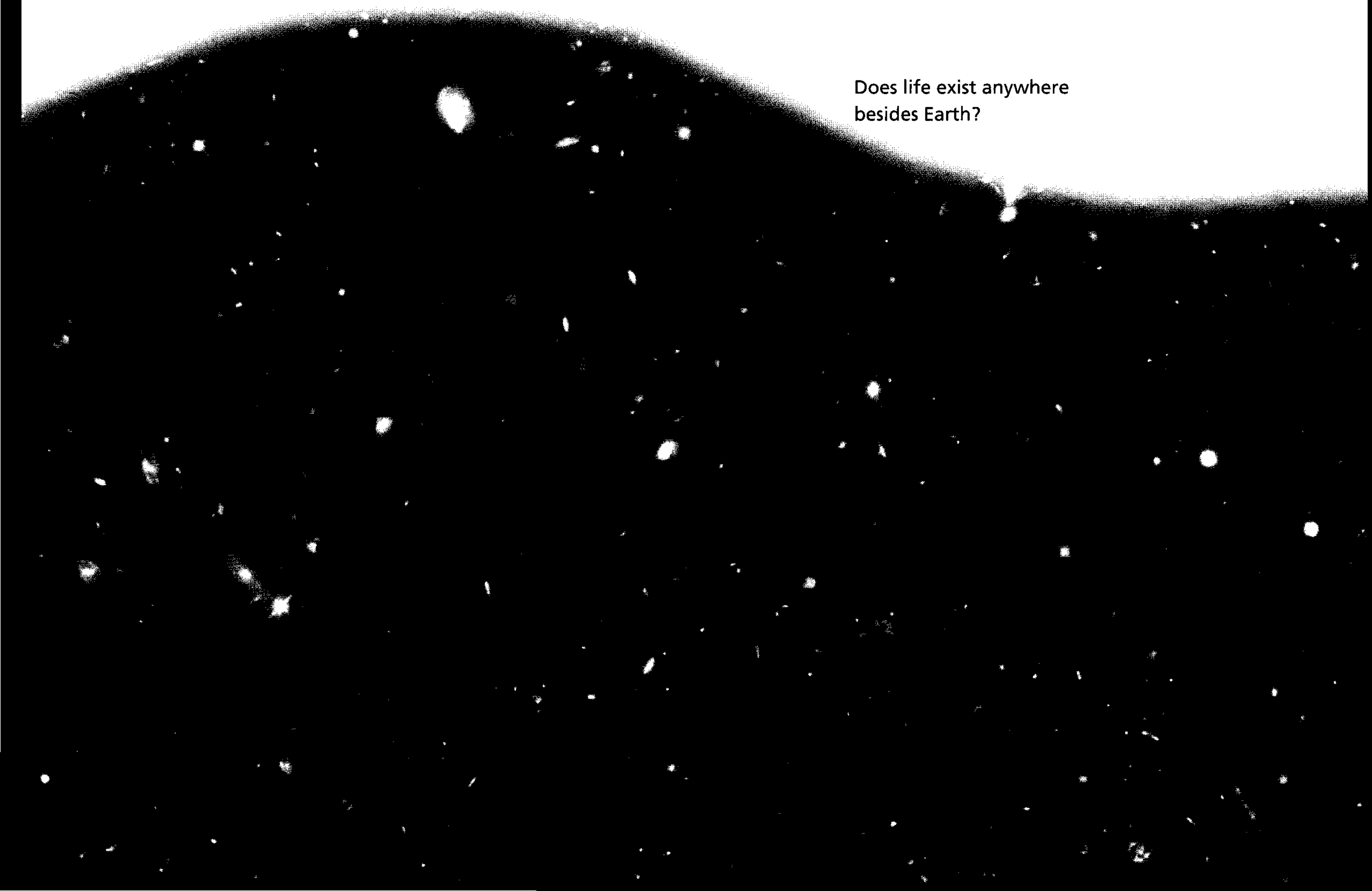
CHAPTER 2

Are We Alone in the Universe?

Water, Biochemistry, and Cells



Does life exist anywhere besides Earth?

2.1 What Does Life Require? *24*

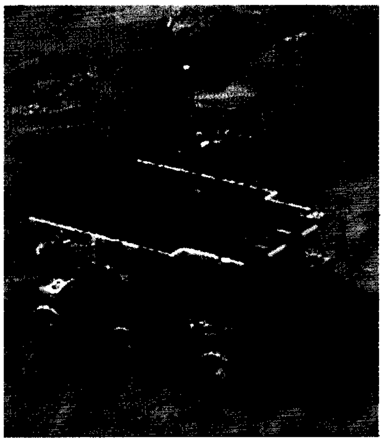
A Definition of Life
The Properties of Water
Organic Chemistry
Structure and Function of Macromolecules

2.2 Life on Earth *35*

Prokaryotic and Eukaryotic Cells
Cell Structure
The Tree of Life and Evolutionary Theory

Popular images aside, we know of no other intelligent life in our solar system.

But there is intriguing evidence that life once existed on Mars.



Humans are willing to expend enormous resources to look for life outside Earth.

In the summer of 1996, Dr. David McKay announced to the world that he and his colleagues had found persuasive, if not conclusive, evidence of life on Mars. People around the world were astounded. How could this cold, dry, harsh planet harbor life?

The evidence of life found by Dr. McKay's team did not in any way resemble the cartoon images often used to depict Martians. Instead, what these scientists found was evidence of life in a 3.6-billion-year-old, potato-sized rock. They believe that the rock had been ejected from the surface of Mars around 15 million years ago and had traveled through space for nearly that entire time. Ultimately the rock crashed to Earth, landing in Antarctica about 13,000 years ago, and remained there until discovered by scientists in 1984. This meteorite, drably named ALH84001, appeared to contain the same features that scientists use to demonstrate the existence of life in 3.6-billion-year-old Earth rocks—there were fossils, various minerals that are characteristic of life, and evidence of complex chemicals typically produced by living organisms. The announcement of this discovery injected new energy into Mars exploration. Since then, multiple robotic rovers and mapping satellites have been sent to the planet, and in January 2004, President George W. Bush announced an initiative to send astronauts to the red planet by the 2020s. While there are many reasons to explore Mars, the question that remains most intriguing—and is a significant focus of several of these missions—is whether life ever existed there.

The fascination about potential Martian life speaks to a fundamental question that many humans share: Are the creatures on Earth the only living organisms in the universe? Our galaxy is filled with countless stars and planets, and the universe teems with galaxies. Even if we find no convincing evidence of life on Mars, there is a seemingly infinite number of places to look for other living beings. In this chapter, we discuss the characteristics and requirements of life and examine techniques that scientists use to search the universe for other living creatures.

2.1 What Does Life Require?

Because the galaxy likely contains billions of planets, scientists looking for life elsewhere seek to identify the range of conditions under which they would expect life to arise. What is it that scientists look for when identifying a planet (or moon) as a candidate for hosting life?

A Definition of Life

In science-fiction movies, alien life-forms are often obviously alive, and even somewhat familiar looking. But in reality, living organisms may be truly alien; that is, they may look nothing like organisms we are familiar with on Earth. So how would we determine whether an entity found on another planet was actually *alive*?

Surprisingly, biologists do not have a simple definition for a "living organism." A list of the attributes found in most earthly life-forms includes growth, **metabolism** (all of the chemical processes that occur in cells, including the breakdown of substances to produce energy, the synthesis of substances necessary for life, and the excretion of wastes generated by these processes), movement, reproduction, and response to external environmental stimuli. However, this definition could apply to things that no one considers to be living. For example, fire can grow, consume energy, give off waste, move, reproduce by sending off sparks, and change in response to environmental conditions. And some organisms that are clearly living do not conform to this definition. For instance, male mules grow, metabolize, move, and respond to stimuli, but they are sterile (unable to reproduce). In practice, most biologists do not attempt to define the characteristics of living organisms; they are content to apply the same standard that U.S. Supreme Court Justice Potter Stewart did when struggling to define "obscene material" in 1964: "I know it when I see it." Unfortunately, when people on Earth are faced with a truly alien life-form, it is not clear that this approach will be sufficient. In fact, it may not be safe to assume that living things on other planets would have the same characteristics as living things on Earth.

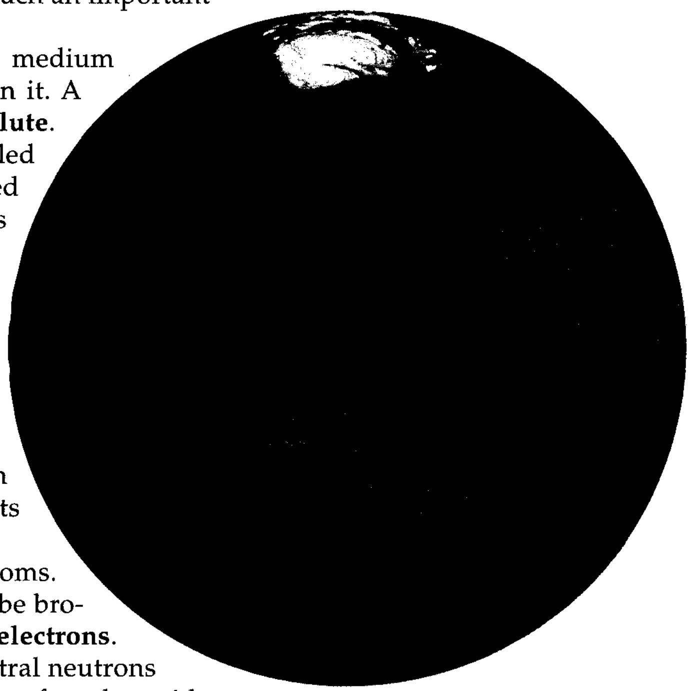
Figure 2.1 Homeostasis. Black-capped chickadees can maintain a core body temperature of 108°F during the day, even when the air temperature is well below zero. This constant internal temperature requires a complex feedback system between multiple sensory and physiological systems that is possible only in living organisms.

If we examine more closely the characteristics of living organisms on Earth, we will see that all organisms contain a common set of biological molecules, are composed of cells, and can maintain **homeostasis**, that is, a roughly constant internal environment despite an ever-changing external environment (Figure 2.1). In addition, populations of living organisms can evolve, that is, change in average physical characteristics over time. If we search the universe for planets that could support life similar to that found on Earth—and thus organisms that we would clearly identify as "living"—the list of planetary requirements becomes more stringent. In particular, an Earth-like planet should have abundant liquid **water** available.

The Properties of Water

Water is a requirement for life. Although Mars does not currently appear to have any liquid water, frozen water is found at its poles, and features of its surface indicate that it once contained salty seas and flowing water (Figure 2.2). The presence of liquid water on Mars fulfills an essential prerequisite for the appearance of life. But why is water such an important feature?

Figure 2.2 Polar ice. This image from the Mars rover indicates that frozen water exists on Mars.



One characteristic of water that makes it a suitable medium for life is that many different substances will dissolve in it. A substance that dissolves in a liquid is called the **solute**. The liquid in which another substance is dissolved is called the **solvent**. Many different molecules can be dissolved in water. Once dissolved, a particular molecule can pass freely throughout the water and may come into contact with another solute with which it can break existing chemical bonds and form new ones. Such changes in the chemical composition of substances are called chemical reactions. Chemical reactions occur when the starting materials or **reactants** are converted into the ending materials or **products**. Water facilitates chemical interactions between molecules. Part of the reason water functions as such a powerful solvent is due to its structure.

Water (H_2O) consists of hydrogen and oxygen atoms. **Atoms** are the smallest units into which a substance can be broken down; they are composed of **protons**, **neutrons**, and **electrons**. The positively charged protons (H^+) and electrically neutral neutrons make up the **nucleus**. The negatively charged electrons are found outside the nucleus in an "electron cloud." Electrons are attracted to the positively charged nucleus. A water molecule is composed of 2 hydrogen atoms and 1 oxygen atom that are bonded together by shared electrons. In general, a **molecule** consists of two or more atoms held together by chemical bonds, and chemical bonds occur between two atoms in a molecule that share electrons—often the shared electrons orbit around the nucleus of both atoms. The structure of chemical bonds within molecules is described in detail on page 27 of this chapter.

Oxygen is more electron-pulling, or electronegative, than most other atoms, including hydrogen. This means that the electrons in a water molecule spend more time near the nucleus of the oxygen atom than near the nuclei of the hydrogen atoms. When shared electrons are closer to one atom than another, the atom to which they are the closest will have a partial negative charge, symbolized by the Greek delta, δ^-. The atom from which the electrons are pulled away will have a partial positive charge, symbolized by δ^+ (Figure 2.3). This unequal sharing of electrons makes water a **polar** molecule, since different regions, or poles, of the molecule have different charges. When atoms of a molecule carry no charge, and thus do not have differing poles, they are said to be **nonpolar**.

Water molecules tend to orient themselves so that the hydrogen atom (with its partial positive charge) of one molecule is near the oxygen atom (with its

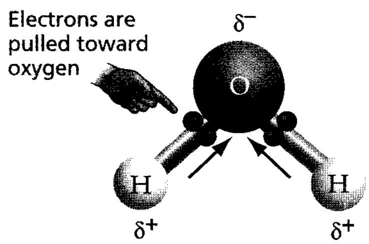


Figure 2.3 Polarity in a water molecule. Water is a polar molecule. Its atoms do not share electrons equally.

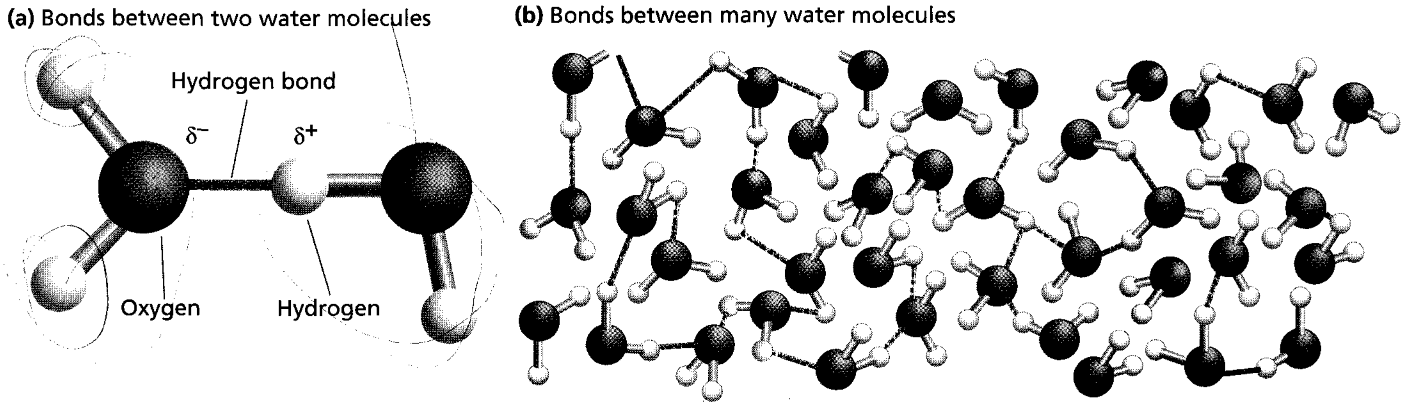


Figure 2.4 Hydrogen bonding between water molecules. The weak attraction between the hydrogen and oxygen atoms of different molecules is an example of hydrogen bonding.

partial negative charge) of another molecule (Figure 2.4a). The weak attraction between the hydrogen atom and the oxygen atom is called a **hydrogen bond.** Hydrogen bonding is a type of weak chemical bond that forms between hydrogen and another atom and is based on the attraction of partial charges for each other. Figure 2.4b shows hydrogen bonding that occurs among water molecules.

Water molecules stick together as a result of this hydrogen bonding. This tendency of molecules to stick together is called **cohesion.** Cohesion is much stronger in water than in most liquids and is an important property of many biological systems. For instance, many plants depend on cohesion to help transport water from the roots to the leaves.

The flowing water that was once found on Mars (Figure 2.5a) is now only in the form of ice. Until scientists can land on Mars and collect ice samples for analysis, its actual composition is a matter of conjecture. However, images taken by a NASA rover have led scientists to believe that some of the rocks on Mars were probably produced from deposits at the bottom of a body of salt

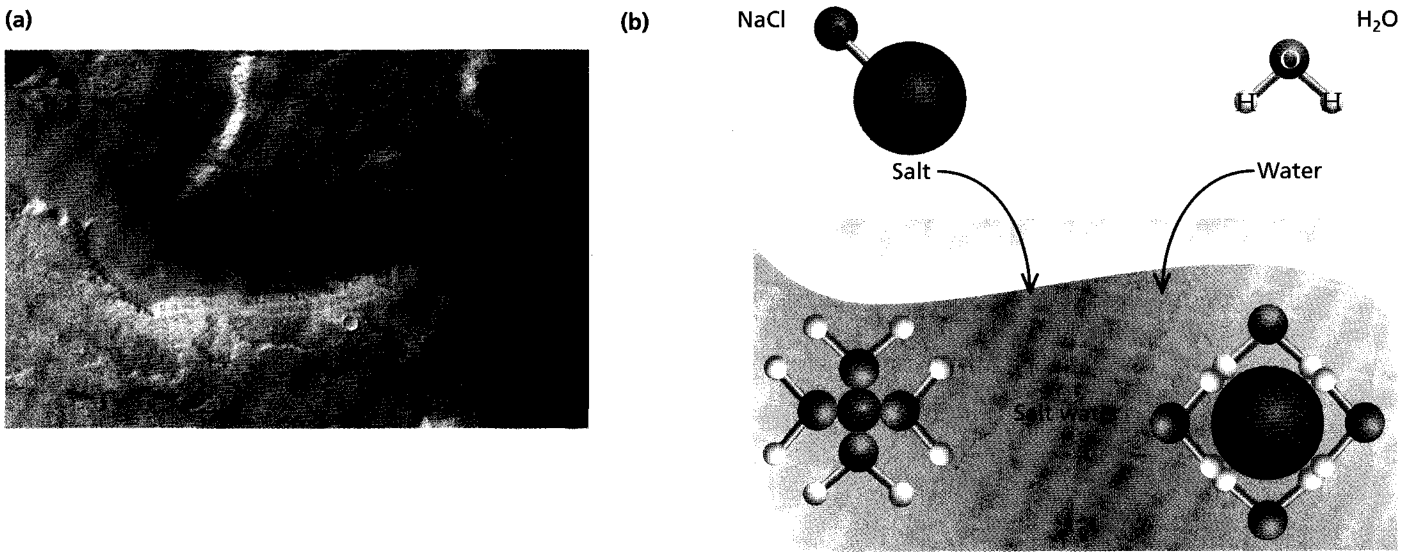


Figure 2.5 Water as a solvent. (a) This photograph, taken by the European Mars express orbiter, shows a channel on Mars that may have been formed by running water. (b) Salty water, such as seawater on Earth and the water that may have existed on Mars, is rich in sodium chloride. Each molecule of sodium chloride is composed of one sodium (Na^+) and one chloride (Cl^-). In this polar molecule, the shared electrons associate more closely to chlorine, giving chlorine a negative charge and sodium a positive charge. When salt is placed in water, the negatively charged regions of the water molecules surround the positively charged sodium, and the positively charged regions of the water molecules surround the negatively charged chlorine, breaking the bond holding sodium and chloride together and dissolving the salt.

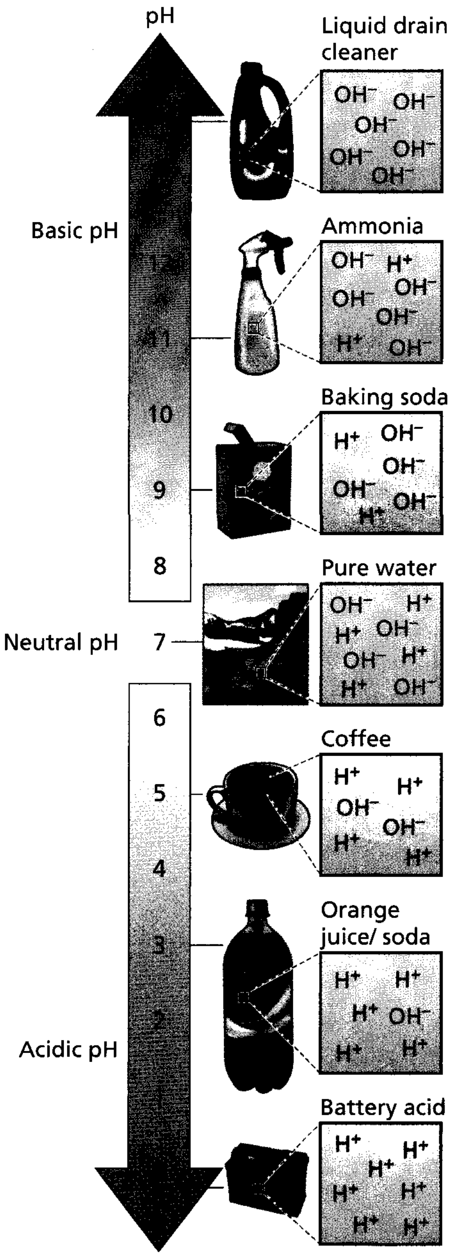


Figure 2.6 The pH scale. The pH scale is a measure of hydrogen ion concentration. The more acidic a solution is, the higher the H^+ concentration is relative to the OH^- ions. Basic solutions have fewer H^+ ions relative to OH^- ions. The scale ranges from 0 (most acidic) to 14 (most basic). Each pH unit actually represents a tenfold (10×) difference in the concentration of H^+ ions. For example, a substance with a pH of 5 has 100 times more H^+ ions than a substance with a pH of 7 does. Water has a pH of 7 and is therefore neutral; that is, it has as many H^+ ions as OH^- ions. The pH of most cells is very close to 7.

water. Salt water on Mars is likely to be the same salt as water on Earth, a solution of the salt sodium chloride. We know from surveying Earth's oceans that salt water is hospitable to millions of different life-forms. In fact, most hypotheses about the origin of life on Earth presume that our ancestors first arose in the salty oceans.

The ability of water to dissolve salts such as sodium chloride is illustrated in Figure 2.5b and is a direct result of its polarity. In the case of sodium chloride, the negative pole of water molecules will be attracted to a positively charged sodium and separate it from a negatively charged chloride. Water can also dissolve other polar molecules, such as alcohol, in a similar manner. Polar molecules are called **hydrophilic** ("water loving") because of their ability to dissolve in water.

Salts are produced by the reaction of an **acid** (a substance that donates H^+ ions to a solution) with a **base** (a substance that accepts H^+ ions). Water can break apart or dissociate into H^+ and OH^- ions. The **pH** scale is a measure of the relative amounts of these ions in a solution (Figure 2.6). These ions can react with other charged molecules and help to bring them into the water solution. At any given time, a small percentage of water molecules in a pure solution will be dissociated. There are equal numbers of these ions in pure water, and so it is neutral, which on the pH scale is 7.

Nonpolar molecules, such as oil, do not contain charged atoms and are referred to as **hydrophobic** ("water hating") because they do not easily mix with water (Figure 2.7). In early 2005, a European Space Agency probe landed on Titan, one of Saturn's moons and a place where the chemical composition of the atmosphere may be similar to that found on early Earth. Photos transmitted by the probe indicate that liquid was present on the surface of this bitterly cold place. At atmospheric temperatures of approximately −292°F the liquid is obviously not water; instead, it is most likely a mixture of ethane and methane, both nonpolar molecules. As a result, oceans on Titan are much poorer solvents than are oceans on Earth, and conditions in these oceans are probably not suitable for the evolution of life.

Organic Chemistry

The Martian meteorite ALH84001 had one characteristic that provided some evidence that the rock once contained living organisms—the presence of complex molecules containing the element carbon. **Elements** are simple chemical substances composed of atoms that cannot be broken down by normal chemical means. Elements differ in the number of subatomic particles in their atoms. All atoms of a particular element have the same number of protons, giving the element its **atomic number**. An atom's **mass number** is the sum of the numbers of protons and neutrons in its nucleus.

All life on Earth is based on the chemistry of the element carbon. In fact, the branch of chemistry that is concerned with complex carbon-containing molecules is called **organic chemistry**, implying that it is the chemistry of life.

Carbon is only one of many essential elements that living organisms require, but it makes up most of their mass. Carbon is an ideal element as a foundation for organic chemistry because of its ability to make bonds with up to four other elements. Like a Tinkertoy™ connector, carbon has multiple

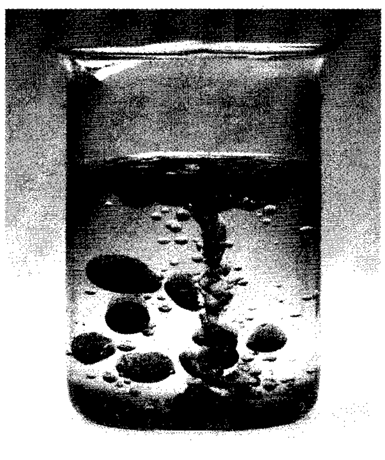


Figure 2.7 Oil and water. Oil is nonpolar and will not mix with water.

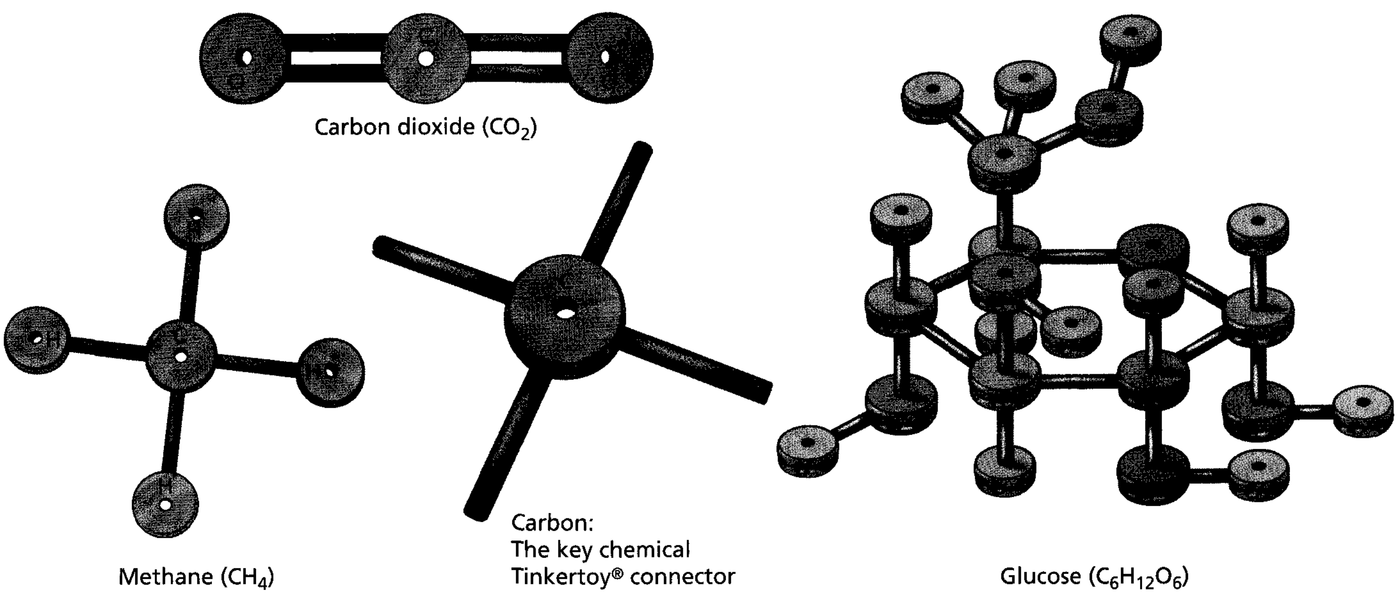


Figure 2.8 Carbon, the chemical Tinkertoy™ connector. Because carbon can connect with up to four other elements, carbon-containing compounds can be very diverse in shape.

sites for connections that allow carbon-containing molecules to take an almost infinite variety of shapes (Figure 2.8).

The ability of carbon, or any element, to make chemical bonds depends on its electron configuration. The electrons in the electron cloud that surrounds the nucleus have different energy levels based on their distance from the nucleus. The first energy level, or **energy shell**, is closest to the nucleus, and the electrons located there have the lowest energy. The second energy level is a little farther away, and the electrons located in the second shell have a little more energy. The third energy level is even farther away, and its electrons have even more energy, and so on. Figure 2.9a shows the electron configuration of carbon.

Each energy level can hold a specific maximum number of electrons. The first shell holds 2 electrons, and the second and third shells each hold a maximum of 8. Electrons fill the lowest energy shell before advancing to fill a higher energy-level shell. Atoms with the same number of electrons in their outermost energy shell, called the **valence shell**, exhibit similar chemical behaviors. When the valence shell is full of electrons, the atom will not normally form chemical bonds with other atoms.

Atoms that have space in their valence shell will combine to form compounds. A **compound** is a substance formed from two or more elements with a fixed ratio determining the composition. For example, water is a compound composed of two hydrogen atoms for every oxygen atom. Atoms with only 1 or 2 electrons in their valence shell tend to lose electrons and therefore become positively charged ions, while atoms with 6 or 7 electrons in the valence shell tend to gain electrons and thus become negatively charged ions. These two types of atoms will often form chemical compounds that are made up of 2 ions; the electrical attraction between a positive ion and a negative ion keeps them together loosely in an **ionic bond**. In aqueous solutions, these bonds are easily disrupted, for instance, when the compound is mixed with a polar solvent such as water.

Atoms with 4 or 5 electrons in the valence shell tend to share electrons to complete their valence shells. When atoms share electrons, a type of bond called a **covalent bond** is formed. Covalent bonds are stronger than ionic bonds and will not break apart in water. Figure 2.9b shows carbon covalently bonded to 4 hydrogens to produce methane, an organic compound that is common in the atmosphere of Titan.

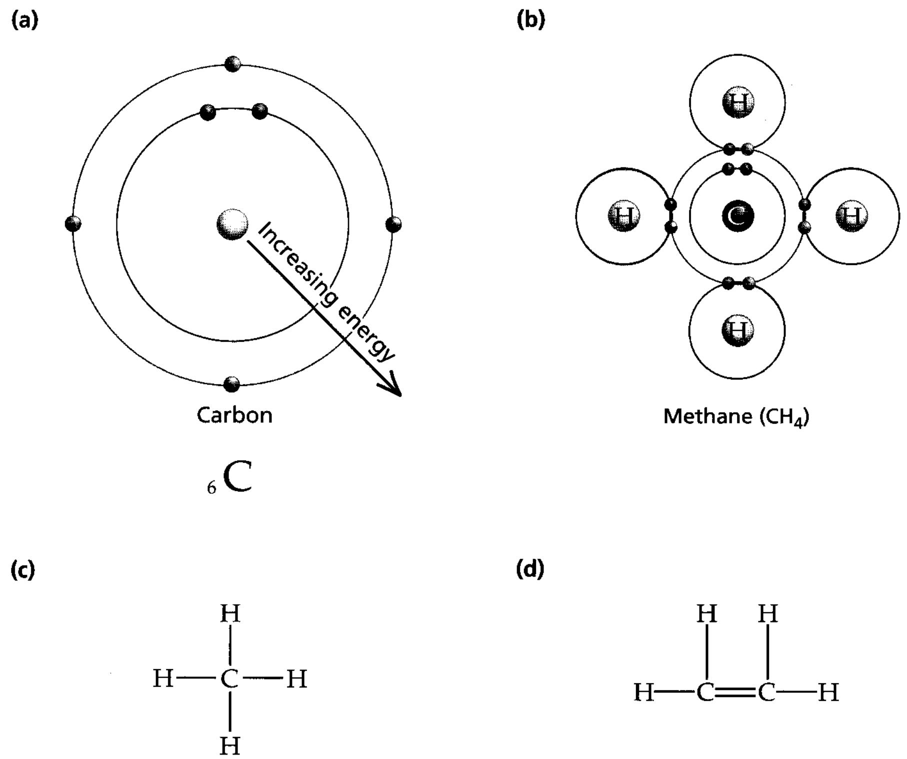


Figure 2.9 Carbon bonding. (a) The electron configuration of carbon. (b) Carbon bonding in the methane molecule. (c) Methane molecule with 4 single covalent bonds. (d) A carbon-to-carbon double bond.

Carbon atoms are often involved in covalent bonding. Covalent bonds are symbolized by a short line indicating a shared pair of electrons (Figure 2.9c). When an element such as carbon enters into bonds involving two *pairs* of shared electrons, this is called a double bond. A carbon-to-carbon double bond is symbolized by two horizontal lines (Figure 2.9d).

The simple organic molecules found in the Martian meteorite that appear to have formed on Mars are carbonates, molecules containing carbon and oxygen, and **hydrocarbons**, made up of chains and rings of carbon and hydrogen. Carbonates and hydrocarbons can form under certain natural conditions even without the presence of life. However, what the meteorite lacked was convincing evidence of organic molecules that are known to be produced only by living organisms called **macromolecules**.

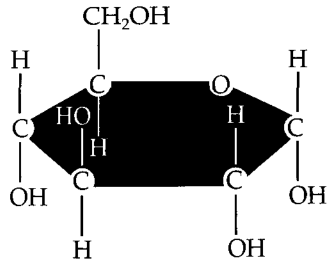
Structure and Function of Macromolecules

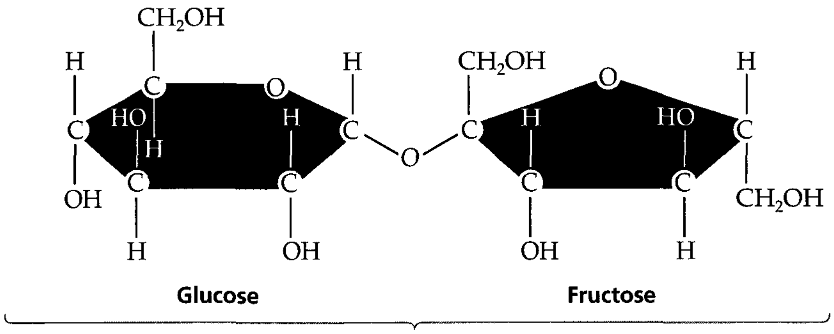
The macromolecules present in living organisms are carbohydrates, proteins, lipids, and nucleic acids. To date, every living organism on Earth has been found to contain these same macromolecules, whether bacteria, plant, or animal.

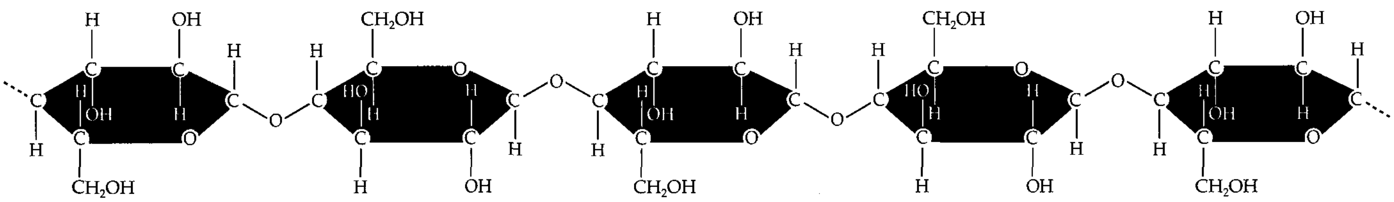
Carbohydrates. Sugars, or **carbohydrates**, are found in every living organism on Earth and provide the major source of energy for daily activities. Carbohydrates also play important structural roles in cells. The simplest carbohydrates are composed of carbon, hydrogen, and oxygen in the ratio (CH_2O). For example, the carbohydrate sugar glucose is symbolized as $6(CH_2O)$ or $C_6H_{12}O_6$. Glucose is a simple sugar, or monosaccharide, which consists of a single ring-shaped structure. Disaccharides are two rings joined together. Table sugar, called sucrose, is a disaccharide composed of glucose and fructose, a sugar found in fruits.

Joining many individual subunits, or monomers, together produces polymers (*poly* means "many"). Polymers of sugar monomers are called **polysaccharides** (Figure 2.10). Plants use tough polysaccharides in their cell walls as a sort of structural skeleton. The polysaccharide cellulose, found in plant cell walls, is the most abundant carbohydrate on Earth. The external skeletons of insects, spiders, and

Figure 2.10 Carbohydrates. Monosaccharides, such as the glucose molecule shown here, are individual sugar molecules, while disaccharides are 2 monosaccharides joined together, and polysaccharides are long chains of sugars joined together. The monosaccharide glucose and the disaccharide sucrose are important sources of energy; and cellulose plays a structural role in plant cell walls.







lobsters are composed of polysaccharides, and the cell walls that surround bacterial cells are rich in structural polysaccharides.

According to David McKay and his colleagues, the particular set of hydrocarbons found on the Martian meteorite is identical to the set formed when carbohydrates in certain bacteria on Earth break down. These trace remains of possible Martian carbohydrates are an important piece of evidence that scientists use to argue that Mars once harbored Earth-like life. Evidence of the presence of proteins on the meteorite is less convincing.

Proteins. Living organisms require **proteins** for a wide variety of processes. Proteins are important structural components of cells; in fact, they make up half the dry weight of most cells. Some cells, such as animal muscle cells, are largely composed of proteins. Proteins called **enzymes** accelerate and help regulate all the chemical reactions that build up and break down molecules inside cells. The catalytic power of enzymes (their ability to drastically increase reaction rates) allows metabolism to occur under normal cellular conditions. Proteins can also serve as channels through which substances are brought into cells, and they can function as hormones that send chemical messages throughout an organism's body.

Proteins are large molecules made of monomer subunits called **amino acids**. There are 20 commonly occurring amino acids. Like carbohydrates, amino acids are made of carbons, hydrogens, and oxygens; but in addition, they have nitrogen as part of an amino ($-NH_2^+$) group along with various side groups. Side groups are chemical groups that give amino acids different chemical properties (Figure 2.11a).

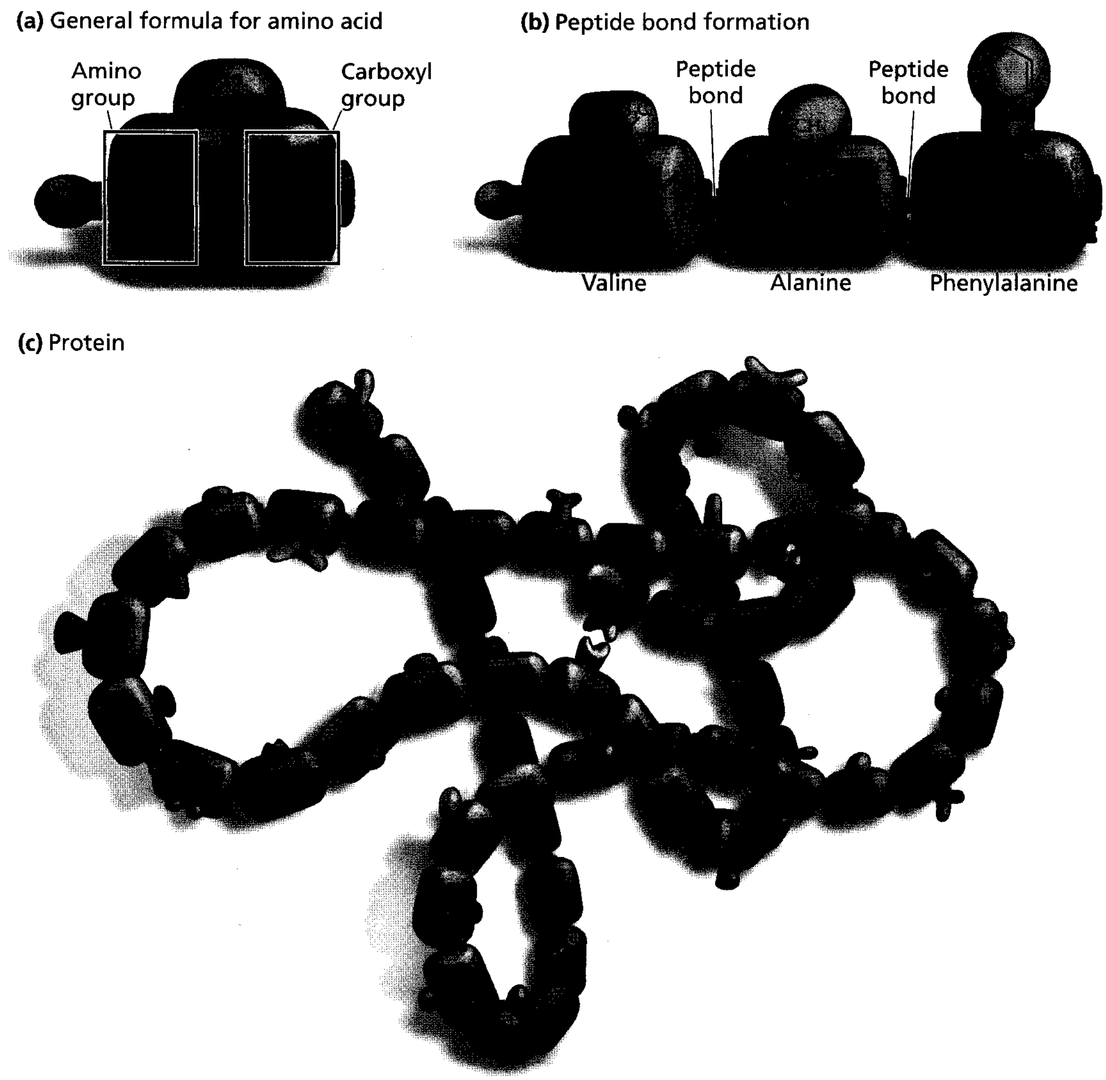


Figure 2.11 Amino acids. (a) All amino acids have the same backbone but different side groups. (b) Amino acids are joined together by chemical bonds called peptide bonds. Long chains of these are called polypeptides. (c) Polypeptide chains fold upon themselves to produce proteins, and different combinations of amino acids produce distinct proteins.

Polymers of amino acids are sometimes called polypeptides. The chemical bond joining adjacent amino acids is a **peptide bond** (Figure 2.11b). Amino acids are joined together in various orders to produce different proteins in much the same manner that children can use differently shaped beads to produce a wide variety of structures (Figure 2.11c). Each amino acid side group has unique chemical properties, including being polar or nonpolar. Since each protein is composed of a particular sequence of amino acids, each protein has a unique shape and therefore specialized chemical properties.

Scientists have found no evidence of proteins on the Martian meteorite, although one group of investigators did report the presence of tiny amounts of three amino acids within the rock. However, it may be the case that these amino acids are contaminants; that is, they are present in the meteor because the meteor has been on protein-rich Earth for several thousand years. In addition, some amino acids are known to form under conditions where life is not present, so the presence of amino acids is not necessarily evidence of life.

Lipids. One type of organic molecule, abundant in living organisms, that has not been found in the Martian meteorite is lipids. **Lipids** are partially or entirely hydrophobic organic molecules made primarily of hydrocarbons. Important lipids include fats, steroids, and phospholipids.

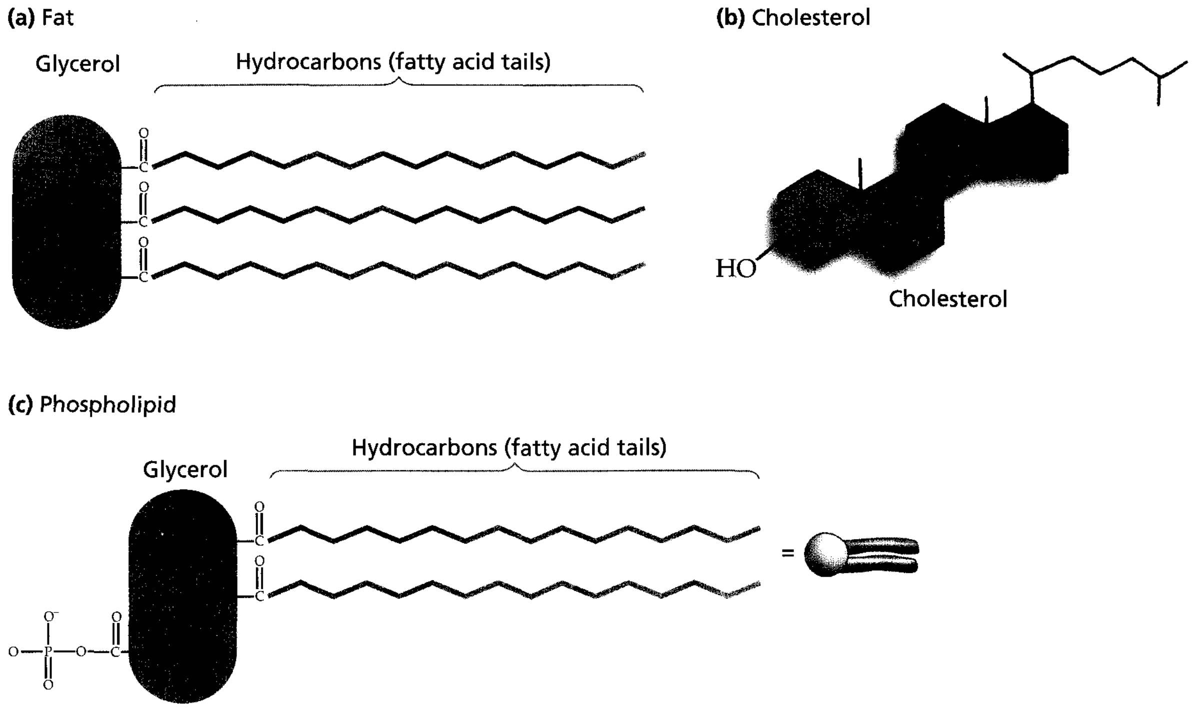


Figure 2.12 Three types of lipids. (a) Fats are composed of a glycerol molecule with three hydrocarbon-rich fatty acid tails attached. (b) Cholesterol is a steroid common in animal cell membranes. (c) Phospholipids are composed of a glycerol backbone with 2 fatty acids attached and 1 phosphate head group. They have hydrophilic heads and hydrophobic tails. In the cartoon drawing to the right, the phosphate head group is symbolized by a circle and the fatty acid tails are red.

Fat. The structure of a **fat** is that of a 3-carbon glycerol molecule with up to three long, hydrocarbon chains attached to it (Figure 2.12a). Like the hydrocarbons present in gasoline, these can be burned to produce energy. The long hydrocarbon chains are called **fatty acid tails** of the fat molecule. Fats are hydrophobic and function in energy storage within living organisms.

Steroids. **Steroids** are composed of 4 fused carbon-containing rings. Cholesterol (Figure 2.12b) is one steroid that you are probably familiar with; its primary function in animal cells (plant cells do not contain cholesterol) is to help maintain the fluidity of membranes. Other steroids include the sex hormones testosterone, estrogen, and progesterone, which are produced by the sex organs and have effects throughout the body.

Phospholipids. **Phospholipids** are similar to fats except that each glycerol molecule is attached to 2 fatty acid tails (not 3, as you would find in a dietary fat). The third bond in a phospholipid is to a phosphate head group. The phosphate head group is hydrophilic, and the two tails are hydrophobic (Figure 2.12c). Phospholipids often have an additional head group, attached to the phosphate, which also confers unique chemical properties on the individual phospholipid. Phospholipids are important constituents of the membranes that surround cells and that designate compartments within cells.

Even if the Martian meteorite contained unambiguous traces of carbohydrates, proteins, and lipids, the source of these molecules would not clearly be living organisms without a mechanism for passing information about their traits to the next generation. The hereditary, or genetic, information common to all life on Earth is in the form of nucleic acids.

Nucleic Acids. Nucleic acids are composed of long strings of monomers called **nucleotides.** A nucleotide is made up of a sugar, a phosphate, and a nitrogen-containing base. The nucleic acid that serves as the primary storage of genetic information in nearly all living organisms is **deoxyribonucleic acid (DNA).** Figure 2.13 shows the three-dimensional structure of a DNA molecule and

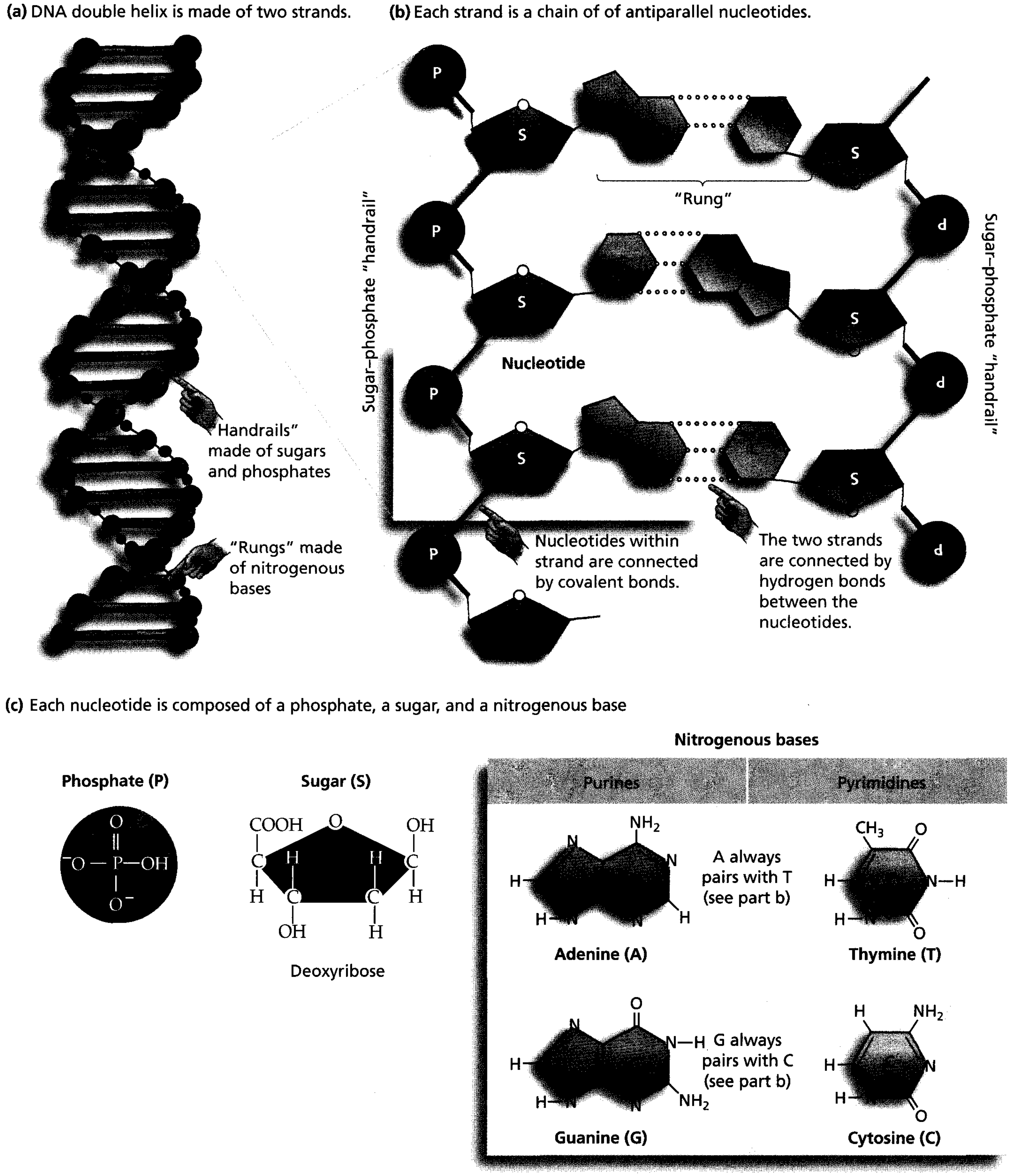


Figure 2.13 DNA structure. (a) DNA is a double-helical structure composed of sugars, phosphates, and nitrogenous bases. (b) Each strand of the helix is composed of repeating units of sugars and phosphates, making the sugar-phosphate backbone, and of nitrogenous bases. (c) A phosphate, a sugar, and a nitrogenous base comprise the structure of a nucleotide. Adenine and guanine are purines, which have a double-ring structure; cytosine and thymine are pyrimidines, which have a single-ring structure.

zooms inward to the chemical structure. You can see that DNA is composed of two curving strands that wind around each other to form a double helix. The sugar in DNA is the 5-carbon sugar deoxyribose. The nitrogen-containing bases, or **nitrogenous bases**, of DNA have one of four different chemical structures, each with a different name: **adenine (A), guanine (G), thymine (T),** and **cytosine (C)**. Nucleotides are joined to each other along the length of the helix by covalent bonds.

Nitrogenous bases form hydrogen bonds with each other across the width of the helix. On a DNA molecule, an adenine (A) on one strand always pairs with a thymine (T) on the opposite strand. Likewise, guanine (G) always pairs with cytosine (C). The term **complementary** is used to describe these pairings. For example, A is complementary to T, and C is complementary to G. Therefore, the order of nucleotides on one strand of the DNA helix predicts the order of nucleotides on the other strand. Thus, if one strand of the DNA molecule is composed of nucleotides AACGATCCG, then we know that the order of nucleotides on the other strand is TTGCTAGGC.

As a result of this **base-pairing rule** (A pairs with T; G pairs with C), the width of the DNA helix is uniform. There are no bulges or dimples in the structure of the DNA helix, because A and G, called **purines**, are structures composed of two rings; and C and T are single-ring structures called **pyrimidines**. A purine always pairs with a pyrimidine and vice versa, so there are always 3 rings across the width of the helix. A to T base pairs have 2 hydrogen bonds holding them together. G to C pairs have 3 hydrogen bonds holding them together.

Each strand of the helix thus consists of a series of sugars and phosphates alternating along the length of the helix, the **sugar-phosphate backbone**. The strands of the helix align so that the nucleotides face "up" on one side of the helix and "down" on the other side of the helix. For this reason, the two strands of the helix are said to be antiparallel.

The overall structure of a DNA molecule can be likened to a rope ladder that is twisted, with the sides of the ladder composed of sugars and phosphates (the sugar-phosphate backbone), and the rungs of the ladder composed of the nitrogenous-base sequences A, C, G, and T. The structure of DNA was determined by a group of scientists in the 1950s, most notably James Watson and Francis Crick (Figure 2.14).

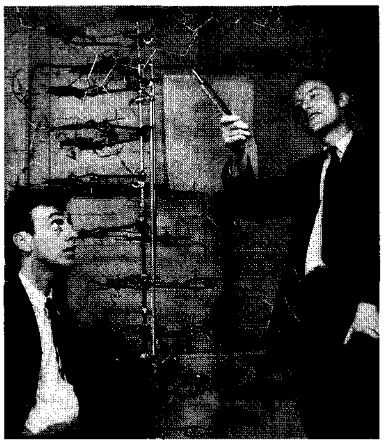


Figure 2.14 American James Watson (left) and Englishman Francis Crick are shown with the 3-dimensional model of DNA they devised while working at the University of Cambridge in England.

How Might Macromolecules on Other Planets Differ? Many scientists argue that the fundamental constituents described here—carbohydrates, proteins, lipids, and nucleic acids—will be essentially similar wherever life is found. They will readily admit that the finer details are very likely to differ, however. For example, all proteins known on Earth contain only 20 different amino acids, despite an infinite number of possibilities. Presumably, proteins on other planets could contain completely different amino acids and many more than 20.

Not all scientists agree with this position, which they call "carbon chauvinism." Carbon is not the only chemical Tinkertoy™ connector; other elements, including silicon, can also make connections with four other atoms. Silicon is also relatively abundant in the universe and could theoretically form the backbone of an alternative organic chemistry. The basic constituents of silicon-based life may be very different from the chemical building blocks of life on Earth.

Even if all life in the universe is based on carbon chemistry, it is very unlikely that the suite of organisms found on another planet will look much like life on our planet. However, understanding the history of life on Earth also provides insight into the possible nature of life elsewhere in the universe.

2.2 Life on Earth

One of the most dramatic features of the Martian meteorite is the presence of fossils that look remarkably like the tiniest living organisms known from Earth. The largest of these fossils is less than 1/100th of the diameter of a human hair, and most are about 1/1000th of the diameter of a human hair—small enough that it would take about 1000 laid end to end to span the dot at the end of this sentence. Some are egg shaped, while others are tubular. These fossils appear similar to the simplest and most ancient of known organisms and are the strongest piece of evidence supporting the hypothesis that Mars once was home to living organisms.

Prokaryotic and Eukaryotic Cells

David McKay and his colleagues argue that the fossil structures in the Martian meteorite are the remains of tiny cells. A **cell** is the fundamental structural unit of life on Earth, separated from its environment by a membrane and often an external wall. Bacteria are composed of single cells, which perform all of the activities required for life. Other organisms such as humans and oak trees are composed of trillions of cells working together and do not have any cells that could survive and reproduce independently.

All cells can be placed into one of two categories, prokaryotic or eukaryotic, based on the presence or absence of certain cellular structures. Bacteria are **prokaryotic** cells. Prokaryotes do not have a nucleus, a separate membrane-bound compartment that contains primarily genetic material in the form of DNA. Nor do they contain any membrane-bound internal structures. Prokaryotic cells are much smaller than eukaryotic cells (Figure 2.15), and according to the fossil record, they predate eukaryotic cells. The fossils in the Martian meteorite resemble modern prokaryotic cells known as nanobacteria.

Eukaryotic cells have a nucleus and other internal structures with specialized functions, called **organelles**, that are surrounded by membranes. Eukaryotic organisms include single-celled organisms such as amoebas and yeast as well as multicellular plants, fungi, and animals. As you will learn in Chapter 12, scientists believe that the first prokaryotic cells appeared on Earth over 3.5 billion years ago and that the first eukaryotes appeared about 1.7 billion years later.

Organells

Many scientists dispute David McKay's interpretation of the tubular structures in ALH84001. In fact, similar structures can be formed in the absence of life by certain minerals under extremes of heat and pressure. If the Martian fossils are indeed cells, they likely contained features found inside earthly cells, some of which should be visible in the fossils. Each living cell can be considered a veritable factory working to break down nutrients and to recycle its components. We will start from the outside of the cell and examine the structure and function of various cell components as we work our way in.

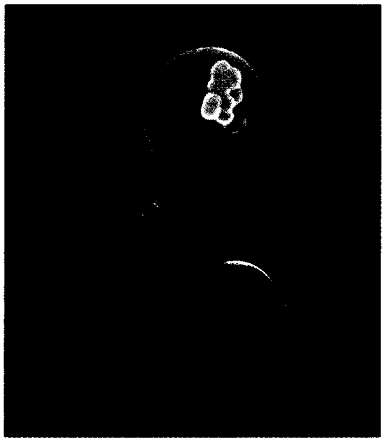


Figure 2.15 Bacterial and eukaryotic cells. Prokaryotic cells, like the blue-tinted bacteria above, are many times smaller than eukaryotic cells. The eukaryotic cell in this image is a red blood cell.

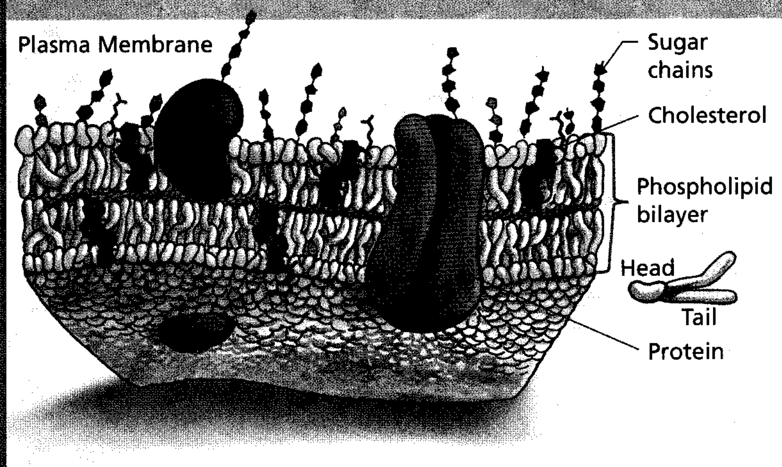
Cell Structure

Plasma Membrane. All cells are enclosed by a structure called a **plasma membrane** (Table 2.1). The plasma membrane defines the outer boundary of each cell, isolates the cell's contents from the environment, and serves as a semi-permeable barrier that determines which nutrients are allowed into and out of the cell. Membranes that enclose structures inside the cell are usually referred to as cell membranes, while the outer boundary is the plasma membrane.

Table 2.1 Cell components. Illustrations and descriptions of cell components and their functions.

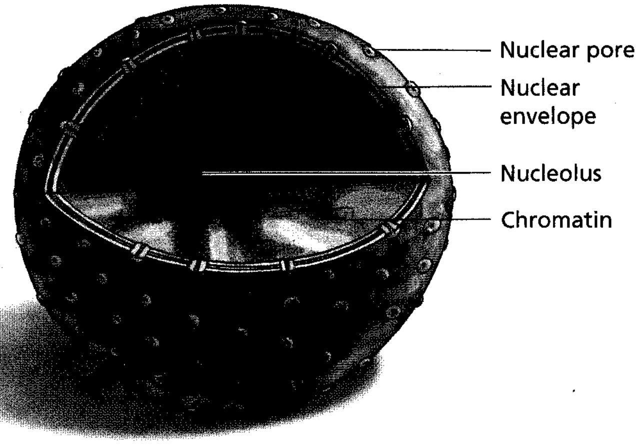
Component	Function

Plasma Membrane



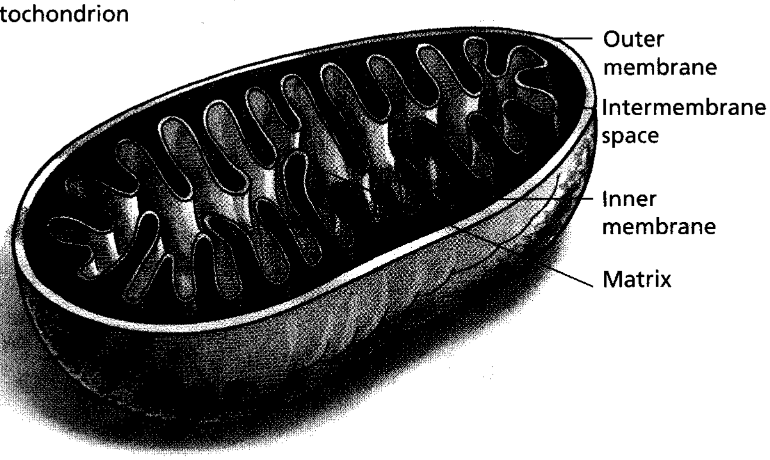
All cells are surrounded by a plasma membrane. It is composed of a bilayer of phospholipids (tails toward the center), perforated by proteins. Proteins in the bilayer help transport substances across the hydrophobic core of the membrane. Cholesterol in the membranes of animal cells helps maintain the fluidity of the membrane. The sugar chains function as identification tags, marking cells as a particular cell type (liver cell, heart cell, etc.)

Nucleus



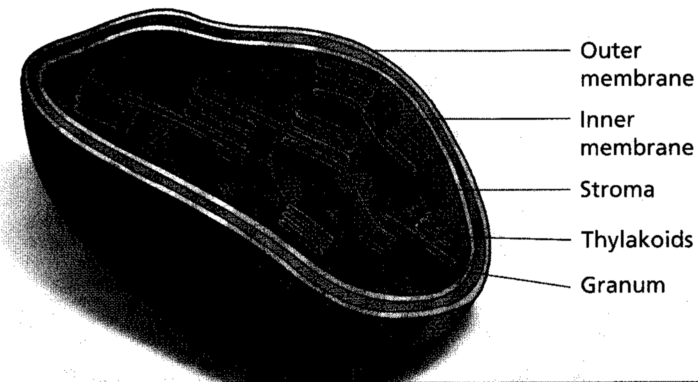
Eukaryotic cells contain a nucleus. The nucleus is a spherical structure surrounded by two membranes, together called the nuclear envelope. The nuclear envelope is studded with nuclear pores that regulate traffic into and out of the nucleus. Inside the nucleus is chromatin, composed of DNA and proteins. The nucleolus is where ribosomes are produced.

Mitochondrion

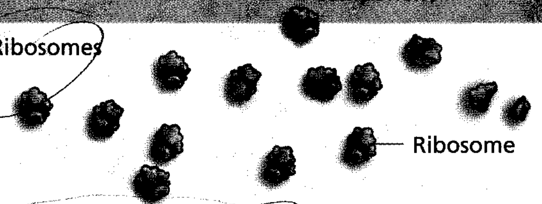
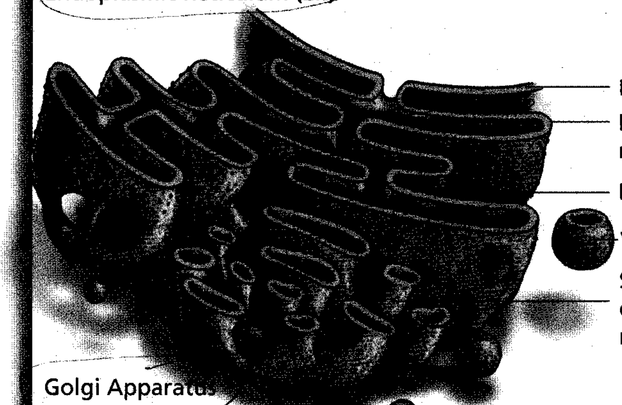
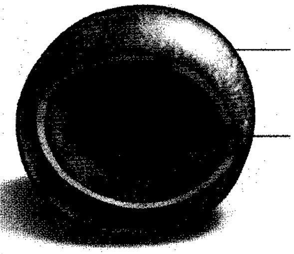
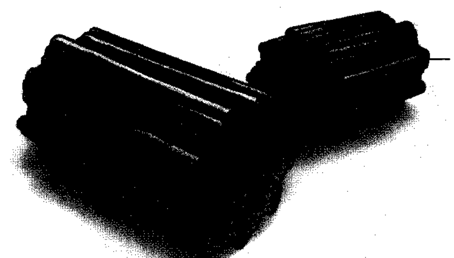
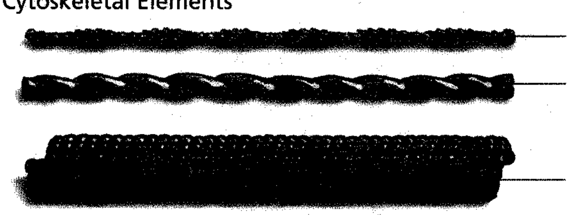


Eukaryotic cells contain mitochondria. Mitochondria are energy-producing organelles surrounded by two membranes. The inner and outer mitochondrial membranes are separated by the intermembrane space. The highly convoluted inner membrane carries many of the proteins involved in producing ATP. The matrix of the mitochondrion is the location of many of the reactions of cellular respiration.

Chloroplast

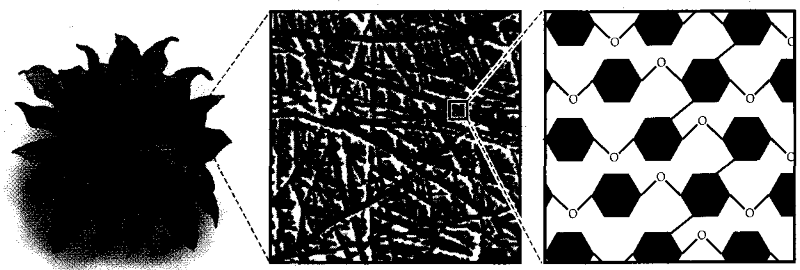
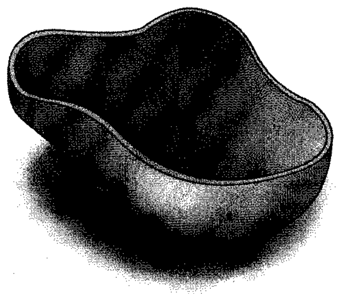


An important organelle present in plant cells, the chloroplast uses the sun's energy to convert carbon dioxide and water into sugars. Each chloroplast has an outer membrane, an inner membrane, a liquid material called the stroma, and a network of flattened membranes called thylakoids that stack on one another to form structures called grana (singular: granum). Chloroplasts also contain pigment molecules that give green parts of plants their color.

Component	Function
Ribosomes 	Ribosomes are found in eukaryotic and prokaryotic cells. Ribosomes are built in the nucleus and shipped out through nuclear pores to the cytoplasm, where they are used as work benches for protein synthesis. They can be found floating in the cytoplasm or tethered to the ER.
Endoplasmic Reticulum (ER) 	The ER is a large network of membranes that begins at the nuclear envelope and extends into the cytoplasm. ER with ribosomes attached is called rough ER. Proteins synthesized on rough ER will be secreted from the cell or will become part of the plasma membrane. ER without ribosomes attached is called smooth ER. The function of the smooth ER depends on cell type but includes tasks such as detoxifying harmful substances and synthesizing lipids. Vesicles are pinched-off pieces of membrane that transport substances to the Golgi apparatus or plasma membrane.
Golgi Apparatus 	The Golgi apparatus is a stack of membranous sacs. Vesicles from the ER fuse with the Golgi apparatus and empty their protein contents. The proteins are then modified, sorted, and sent to the correct destination in new transport vesicles that bud off from the sacs.
Lysosome 	A lysosome is a membrane-enclosed sac of digestive enzymes that degrade proteins, carbohydrates, and fats. Lysosomes roam around the cell, and engulf targeted molecules and organelles for recycling.
Centrioles 	Centrioles are barrel-shaped rings composed of nine microtubule triplets. Microtubules help move chromosomes around when a cell divides. Centrioles are involved in microtubule formation during cell division and the formation of cilia and flagella.
Cytoskeletal Elements 	Cytoskeletal elements are protein fibers in the cytoplasm that give shape to a cell, hold and move organelles (including transport vesicles), and are typically involved in cell movement.

(*table continued on next page*)

(Table 2.1 continued)

Component	Function
Cell wall  Plant Cellulose fibrils Cellulose	The cell wall is found outside the plasma membrane of plant and bacterial cells. The cell wall in plants is rich in the polysaccharide cellulose. Cellulose is assembled into strong fibrils, and embedded in a matrix.
Central vacuole 	Plant cells also have membrane-bound, fluid filled vacuoles that can occupy as much as 90 percent of a cell's total volume. The plant vacuole contains a variety of dissolved molecules, including sugars and pigments that give color to flowers and leaves. Vacuoles also function to maintain pressure inside individual cells which helps support the upright plant.

Internal and external cell membranes are composed, in part, of phospholipids. The chemical properties of these lipids make membranes flexible and self-sealing. When phospholipid molecules are placed in a watery solution, such as in a cell, they orient themselves so that their hydrophilic heads are exposed to the water and their hydrophobic tails are away from the water. They cluster into a form called a **phospholipid bilayer**, in which the tails of the phospholipids interact with themselves and exclude water, while the heads maximize their exposure to the surrounding water both inside and outside of the membrane. The bilayer of phospholipids is stuffed with proteins that carry out enzymatic functions and help transport substances.

A Fluid Mosaic of Lipids and Proteins. All of the lipids and proteins in the plasma membrane are free to bob about, sliding from one location in the membrane to another. However, they cannot readily cross from one layer of the bilayer to another, because this would require the hydrophilic portions of a phospholipid or protein to traverse the hydrophobic core of the bilayer. Because lipids and proteins can move about laterally within the membrane, the membrane is a **fluid mosaic** of lipids and proteins. The membrane is fluid since the composition of any one location on the membrane can change. In the same manner that a patchwork quilt is a mosaic (different fabrics making up the whole quilt), so too is the membrane a mosaic with different regions of membrane being composed of different types of phospholipids and proteins.

Cell membranes are **semipermeable** in the sense that they allow some substances to cross and prevent others from crossing. This characteristic allows cells to maintain a degree of independence from the surrounding solution.

The permeability of the plasma membrane to water presents a problem for many organisms. In environments where the water contains low levels of solutes, water from outside the cell will flow into the cell, causing it to burst. Bacterial cells have a **cell wall** that helps them maintain their shape in these conditions. The fossils in the Martian meteorite show no evidence of similar walls, calling into question their supposed biological origin.

Nucleus. In addition to being surrounded by a plasma membrane, all eukaryotic cells contain a nucleus, which houses the DNA.

Cytosol. Between the nucleus and the plasma membrane lies the cytosol, a watery matrix containing water, salts, and many of the enzymes required for cellular reactions. The cytosol houses the subcellular structures called organelles. The term **cytoplasm** includes the cytosol and organelles.

Organelles. Organelles are to cells as organs are to the body. Each organelle performs a specific job required by the cell, and all organelles work together to keep an individual cell healthy and to produce the raw materials that the cell needs to survive. Some organelles are involved in metabolism. For example, organelles called **mitochondria** help the cells convert food energy into a form usable by cells, called ATP, while **chloroplasts** in plant cells use energy from sunlight to make sugars. **Lysosomes** help break down food that is ingested before it is sent to the mitochondria. Other organelles are involved in producing proteins. The **ribosomes** are workbenches where proteins are assembled. Many proteins are assembled on the membranes of the **endoplasmic reticulum** and modified and sorted in a membranous structure called the **Golgi apparatus**. Some subcellular structures help cells divide and maintain their shape. **Centrioles** are involved in moving genetic material around when a cell divides, and many subcellular fibers help maintain the cell shape. Some subcellular structures are found in certain cell types only. For instance, in addition to having a cell wall, the plant cell also has a **vacuole** to store sugars and pigments. Table 2.1 describes the structures and functions of most cellular organelles in greater detail. Figure 2.16 shows an animal cell and a plant cell complete with their complement of organelles.

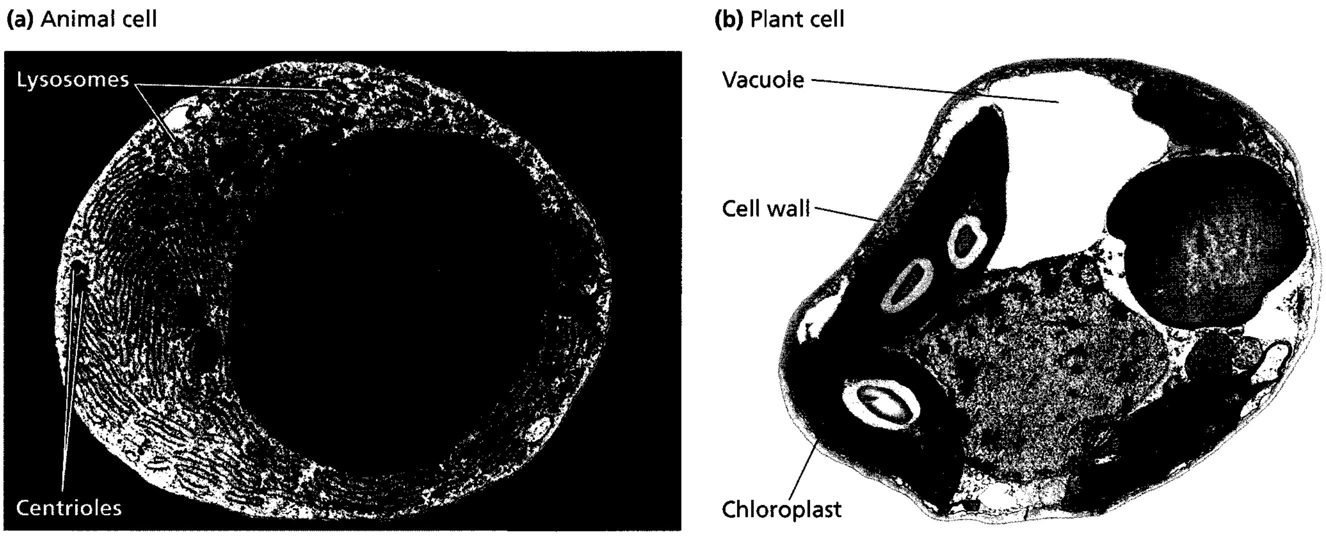


Figure 2.16 Animal and plant cells. (a) Animal cells contain lysosomes and centrioles, and plant cells do not. (b) Plant cells have a cell wall, vacuole, and chloroplasts, and animal cells do not.

The Tree of Life and Evolutionary Theory

Biologists disagree about the total number of different **species**, or types of living organisms, that are present on Earth today. This uncertainty stems from lack of knowledge. Although scientists likely have identified most of the larger organisms—such as land plants, mammals, birds, reptiles, and fish—millions of species of insects, fungi, bacteria, and other microscopic organisms remain unknown to science. Amazingly, credible estimates of the number of species on Earth range from 5 million to 100 million; given the uncertainty, most biologists think that the likeliest number is near 10 million.

Theory of Evolution. While the diversity of living organisms is tremendous, there exist remarkable similarities among all known species. All have the same basic biochemistry, including carbohydrates, lipids, proteins, and nucleic acids. All consist of cells surrounded by a plasma membrane. All eukaryotic organisms (including fungi, animals, and plants) contain nearly the same suite of cellular organelles. The best explanation for the shared characteristics of all species, what biologists refer to as "the unity of life," is that all living organisms share a common ancestor that arose on Earth nearly 4 billion years ago. The divergence and differences among modern species arose as a result of changes in the characteristics of populations, both in response to environmental change (a process called natural selection) and due to chance. These ideas underlie the entire science of biology and are known as the **theory of evolution.**

The common ancestor can be thought of as the starting place for life on Earth, and the continual divergence among species and groups of species can be thought of as life's branching. Modern organisms can therefore be arranged on a tree of life that reflects their basic unity and relationships. According to current understanding, living organisms can be grouped into three large groups: two that are prokaryotic and one containing all eukaryotes. Eukaryotes can be further grouped into several categories made up primarily of free-living, single-celled organisms (such as amoebas and algae) and the three major multicellular groups—plants, fungi, and animals (Figure 2.17). Chapter 12 provides a deeper exploration of the diversity of life on Earth.

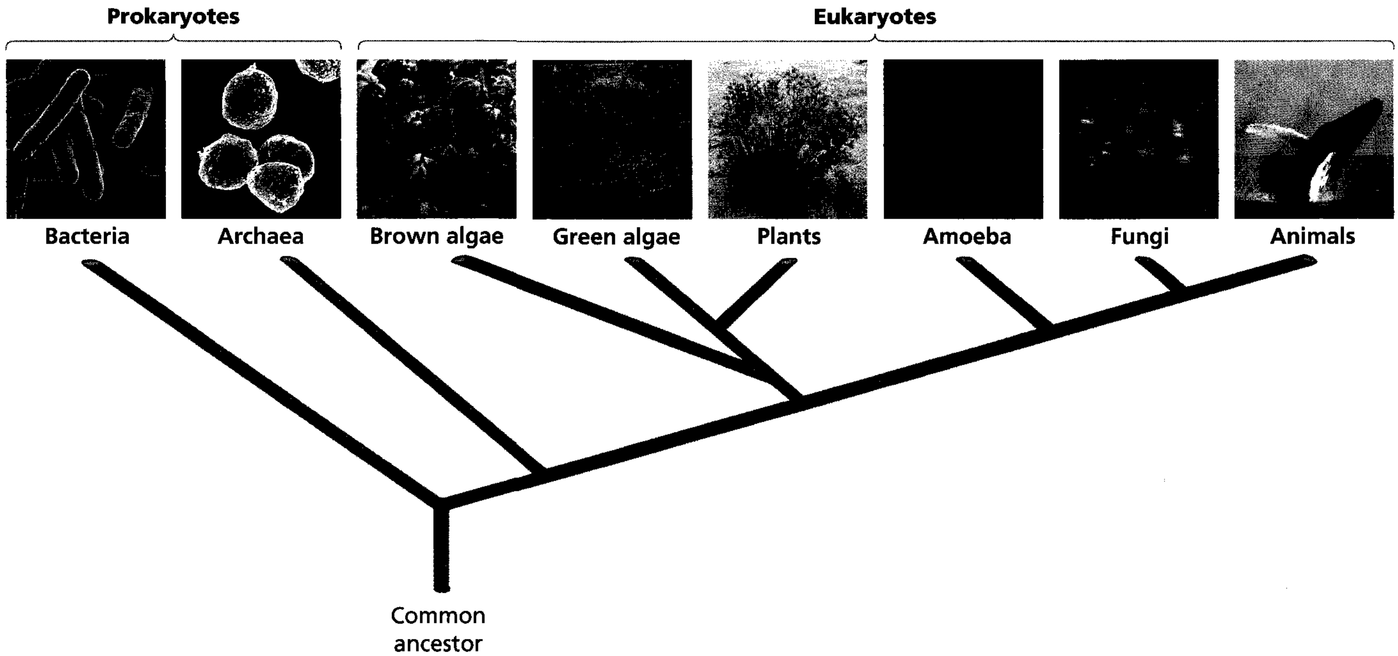


Figure 2.17 Tree of life. All life on Earth shares basic characteristics and can be arranged into a tree of life based on more specific similarities. In this illustration, many groups are omitted for simplicity.

Because evolutionary change results from chance events and environmental changes (including the appearance of other species), the group of species present on Earth today represents only one set of an infinite number of possibilities. In other words, life on other planets need not look identical to life on Earth. For example, instead of the common body form found in animals, called bilateral symmetry, where bodies can be visually divided into two mirror-image halves, life on other planets could be primarily radially symmetric and thus look very different (Figure 2.18). In fact, it is possible that life on other planets might not even be based on carbon. Scientists have no examples of what living organisms would look like on a planet where the organic molecules were based on silicon or bathed in liquid methane.

Figure 2.18 Diversity of body form. Not all animals are bilaterally symmetric like us, with two eyes, two ears, two arms, two legs, a clear head and "tail," and one central axis. A sea star is radially symmetric—it can be divided into two equal halves in any direction. If most animals on another planet were radially symmetric, then that world would look very different from Earth.

Life in the Universe. Do other living organisms exist in the universe? Given the universe's sheer size and complexity, most scientists who study this question think that the existence of life on other planets is nearly certain. While the evidence of life in the Martian meteorite is unconvincing to many scientists, we may find out in our lifetimes that life exists, or once existed, on our planetary neighbor.

What about the existence of intelligent life that could communicate with us? Some scientists argue that as a result of natural selection, the evolution of intelligence is inevitable wherever life arises. Others point to the history of life on Earth—consisting of at least 2.5 billion years, during which all life was made up of single-celled organisms—to argue that most life in the universe must be "simple and dumb." It is clear from our explorations of the solar system that none of the sun's other planets host intelligent life. The nearest sun-like stars that could host an Earth-like planet, Alpha Centauri A and B, are over 4 light years away—nearly 40 trillion miles. With current technologies, it would take nearly 50,000 years to reach the Alpha Centauri stars, and there is certainly no guarantee that intelligent life would be found on any planets that circle them. For all practical purposes, at this time in human history, we are still unique and alone in the universe.

CHAPTER REVIEW

Summary

2.1 What Does Life Require?

- Living organisms must be able to grow, metabolize substances, reproduce, and respond to external stimuli (p. 24).
- Living organisms contain a common set of biological molecules, are composed of cells, and can maintain homeostasis and evolve (p. 24).
- A water molecule is composed of 2 hydrogen atoms and 1 oxygen atom, bonded together by shared electrons (p. 25).
- Water is a good solvent, in part because the weak attraction between the hydrogen atom and the oxygen atom forms a hydrogen bond (p. 26).
- Hydrogen bonding is also responsible for cohesion among water molecules (p. 26).
- The polarity of water also facilitates the dissolving of salts. Salts are produced by the reaction of an acid with a base (pp. 26–27).
- The pH scale is a measure of the relative percentages of these H^+ and OH^- ions in a solution and ranges from 0 (acidic or rich in H^+ ions) to 14 (basic or rich in OH^- ions) (p. 27).
- Life on Earth is based on the chemistry of the element carbon, which can make bonds with up to four other elements (pp. 27–28).
- Chemical bonding depends on an element's electron configuration. Electrons closer to the nucleus have less energy than those that are farther away from the nucleus. Each energy level can hold a specific maximum number of electrons. Atoms that have space in their valence shell will combine to form compounds (p. 28).
- Ionic bonds form between positively and negatively charged ions. These tend to be weak bonds (p. 28).
- Covalent bonds form when atoms share electrons. These tend to be strong bonds (p. 28).

- Carbohydrates function in energy storage and play structural roles. They can be single-unit monosaccharides or multiple-unit polysaccharides with sugar monomers arranged in different orders (p. 29).
- Proteins play structural, enzymatic, and transport roles in cells. They are composed of amino acid monomers arranged in different orders (p. 30).
- Lipids are partially or entirely hydrophobic and come in three different forms. Fats are composed of glycerol and three fatty acids. Fats store energy. Phospholipids are composed of glycerol, two fatty acids, and a phosphate group. They are important structural components of cell membranes. Steroids are composed of four fused rings. Cholesterol is a steroid found in some animal-cell membranes and helps maintain fluidity. Other steroids function as hormones (pp. 31–32).
- Nucleic acids are polymers of nucleotides, each of which is composed of a sugar, a phosphate, and a nitrogen-containing base (pp. 32–34).

Web Tutorial 2.1 Chemistry and Water
Web Tutorial 2.2 Nucleic Acids

2.2 Life on Earth

- There are two main categories of cells: Those with nuclei and membrane-bound organelles are eukaryotes; those lacking a nucleus and membrane-bound organelles are prokaryotes (p. 35).
- The plasma membrane that surrounds cells is a semipermeable boundary composed of a phospholipid bilayer that has embedded proteins and cholesterol (pp. 35–38).
- Lipids and proteins can move about the membrane. This fluidity of the membrane allows changes in the protein and lipid composition (p. 38).
- Some organisms, such as plants and bacterial cells, have a cell wall outside the plasma membrane that helps protect these cells and maintain their shape (p. 39).
- Subcellular organelles and structures perform many different functions within the cell. Mitochondria and chloroplasts are involved in energy conversions. Lysosomes are involved in breakdown of macromolecules. Ribosomes serve as sites for protein synthesis. Membranous endoplasmic reticulum to help localize protein synthesis. The Golgi apparatus sorts proteins and sends them to their cellular destination. Centrioles help cells divide. The plant cell vacuole stores water and other substances (p. 39).
- The number of living species on Earth is unknown, but there may be nearly 10 million unique life-forms. Despite all of this diversity, all life on Earth shares the same organic chemistry, genetic material, and basic cellular structures (p. 40).
- The similarities among living organisms on Earth provide support for the theory of evolution, which states that all life on Earth derives from a common ancestor. The process of evolutionary change since the origin of that ancestor led to the modern relationships among organisms, described as the "tree of life." (pp. 40–41)

Web Tutorial 2.3 A Comparison of Prokaryotic and Eukaryotic Cells

Learning the Basics

1. What are the building-block molecules of a carbohydrate, a protein, and a fat?

2. List the roles of the organelles discussed in this chapter.

3. Describe the structure of the plasma membrane.

4. Water ______________.

   A. is a good solute; **B.** dissociates into H^+ and OH^- ions; **C.** serves as an enzyme; **D.** makes strong covalent bonds with other molecules; **E.** has an acidic pH

5. Electrons ______________.

   A. are negatively charged; **B.** along with neutrons comprise the nucleus; **C.** are attracted to the negatively charged nucleus; **D.** located closest to the nucleus have the most energy; **E.** all of the above are true

6. Which of the following terms is least like the others?

   A. monosaccharide; **B.** phospholipid; **C.** fat; **D.** steroid; **E.** lipid

7. Different proteins are composed of different sequences of ______________.

   A. sugars; **B.** glycerols; **C.** fats; **D.** amino acids

8. Proteins may function as ______________.

   A. the genetic material; **B.** cholesterol molecules; **C.** fat reserves; **D.** enzymes; **E.** all of the above

9. A fat molecule consists of ______________.

   A. carbohydrates and proteins; **B.** complex carbohydrates only; **C.** saturated oxygen atoms; **D.** glycerol and fatty acids

10. Eukaryotic cells differ from prokaryotic cells in that ______________.

    A. only eukaryotic cells contain DNA; **B.** only eukaryotic cells have a plasma membrane; **C.** only eukaryotic cells are considered to be alive; **D.** only eukaryotic cells have a nucleus; **E.** only eukaryotic cells are found on Earth

Analyzing and Applying the Basics

1. A virus is made up of a protein coat surrounding a small segment of genetic material (either DNA or RNA) and a few proteins. Some viruses are also enveloped in membranes derived from the virus's host cell. Viruses cannot reproduce without taking over the genetic "machinery" of their host cell. Based on this description and biologists' definition of life, should a virus be considered a living organism?

2. Any molecule containing oxygen can be polar. The structure of methanol (CH_3OH) is drawn in Figure 2.19. Which part of this molecule will have a partial negative charge, and which will have a partial positive charge?

3. Some scientists have argued that silicon (Si) could also be an appropriate basis for organic chemistry because it is abundant and can form bonds with many other atoms. Carbon contains 6 electrons, and silicon contains 14. Recalling that the lowest electron shell contains 2 electrons, and the next 2 shells can contain a maximum of 8, how many "spaces" does silicon have in its valence shell? How does this compare to carbon?

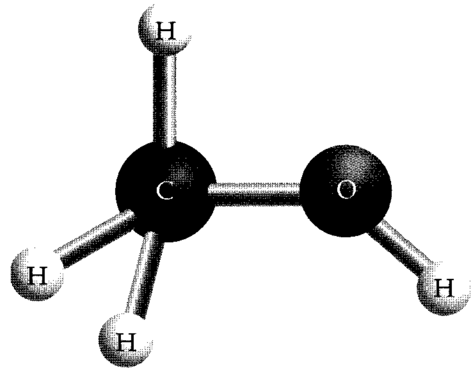


Figure 2.19 Methanol.

Connecting the Science

1. Water's characteristic as an excellent solvent means that many human-created chemicals (including some that are quite toxic) can be found in water bodies around the globe. How would our use and manufacture of toxic chemicals be different if most of these chemicals could not be dissolved and diluted in water, but instead accumulated where they were produced and used?

2. Do you believe that humans should expend considerable energy and resources looking for life, even intelligent life, elsewhere in the universe? Why or why not?