time, have led to the spontaneous formation of amino acids and other biologically significant molecules.

2. What molecules are thought to have been present in the atmosphere of the early earth? Which molecule that was notably absent then is now a major component of the atmosphere?



• Origin of Life



• Art Quizzes:
-Miller-Urey Experiment
-Miller-Urey Experiment Results

4.3 The first cells had little internal structure.

- The first cells are thought to have arisen from aggregations of molecules that were more stable and, therefore, persisted longer.
- It has been suggested that RNA may have arisen before cells did, and subsequently became packaged within a membrane.
- Bacteria were the only life-forms on earth for about 1 billion years. At least three kinds of bacteria were present in ancient times: methane utilizers, anaerobic photosynthesizers, and eventually O₂-forming photosynthesizers.

3. What evidence supports the argument that RNA evolved first on the early earth? What evidence supports the argument that proteins evolved first?



• Art Quiz:
Current Bubble Hypothesis

4. What are coacervates, and what characteristics do they have in common with organisms? Are they alive? Why or why not?

5. What were the earliest known organisms like, and when did they appear? What present-day organisms do they resemble?

4.4 The first eukaryotic cells were larger and more complex than bacteria.

- The first eukaryotes can be seen in the fossil record about 1.5 billion years ago. All organisms other than bacteria are their descendants.
- Biologists group all living organisms into six “kingdoms,” each profoundly different from the others.
- The two most ancient kingdoms contain prokaryotes (bacteria); the other four contain eukaryotes.
- There are approximately 10²⁰ stars in the universe similar to our sun. It is almost certain that life has evolved on planets circling some of them.

6. When did the first eukaryotes appear? By what mechanism are they thought to have evolved from the earlier prokaryotes?

7. What sorts of organisms are contained in each of the six kingdoms of life recognized by biologists?



• Key Events in Earth's History

