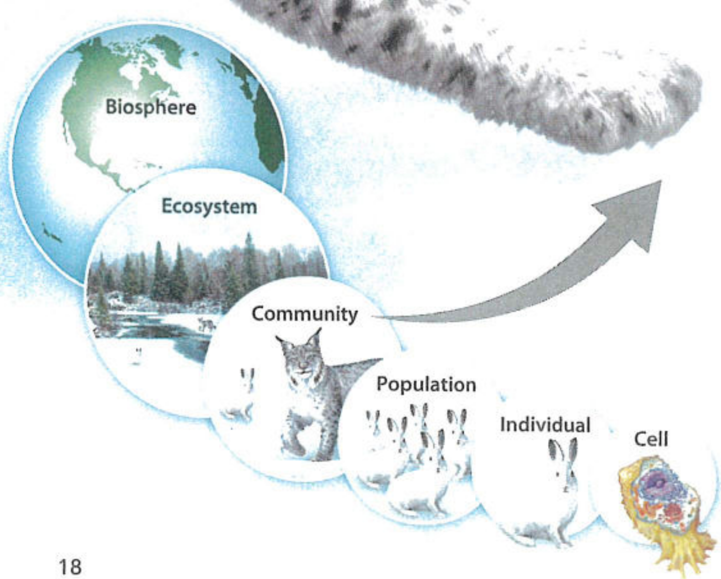
VISUAL SYNTHESIS 1.1 THE FOUR BIG IDEAS OF AP® BIOLOGY

We can describe four Big Ideas that connect and unite the many dimensions of biology: Evolution, Energetics, Information Storage and Transmission, and Systems Interactions. These four ideas are introduced in Unit 1 and will be visited again and again throughout the book. By the time you finish this book, you will have an understanding of how life works, from the molecular

The Four Big Ideas of AP® Biology

Evolution investigates changes in the genetic makeup of a population over time. Through the process of natural selection, species become adapted to their environments. For example, ancestors of the snowshoe hare and Canada lynx evolved to have adaptations that increased their survival and reproduction. This includes the hare's ability to change coat color with the seasons.



Systems Interactions examines the way the components of biological systems interact with and affect one another. A system can be as small as a cell or as large as the biosphere. New properties of biological systems emerge through the interactions of organisms such as Canada lynx and snowshoe hares, and through interactions between species and their environment.

machines inside cells and the metabolic pathways that cycle carbon through the biosphere, to the process of evolution, which has shaped the living world that surrounds and includes us. The four Big Ideas are fundamental to understanding and organizing such diverse aspects of biology.

Energetics considers the processes used by cells and organisms to exchange matter and energy with their environment. For example, Canada lynx and showshoe hares acquire, store, and use the energy and matter obtained from the environment to maintain homeostasis, grow, and reproduce.

Information Storage and Transmission explores how information is stored, used, and transmitted by cells and organisms. Using information stored in DNA and through experience, the Canada lynx knows how to hunt its prey and the snowshoe hare knows how to evade its predator. These behaviors are transmitted to offspring through DNA and through the process of learning.

Module 1
Elements of Life

LEARNING GOALS
- ▶**LG 1.1** Matter and energy govern the properties of life.
- ▶**LG 1.2** The atom is the fundamental unit of matter.
- ▶**LG 1.3** Atoms combine to form molecules linked by chemical bonds.
- ▶**LG 1.4** Carbon is the backbone of organic molecules.

Take a look around you. Everything you see and feel is made of matter, the material that makes up physical objects. **Matter** is anything that has mass and takes up space. Matter may be a gas, a liquid, or a solid. Even you are made of matter. To grow, reproduce, and maintain their organization, all organisms exchange matter with their environment. They also require energy. The study of biology is based on an understanding of the pathways and transformations of matter and energy. Therefore, to understand why organisms look and act as they do, we need to gain a basic understanding of matter and energy. In this module, we will examine the fundamentals of both. We will look at properties of the basic unit of matter, the **atom.** We will also look at the use and flow of energy. We will explore how chemical bonds enable atoms to form a wide variety of **molecules,** which are chemicals made up of two or more atoms, and will examine the chemical properties of molecules that are used by all living things.

PREP FOR THE AP® EXAM

FOCUS ON THE BIG IDEAS

ENERGETICS: Look for the elements that make up all organisms, and the way in which organisms exchange these elements with the environment.

1.1 Matter and energy govern the properties of life

Because organisms are composed of matter and require energy, it follows that organisms are subject to the physical laws and principles that govern matter and energy. In this section, we will first review some of the properties of matter and energy, and how they flow through communities of living organisms.

Flow of Matter

Let's begin by following the path of matter as it flows through living systems. Imagine that we could tag a carbon atom at its moment of origin and then follow its trip through time and space. Formed in a nuclear blast furnace deep within an ancient star and then ejected into space as the star exploded in death, our atom was eventually swept up with other materials to form Earth, a small planet orbiting a newer star we now call the sun. Volcanoes introduced our carbon atom into Earth's early atmosphere as carbon dioxide (CO_2). Slowly, over millions of years, this carbon dioxide reacted with water and rocks, transferring the carbon from the air to the seafloor. Here, our atom sat for many millions of years, until earthquakes, erosion, or other geologic activities returned it to the atmosphere as carbon dioxide once again. Slowly but surely, geologic processes on early Earth cycled carbon from atmosphere to rocks and back again. This slow movement of carbon between Earth and atmosphere continues today.

Sometime between 4 and 3.5 billion years ago, as life took hold on Earth, our carbon atom began to cycle more rapidly—much more rapidly. Microorganisms were able to convert the carbon dioxide in the environment into **organic molecules,** which are biological molecules that contain carbon. Other microorganisms broke down organic molecules and returned carbon dioxide to the environment. To this day, carbon cycles continuously from the atmosphere and oceans to organisms and back again.

This intricately linked network of geological and biological processes that shuttles carbon among rocks, soil, ocean, air, and organisms is called the carbon cycle. Why focus on carbon? The carbon cycle provides an organizing principle for understanding life on Earth. The chemistry of life is, in no small part, the chemistry of carbon because organic molecules are made up of carbon.

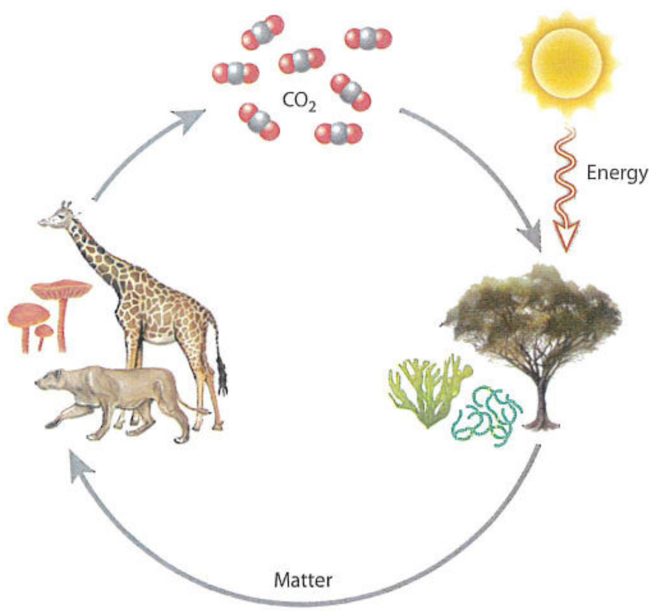


FIGURE 1.1 Flow of matter and energy

Matter, such as a carbon atom, cycles among organisms and the physical environment. Energy, like solar and chemical energy, is harnessed by organisms to do work and needs to be constantly added to the system to sustain life.

The carbon cycle also teaches that matter moves through organisms and the physical environment in a cycle, as shown in **FIGURE 1.1**. In other words, the same atoms are reused over and over. Organisms must exchange matter with other organisms and the environment to grow, reproduce, and maintain organization. For instance, when a leaf or a plant in the forest dies, it is usually consumed by the animals or microbes in the forest. These organisms use the dead leaf to build their biomass. In turn, these organisms recycle matter through the wastes they release or when they die. The released matter is used by other organisms, including plants, animals, and microbes, to build their biomass.

Flow of Energy

As organisms move carbon, they also transfer energy. Carbon and energy are closely intertwined for the simple reason that the energy sources for many organisms are the carbon-rich organic molecules in the organisms they eat or the molecules they build themselves. Unlike carbon, energy does not move in a cycle. Instead, energy must continually be harvested from the environment to sustain the community. In essentially all habitats where sunlight is available, the sun provides the entry point for energy into living systems, as shown in Figure 1.1. Plants, algae, and certain bacteria capture energy from the sun and use it to synthesize energy-rich organic molecules. Where sunlight is absent, especially in the vast depths of the ocean, energy instead comes from chemical compounds.

Organisms transform energy. That is, they acquire energy from the environment and convert it into a chemical form that their cells can use. For instance, some of the solar energy striking a forest is captured by plants, which transform it into chemical energy in the form of sugars. Some of this energy is used by the organism to do work—such as building cellular components, moving, and reproducing. The rest of this energy is dissipated as heat and is no longer available for the organism to use. We will look more closely at the flow of energy and the cycling of matter in Units 3 and 8. "Analyzing Statistics and Data: Standard Deviation and Error Bars" gives you an opportunity to practice using data analysis skills on a question involving plants and energy capture.

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AP® EXAM TIP

You should know that matter and energy both flow through communities, but they take different paths. Matter travels in a cycle, with the same atoms moving back and forth among organisms and the physical environment. By contrast, energy is not recycled. Instead, an input of energy from the environment is constantly required to sustain cells and organisms. Be prepared to give examples of the ways that matter and energy flow through communities and therefore sustain life.

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AP® EXAM TIP

Make sure you understand that no overlap between error bars indicates a statistically significant difference.

✓ Concept Check

1. **Describe** how matter and energy flow through living systems.
2. **Describe** how the flow of matter depends on the flow of energy in communities.

Your Turn

Researchers in an aquatic biology lab have collected data on the mass of algae in a recent experiment. The data are shown in the following table:

Experimental tank	Algae mass (g)	Experimental tank	Algae mass (g)
1	0.36	9	0.66
2	0.51	10	0.31
3	0.25	11	0.22
4	0.42	12	0.29
5	0.22	13	0.33
6	0.25	14	0.32
7	0.28	15	0.48
8	0.27		

1. What is the standard deviation of this dataset?
2. If you were to graph error bars for these data, what range of values would represent a 95% confidence interval of the mean?

1.2 The atom is the fundamental unit of matter

When biologists speak of diversity, they commonly point to the 2 million or so species named and described to date, or to the 10–100 million living species thought to exist in total. Life's diversity can also be found at a very different level of observation: in the molecules within cells. Life depends critically on many essential functions, which ultimately depend on the chemical characteristics of the organic molecules that make up cells and organisms.

In spite of the diversity of molecules and functions, the chemistry of life is based on just a few types of organic molecules, which in turn are made up of just a few types of atoms. In this section, we will look at the structure of atoms and identify the major atoms that make up organic molecules.

Atomic Structure

The study of life begins with the basic unit of matter, the atom. An atom contains a dense central **nucleus.** The nucleus is made of positively charged particles called **protons** and electrically neutral particles called **neutrons.** A third type of particle, the negatively charged **electron,** moves around the nucleus at some distance from it. For example, a carbon atom, illustrated in **FIGURE 1.2**, typically has six protons, six neutrons, and six electrons. The number of protons is known as the **atomic number.** The atomic number specifies an atom as a particular **element,** a chemical that cannot be further broken down by the methods of chemistry. For example, the atom with one proton is hydrogen (H) and the atom with six protons is carbon (C).

Each proton and neutron, by definition, has a mass of 1 atomic mass unit, whereas electrons have negligible mass. Together, protons and neutrons determine an atom's **atomic mass,** which is the total mass of the atom.

The number of neutrons in atoms of a single element can differ, which changes its mass. **Isotopes** are atoms of the same element that have different numbers of neutrons. The atomic mass is sometimes indicated as a superscript to the left of the chemical symbol. ^{12}C is the isotope of carbon with six neutrons and six protons. If we want to symbolize both the atomic number and atomic mass for an element or isotope, we indicate the atomic mass by a superscript and the atomic number by a subscript. For example, the carbon isotopes with the mass of 12 and 14 would be written as $^{12}_{6}C$ and $^{14}_{6}C$, respectively.

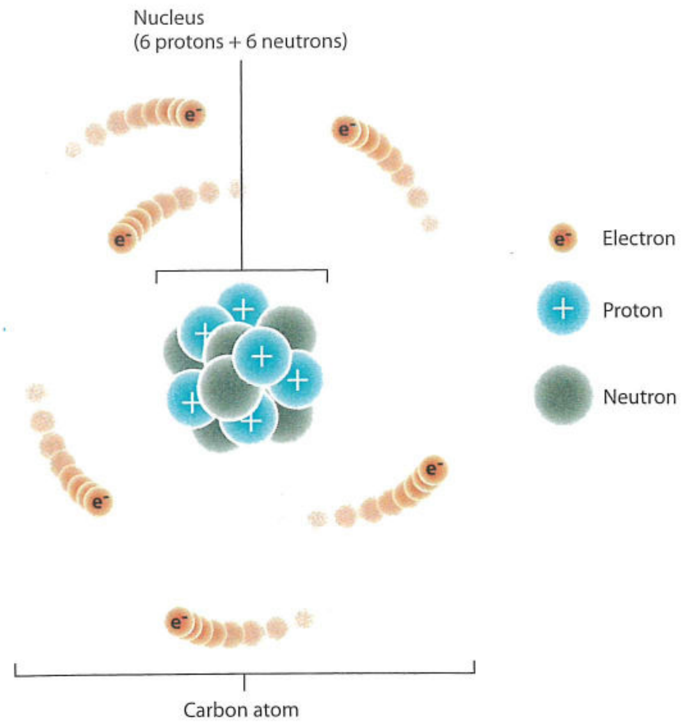


FIGURE 1.2 A carbon atom

Most carbon atoms have six protons, which are positively charged; six neutrons, which are neutral; and six electrons, which are negatively charged.

Typically, an atom has equal numbers of protons and electrons. As you can see in Figure 1.2, carbon possesses six positively charged protons and six negatively charged electrons. The charges add up to zero, so this carbon atom is electrically neutral.

Certain chemical processes cause an atom to either gain or lose electrons. An atom that has lost an electron is positively charged, and one that has gained an electron is negatively charged. Electrically charged atoms are called **ions.** The charge of an ion is specified as a superscript to the right of the chemical symbol. For example, H^+ indicates a hydrogen ion that has lost an electron and is positively charged. Positively charged ions are called cations and negatively charged atoms are anions.

Electrons

The movement of electrons from one molecule to another is the foundation of energy transfer in many biological reactions. Therefore, understanding electron transfer is essential to the study of cellular biochemistry.

Electrons move around the nucleus as a cloud of points that is denser where the electron is most likely to be. The exact path of an electron varies, but it is possible to identify a region in space where an electron is present most of the time. The area in space where electrons circle around the nucleus is known as an **energy level** or **electron shell.** The innermost energy level may contain one or two electrons. As you can see in **FIGURE 1.3**, hydrogen has one electron in the first energy level, which is also its only energy level. Many elements that are important in biology, such as carbon, nitrogen, and oxygen, contain two energy levels. In these atoms, the second energy level may hold up to eight electrons. Figure 1.3 shows how carbon's six electrons are placed in the energy levels: two are in the first energy level and four are in the second energy level.

The amount of energy in a level depends on its location. Electrons closer to the nucleus have less energy and are less reactive than those further from the nucleus. Atoms are most stable when their energy levels are full. When electrons fill the energy levels closest to the nucleus, rather than ones further away, the element becomes more stable. If an electron gains energy and moves or "jumps" to a level further away from the nucleus, the atom is less stable. As we will see later, molecules are often formed when atoms share electrons to fill their outermost energy levels.

Since chemicals often react to complete their outermost energy levels, simple diagrams like those in Figure 1.3 give a sense of how many electrons an element must gain or lose to have a full outermost energy level. In the case of carbon, it must gain four electrons in the outer shell for a total of eight electrons. Hydrogen may either gain one electron or lose an electron to have its outermost shell complete. If an electron is lost, a hydrogen ion (H^+) forms because it now has one more proton than electrons. We will study hydrogen in greater detail when we discuss cellular energetics in Unit 3.

Chemical Properties of Elements

The electrons in an element's outermost energy level are known as the **valence electrons.** The **periodic table of**

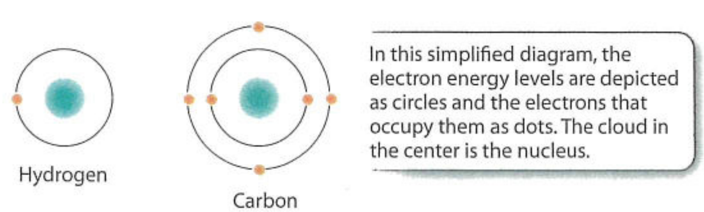


FIGURE 1.3 Energy levels for hydrogen and carbon

The hydrogen atom contains one energy level with a single electron, while the carbon atom has two energy levels with two electrons in the first energy level and four electrons in the second. The energy levels are depicted as circles and the electrons as orange dots.

At the right end of the row, the energy level has a full complement of electrons.

The elements in a vertical column of the periodic table are called a group or family. Members of a group all have the same number of electrons in their outermost level. For example, carbon (C) and lead (Pb) both have four electrons in their outermost level. The number of electrons in the outermost level determines in large part how elements interact with other elements to form a diversity of molecules, as we will explore in the next section.

All living organisms are made up of atoms that can be combined to make molecules.

Abundance in cells: High | Low | Trace | Rare or none

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71 La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103 Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

FIGURE 1.4 The periodic table of the elements

Elements are arranged by increasing number of protons, the atomic number. The atomic number is shown above the element. The elements in a column share similar chemical properties.

the elements, shown in **FIGURE 1.4**, describes valence electrons and other properties of elements. In the periodic table, the elements are indicated by their chemical symbols and arranged in order of increasing atomic number. For example, the second row of the periodic table begins with lithium (Li), which has 3 protons and ends with neon (Ne), which has 10 protons.

For the second and third horizontal rows in the periodic table, elements in the same row have the same number of energy levels. Moving across a row, each element has one more proton and one more electron than the preceding element.

Let's take a look at the second row of elements, those that span from lithium (Li) to neon (Ne), shown in **FIGURE 1.5**. All of these elements have two energy levels. The innermost level of all of these elements is full. Only the outermost energy level has a varied number of electrons, starting with one for lithium and progressively adding one electron to the outer shell of the elements as we move from left to right across the row, ending with eight electrons in neon's outer energy level.

The four elements common to every organism on the planet are carbon (C), hydrogen (H), oxygen (O), and nitrogen (N). Although organisms use elements in the first five rows of the periodic table, these most highly used elements belong to rows 1 and 2. Phosphorus, a member of the third row, is also present in large amounts in organic molecules.

✓ Concept Check

3. **Describe** the components of an atom.
4. **Describe** how the rows and columns of the periodic table of the elements are organized.
5. **Identify** what the superscripts of ^{14}N and ^{15}N signify.
6. **Calculate** how many additional electrons would be needed to fill the outer energy level of C.
7. **Identify** the location of the electrons around an atom that have the most energy associated with them.

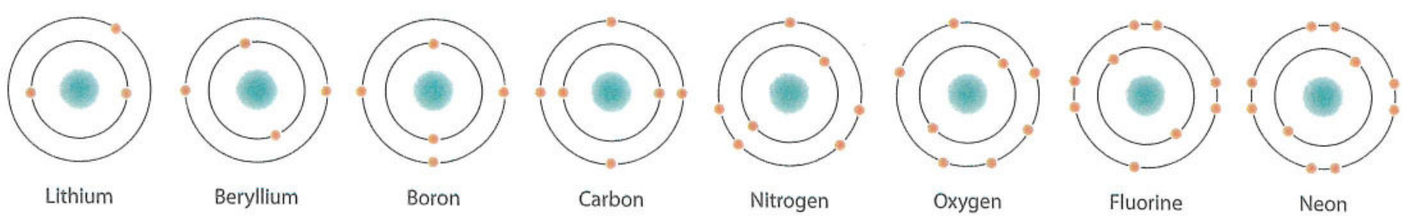


FIGURE 1.5 Number of electrons across row 2 of the periodic table

Moving from left to right, each atom contains one more electron than the last, from lithium to neon. Neon has a full complement of eight electrons in its outer energy level.

1.3 Atoms combine to form molecules linked by chemical bonds

Atoms combine to make a great diversity of molecules in cells, which in turn leads to the diversity of life. Atoms bond with other atoms to form molecules, which are groups of two or more atoms bonded together that act as a single unit. An example of a molecule is hydrogen gas (H_2), made when two atoms of hydrogen bond, as you'll see below. Note that a chemical formula is written as the letter abbreviation for each element, followed by a subscript giving the number of that type of atom in the molecule. When molecules form, the individual atoms interact through what is called a **chemical bond,** a type of attraction between atoms that holds them together. For example, joining one atom of carbon with four atoms of hydrogen creates the compound methane (CH_4), which is also known as natural gas and is used in cooking, heating, and industry. There are several ways in which atoms can interact with one another, forming different types of chemical bonds. In this section, we will look at these chemical bonds.

Covalent Bonds

The ability of atoms to combine with other atoms is determined in large part by the electrons furthest from the nucleus, the valence electrons. When atoms combine with other atoms to form a molecule, the atoms share valence electrons with each other. Specifically, when the outermost energy levels of two atoms come in close proximity, the shells may overlap with one another so that electrons are shared between the two atoms. When a pair of electrons are shared between the two atoms, a **covalent bond** is formed.

Molecules tend to be the most stable when the two atoms forming a bond share enough electrons to completely fill the outermost energy level. Chemical stability occurs when an atom or molecule has the lowest possible energy state. Stable molecules are less likely to react because they require significant inputs of energy to change bonding partners, which is what happens during chemical reactions. Very little energy is required, for example, to get dynamite to react. A stable molecule, such as nitrogen gas, requires a large amount of energy to react.

FIGURE 1.6 shows an example of the formation of covalent bond between one carbon (C) atom and four fluorine (F) atoms. Each fluorine atom (F) has seven valence electrons. When each of these F atoms forms a covalent bond with the carbon (C) atom, the outermost shells overlap due to the sharing of electrons, allowing each atom to fill its outer shell with electrons. The resulting compound, carbon tetrafluoride (CF_4), consists of one C atom covalently bound to four F atoms.

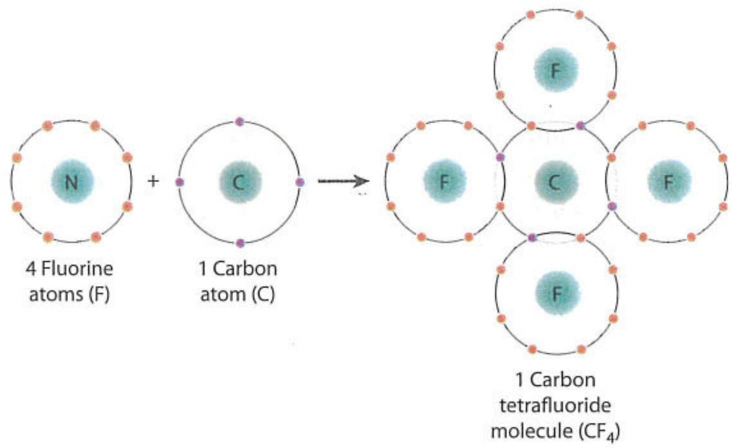


FIGURE 1.6 Covalent bonds

Covalent bonds form when atoms share a pair, or pairs, of electrons in their outermost energy levels. Four individual F atoms, each containing seven electrons in its outermost energy level, form covalent bonds with a single C atom. The C atom shares four electrons, one with every F atom, while each individual F atom shares a single electron with the C atom. By sharing electrons, each F atom and the C atom fill their outer levels.

When two atoms share two electrons in a covalent bond, a **single bond** is formed. When two atoms share two pairs of electrons covalently, a **double bond** is formed. In practice, the word "covalent" is often omitted, as it is understood that these bonds arise through a sharing of electrons and are thus covalent. A double bond is denoted by a double line connecting the two chemical symbols for the atoms. **FIGURE 1.7** shows how double bonds are represented in ethylene, a molecule that is made of two carbon atoms and four hydrogen atoms. The two carbon atoms share four electrons with each other, creating a C═C double bond. By contrast, each carbon atom shares only two electrons with a single H atom, creating a C—H single bond.

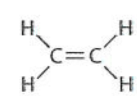


FIGURE 1.7 The double covalent bond of carbon atoms in ethylene

The double line represents four electrons shared between the two carbon atoms; each line denotes two shared electrons. The single lines connecting carbon and hydrogen represent single covalent bonds.

Polar Covalent Bonds

In molecules such as hydrogen (H_2) and oxygen (O_2) gases, electrons are shared equally by the atoms. In many covalent bonds, however, the electrons are not shared equally. A notable example, shown in **FIGURE 1.8**, is the water molecule (H_2O). A water molecule consists of two hydrogen atoms, each of which is covalently bound to a single oxygen atom. In a molecule of water, the region around the oxygen atom has a partial negative charge, while the area around each of the two hydrogen atoms has a partial positive charge. In the figure, charges are shown using the symbol δ^+ for a partial positive charge near the H atoms, and the δ^- symbol for a partial negative charge near the O atom.

Electrons are shared unequally because of a difference in the ability of the atoms to attract electrons, a property known as **electronegativity.** Oxygen is more electronegative than hydrogen. As a result, in a molecule of water, oxygen has a partial negative charge, while the two hydrogen atoms have a partial positive charge. When electrons are shared unequally between two atoms, the interaction is described as a **polar covalent bond.**

By contrast, a covalent bond where atoms are shared equally is sometimes referred to as a **nonpolar covalent bond.** The molecules of hydrogen gas (H_2), oxygen gas (O_2), and nitrogen gas (N_2) all have nonpolar covalent bonds. If two different kinds of atoms have similar electronegativities, then the covalent bonds between them also tend to be nonpolar because the electrons are shared equally, or nearly equally, by the atoms. Of the atoms commonly found in organic molecules, C and H frequently form nonpolar covalent bonds. For example, methane gas (CH_4) is a nonpolar compound.

Electronegativity tends to increase across a row in the periodic table. As the number of positively charged protons across a row increases, negatively charged electrons are held more tightly to the nucleus. This principle helps to explain why O is more electronegative than N and why N is more electronegative than either C or H.

You can think of electronegativity as the "greed" of an atom for electrons. Oxygen (O) is greedier for electrons than is nitrogen (N), carbon (C), or hydrogen (H). Note, too, that carbon, hydrogen, nitrogen, and oxygen vary in their electronegativity. Carbon and nitrogen (C—N) and carbon and oxygen (C—O) each form polar covalent bonds because electrons are not shared equally between two atoms. Atoms that are closer together in electronegativity, such as carbon and hydrogen, form covalent bonds that are not polar. When a covalent bond is established between two atoms of the same type, for instance, between two H atoms or two O atoms, both of the atoms have the same degree of electronegativity and hence the electrons are shared equally.

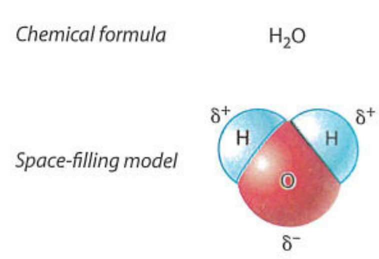


FIGURE 1.8 A polar covalent bond

In a polar covalent bond, the two atoms do not share the electrons equally. In water, the shared electrons spend more time near the O atom than either of the H atoms. The result is that the O atom has a partial negative charge, written as δ^-, while the H atoms have partial positive charges, noted as δ^+.

PREP FOR THE AP® EXAM

AP® EXAM TIP

Nonpolar and polar covalent bonds govern many of the properties of organic molecules. Knowing these concepts will help you understand how these molecules function, which will help you succeed on the AP® Biology Exam.

Ionic Bonds

In a molecule of water, the difference in electronegativity between the oxygen and hydrogen atoms leads to unequal sharing of electrons. In more extreme cases, when an atom of high electronegativity is paired with an atom of low electronegativity, the difference in electronegativity may be so great that the electronegative atom "steals" the electron from its less electronegative partner. This creates an electrically charged atom, which you may recall is known as an ion. The atom with the extra electron contains more electrons than protons, which gives it a negative charge. The atom that lost the electron has a positive charge because it now has more protons than electrons. The two ions form an **ionic bond,** a chemical bond in which two ions with opposite electrical charges associate with each other because of the differences in charge. Some atoms may gain or lose more than one electron when they form an ionic bond. For instance, the calcium ion, which is often used by cells, may be either a single (Ca^+) or a double (Ca^{++}) positively charged ion.

Sodium chloride (NaCl), which is common table salt, is an example of a compound formed by the attraction of

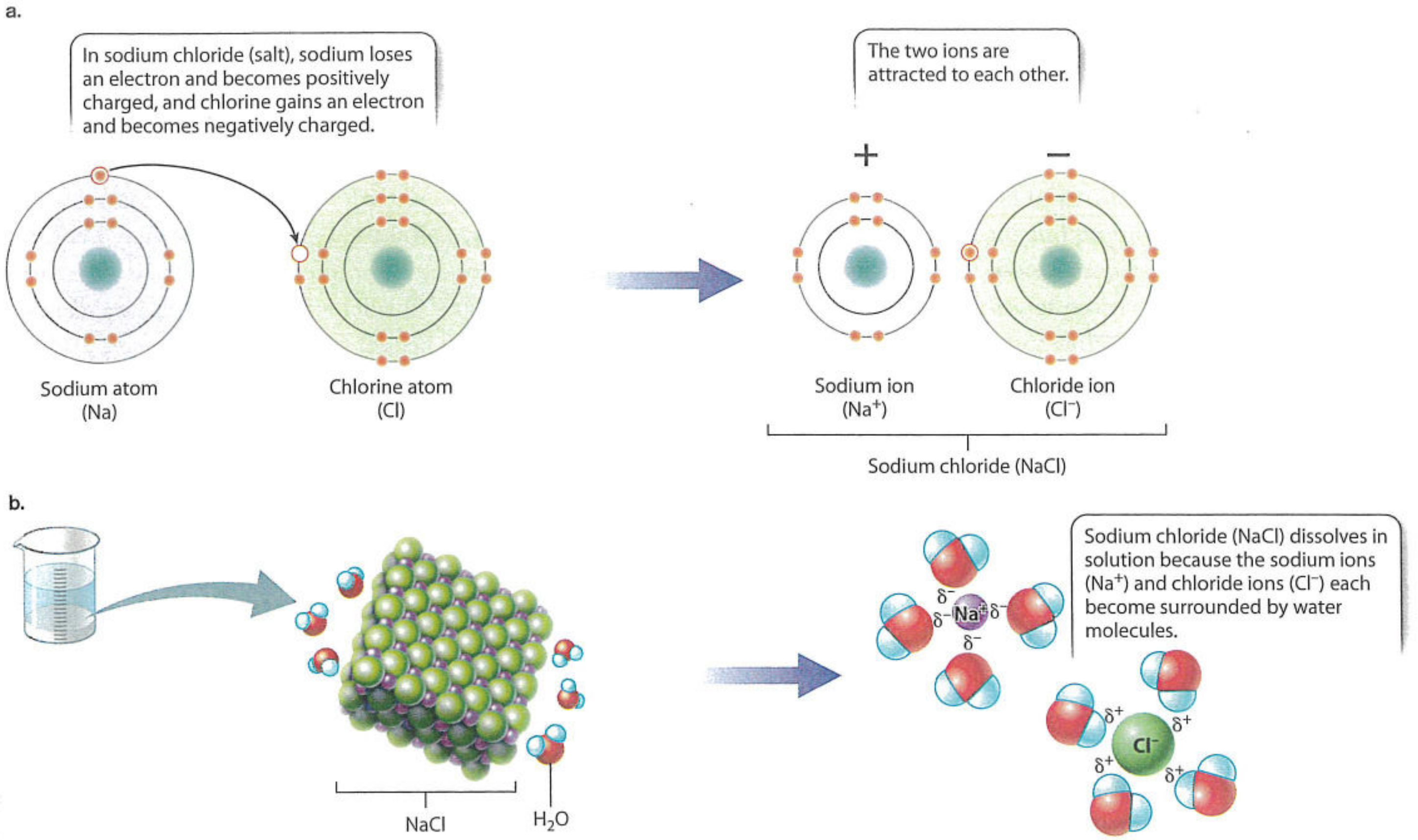


FIGURE. 1.9 An ionic bond

This figure shows how sodium chloride is formed and dissolved. (a) Sodium chloride is formed when a sodium atom gives up an electron to a chloride atom, forming Na^+ and Cl^- ions. The two ions are then attracted to each other by their opposite charges. (b) In solution, the polarity of water causes the ions to dissociate from each other and to become surrounded by water molecules, with water's negative (oxygen) ends surrounding the Na^+ ions and its positive (hydrogen) ends surrounding the Cl^- ions.

positive and negative ions. **FIGURE 1.9** illustrates the formation of sodium chloride. Sodium loses an electron and becomes a positively charged cation, while chloride gains an electron and becomes a negatively charged anion, as shown in Figure 1.9a. The two ions are then attracted to each other by their opposite charges. While covalent bonds are represented by lines like those shown in Figure 1.7, ionic bonds are indicated by superscripts showing charge, such as Na^+Cl^-.

Figure 1.9b illustrates what happens when sodium chloride is placed in water. The negatively charged ends of water molecules are attracted to the positively charged sodium ions, and the positively charged ends of water molecules are attracted to the negatively charged chloride ions. The ions are pulled apart in the water and become surrounded by polar water molecules as sodium chloride dissolves in the water. Chemicals that dissolve well in water tend to have polar or charged regions in the molecule.

In solution, sodium and chloride ions are completely surrounded by water molecules. If the water is then removed from this solution, ionic bonds will again form between the sodium and chloride ions. As the water evaporates, the concentrations of Na^+ and Cl^- increase and the two ions come together to the point where they join and precipitate as salt crystals.

Chemical Reactions

The chemical bonds that link atoms in molecules can change in a **chemical reaction,** a process by which atoms or molecules are transformed into different molecules. The atoms or molecules that are changed in a chemical reaction are called **reactants.** The molecules formed from the reaction are known as **products.** In biological systems, chemical reactions provide a way to build and break down molecules for use by the cell, as well as to harness energy.

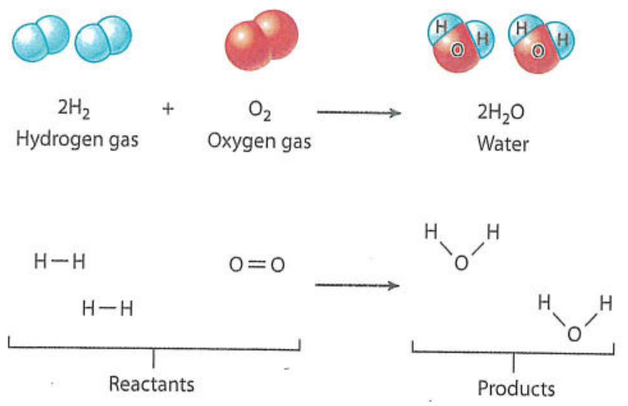


FIGURE 1.10 A chemical reaction

During a chemical reaction, atoms retain their identity, but their connections change as bonds are broken and new bonds are formed. In this reaction, a hydrogen molecule (H—H) reacts with one of the O atoms of an oxygen molecule (O═O), exchanging bonding partners and establishing H—O—H, also written as H_2O. Because this happens twice, two H_2O molecules are formed.

FIGURE 1.10 shows an example of a chemical reaction. In this case, two molecules of hydrogen gas ($2H_2$) and one molecule of oxygen gas (O_2) react to form two molecules of water ($2H_2O$). In this reaction, the numbers of each type of atom are conserved, meaning that the number of atoms does not change, but their arrangement in the reactants is different from the arrangement in the products. Specifically, the H—H single bond in hydrogen gas and the O═O double bond in oxygen gas are broken. At the same time, each oxygen atom forms new covalent bonds with two hydrogen atoms, making the products of the reaction two molecules of water.

In fact, this reaction is the origin of the word "hydrogen," which literally means "water former." The reaction releases a good deal of energy and is used in some rockets as a booster in satellite launches. Certain microorganisms also perform this reaction in a much smaller and more controlled manner. These microorganisms benefit from the released energy, which they use to perform some of their cellular biochemistry.

In biological systems, chemical reactions provide a way to build and break down molecules for use by the cell, as well as to harness energy, which can be held in chemical bonds. We explore these topics in more detail in Unit 3.

✓ Concept Check

8. **Describe** the differences among covalent bonds, polar covalent bonds, nonpolar covalent bonds, and ionic bonds.
9. Use the polar property of water to **describe** the process by which water (H_2O) dissolves sodium chloride (NaCl).
10. In the reaction $3H_2 + N_2 \rightarrow 2NH_3$, **identify** the reactants and the products.

1.4 Carbon is the backbone of organic molecules

When you first learned to read, you probably began by learning the shapes and sounds of the letters of the alphabet. After that you learned letter combinations and then simple words. Our introduction to the basic chemistry of life is similar. Now that we've reviewed the basic nature of atoms and molecules, we can turn to the chemistry of life. As we mentioned earlier, the chemistry of life is based on carbon. In this section, we will examine what makes carbon well suited to its role as the chemical backbone of living things, and introduce the four major types of organic molecules.

The Chemistry of Carbon

Hydrogen and helium are by far the most abundant elements in the universe. In contrast, the solid Earth is dominated by silicon, oxygen, aluminum, iron, and calcium. In other words, Earth is not a typical sample of the universe. Similarly, the cell is not a typical sample of the solid Earth. **FIGURE 1.11** shows the relative abundance by mass of chemical elements present in human cells after all the water has been removed. Just four elements—carbon (C), oxygen (O), hydrogen (H), and nitrogen (N)—account for approximately 90% of the total dry mass, and the most abundant element is carbon.

While other types of cells may vary somewhat, virtually all contain about the same ratios of these elements. Human life, and all life as we know it, is based on carbon. Carbon-containing molecules play such an important role in living organisms that they have a special name, as we saw earlier—they are called organic molecules. Carbon has the ability to combine with many other elements to form a wide variety of molecules, each specialized for the functions it carries out in the cell. For example, carbon-based molecules make up the structure of cells, participate in and speed up chemical reactions, and store energy for use by the cell.

Why has life evolved with carbon as its key element? Of the elements commonly observed in cells, carbon is unique in its bonding capacities. Of a carbon atom's six electrons, four are in its outermost shell and are available to form

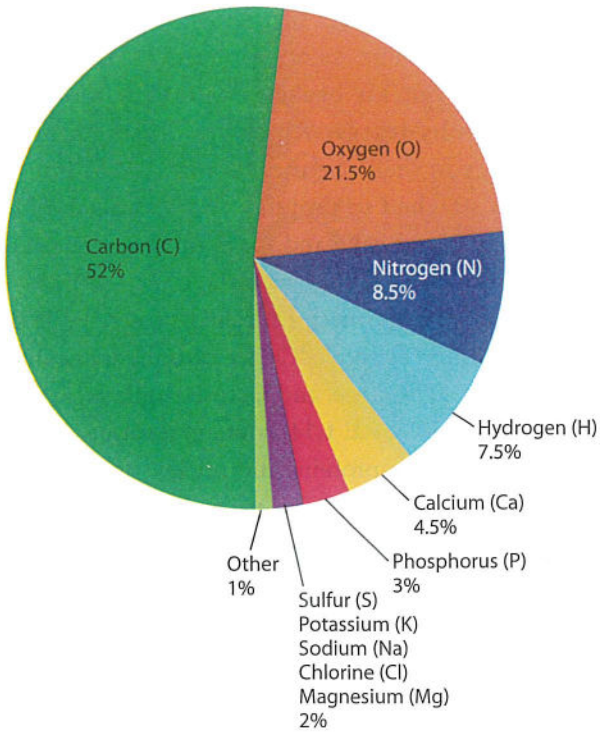


FIGURE 1.11 Approximate percentages by dry mass of chemical elements found in human cells

Carbon is the most abundant element in human cells when all of the water has been removed. Oxygen, nitrogen, and hydrogen are also relatively common. While other organisms may vary somewhat, virtually all use about the same ratios of these elements.

covalent bonds. Carbon commonly forms covalent bonds with itself, oxygen, nitrogen, and hydrogen.

FIGURE 1.12 shows methane gas (CH_4), which is formed when one atom of carbon combines with four atoms of hydrogen. Each of the four valence electrons of carbon becomes part of a covalent bond with an electron from an H atom. The bonds formed can move, or rotate, freely about their axis. In addition, the carbon atom lies at the center of a specific three-dimensional structure, called

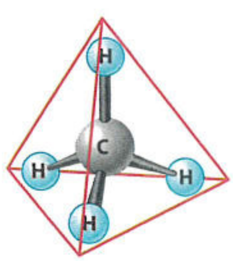


FIGURE 1.12 The shape and structure of methane

In methane gas (CH_4), a carbon atom is covalently bonded to four hydrogen atoms. The carbon atom lies at the center of a three-dimensional structure, called a tetrahedron, and the four covalent bonds with hydrogen extend the hydrogen atoms toward the four corners of this structure.

a tetrahedron, and the four covalent bonds with H extend the H atoms toward the four corners of this structure.

Because of its shape and because its single bonds rotate freely, carbon is able to make compounds in a variety of three-dimensional shapes. This ability to form many varied structures enables carbon to perform a wide variety of functions necessary to sustain and promote life.

Carbon has other special properties that contribute to its ability to form a diversity of molecules. For example, carbon atoms can link with other carbon atoms through covalent bonds, forming long chains. These chains can be branched, or two carbons at the ends of the chain or within the chain can link to form a ring. We also discussed earlier how carbon can form single and double bonds with other carbon atoms.

As a result of all of these properties, carbon-based molecules are structurally and functionally diverse. In other words, they can form an astonishing variety of molecules that can perform many different of roles in the cell. We might ask whether carbon is uniquely suited for life. Put another way, if we ever discover life on a distant planet, will it be based on carbon? Silicon, which is found just below carbon in the periodic table (see Figure 1.4), is the one other element that is both abundant on Earth and characterized by an outer shell with four valence electrons. Some scientists have speculated that silicon might therefore provide an alternative to carbon as a chemical basis for life. However, silicon readily binds with oxygen. On Earth, nearly all of the silicon atoms found in molecules are covalently bound to oxygen. Studies of Mars and meteorites show that silicon is tightly bound to oxygen throughout our solar system. As a result, the diversity of silicon-based molecules is far less than the millions of carbon-based molecules. If we ever discover life beyond Earth, very likely its chemistry will be based on carbon.

Organic Molecules

Four classes of organic molecules are of particular significance in biological systems: *proteins, nucleic acids, carbohydrates,* and *lipids*. Although they have different structures and roles, they share at least two properties. First, as we just discussed, they all contain carbon. Second, most of them are long chains, called **polymers,** built from smaller repeating subunits, called **monomers.** A polymer is like a necklace made of beads, and a monomer is a single bead, as shown in **FIGURE 1.13** on page 38. Here we take a first look at these four types of organic molecules. Later in this unit, we will examine each in greater detail.

Proteins are organic molecules that do much of the cell's work. They speed up chemical reactions and provide structural support for the cell. The white of an egg, for

FIGURE 1.13 Polymer

A polymer is a long chain of repeating subunits called monomers, similar to this necklace made up of individual beads. Photo: LionGate/Alamy Stock Photo

example, is mostly made up of proteins. Proteins are composed of subunits called **amino acids.** Returning to our necklace example, we would say that a protein is a necklace, and an amino acid is a bead.

A single cell has thousands of proteins with different functions. For example, some proteins form scaffolds that help to determine the shape of cells. Other proteins serve as chemical messengers, traveling from one cell to another to convey a message. Still other proteins accelerate the rate of chemical reactions. These various functions depend on the structure, or shape, of the protein. In fact, structure and function are closely connected. As a result, scientists can sometimes infer what a protein does by examining its shape. Furthermore, anything that disrupts the shape of a protein will often disrupt its function. The shape of a protein is determined by its sequence of amino acids. We will discuss proteins in more detail in Module 4.

Nucleic acids are responsible for encoding and transmitting genetic information. There are two types of nucleic acids. Module 0 mentioned deoxyribonucleic acid (DNA). The second nucleic acid is **ribonucleic acid (RNA).** Like proteins, nucleic acids are long polymers made up of repeating subunits, called **nucleotides.**

Nucleic acids are examples of informational molecules—that is, large molecules that carry information in the sequence, or order, of nucleotides that make them up. This molecular information is much like the information carried by the letters in an alphabet, but, in the case of nucleic acids, the information is in chemical form. DNA is the genetic material in all organisms. It is transmitted from parents to offspring, and it contains the information needed to specify the amino acid sequence of proteins. RNA has multiple functions, but one of its most important is in the synthesis of proteins. We will discuss nucleic acids in more detail in Module 5.

Many of us, when we feel tired, reach for a candy bar for a quick energy boost. The energy in a candy bar comes from sugars, which are quickly broken down to release energy. Sugars are **carbohydrates,** which are organic molecules that store energy in their chemical bonds. In addition, they are sometimes attached to proteins on the surface of cells, such as your red blood cells, and make up the external layer of the cells in plants, algae, and bacteria.

Carbohydrates are sometimes called sugars. Table sugar (sucrose) is a familiar example. Other carbohydrates include the sugars glucose, galactose, and lactose (milk sugar). Fruit, like that shown in **FIGURE 1.14**, contains a variety of sugars, including fructose. Like proteins and nucleic acids, carbohydrates are composed of repeating units of individual sugars, called monosaccharides.

As we have seen, proteins, nucleic acids, and carbohydrates all are polymers made up of smaller, repeating units. Lipids are different. Instead of being defined by a chemical structure, they share a particular property: **lipids** are organic molecules that are *hydrophobic.* **Hydrophobic** means "water fearing" and it describes nonpolar molecules that don't dissolve in water. Instead, they tend to associate with other lipids and minimize their contact with water. Think of what happens when oil, which is hydrophobic, is mixed with water. The oil forms droplets that minimize their contact with water, as pictured in **FIGURE 1.15**. By contrast, **hydrophilic** means "water loving" and it describes polar molecules that readily associate with and dissolve in water. For example, when sugar is placed in water, it dissolves as the individual sugar molecules associate with water molecules.

Because they share a property rather than a structure, lipids are chemically and functionally diverse. Their hydrophobic property allows them to be effective membranes, or barriers,

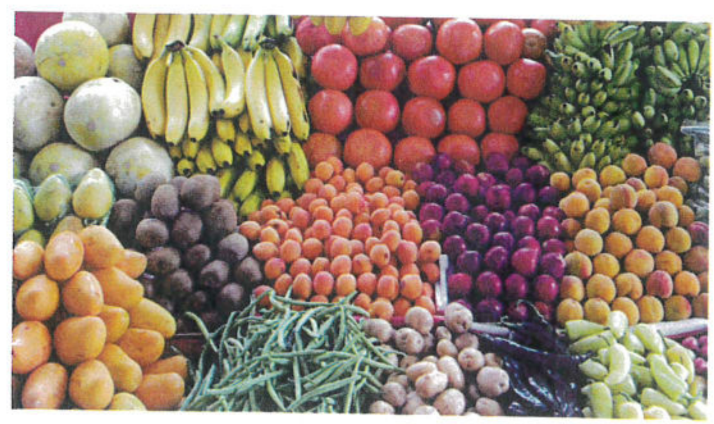


FIGURE 1.14 Carbohydrates

Fruit, such as these items at a market, contains fructose along with several other types of sugars. Sugars are types of carbohydrates. Photo: OGphoto/Getty Images

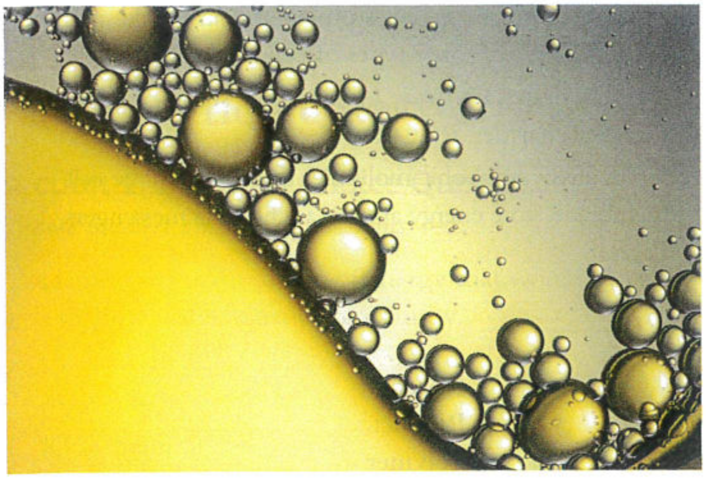


FIGURE 1.15 Lipids

When oil, which is a lipid, is mixed in water, it forms droplets to minimize its contact with water. Oil, like all lipids, is hydrophobic.
Photo: ThomasVogel/Getty Images

between a cell's watery internal and external environments. They also include signaling molecules and familiar fats that store energy and make up part of our diet. Lipids will be discussed along with carbohydrates in more detail in Module 3.

✓ Concept Check

11. **Identify** the four most common atoms in organic molecules.
12. **Describe** how the number of valence electrons in a carbon atom is responsible for carbon's ability to form a large diversity of molecules.
13. **Identify** the four major types of organic molecules.
14. **Describe** a polymer.
15. **Describe** the property of lipids that allows them to function as a barrier between a cell's interior and external environments.

Module 1 Summary

PREP FOR THE AP® EXAM

REVISIT THE BIG IDEAS

ENERGETICS: Using the content in this module, **identify** the key elements that all organisms obtain from the environment and exchange with the environment.

LG 1.1 Matter and energy govern the properties of life.

- All organisms are made up matter and require energy to sustain life. Page 26
- Organisms obtain matter from other organisms and the environment, and matter therefore moves in a cycle, with the same atoms used and reused. Page 26
- Energy from the sun or chemical compounds is used by organisms to do work but cannot be reused. Page 27

LG 1.2 The atom is the fundamental unit of matter.

- Atoms consist of protons, neutrons, and electrons. Page 30
- The atomic number is the number of protons an element contains, and it determines the identity of the element. Page 30
- The atomic mass is the number of protons and neutrons an element contains. Page 30
- Isotopes are elements with the same number of protons but different numbers of neutrons. Page 30
- Electrons occupy energy shells or levels that move around the nucleus. Page 31
- The periodic table organizes all of the elements in a way that describes their properties. Page 31

LG 1.3 Atoms combine to form molecules linked by chemical bonds.

- Valence electrons are the electrons in an atom's outermost energy shell and determine the ability of an atom to combine with other atoms to form molecules. Page 31
- Covalent bonds arise when two elements share one or more pairs of electrons. Page 33
- Covalent bonds may be either nonpolar or polar. Page 34
- Ionic bonds result from the attraction of oppositely charged ions. Page 34
- Chemical reactions involve the breaking and forming of chemical bonds, forming new molecules. Page 35

LG 1.4 Carbon is the backbone of organic molecules.

- Carbon's electron configuration allows it to form four covalent bonds. Page 36
- Carbon's bonding allows a diversity of molecules to be formed. Page 37
- The four major classes of organic molecules are proteins, nucleic acids, carbohydrates, and lipids. Page 37
- Proteins play a role in the structure of cells and can speed up the rate of chemical reactions. Page 37

- Proteins are made up of subunits called amino acids. Page 38
- Nucleic acids are information molecules and the molecules of heredity. Page 38
- Nucleic acids are made up of subunits called nucleotides. Page 38
- Carbohydrates, or sugars, store energy and make up the external layer of some types of cells. Page 38
- Carbohydrates are made up of simple sugars, called monosaccharides. Page 38
- Lipids are hydrophobic molecules that make up the cell membrane, store energy, and act as chemical messengers. Page 38

Key Terms

Matter
Atom
Molecule
Organic molecule
Nucleus
Proton
Neutron
Electron
Atomic number
Element
Atomic mass
Isotope
Ion
Energy level
Electron shell
Valence electron
Periodic table of the elements
Chemical bond
Covalent bond
Single bond
Double bond
Electronegativity
Polar covalent bond
Nonpolar covalent bond
Ionic bond
Chemical reaction
Reactant
Product
Polymer
Monomer
Protein
Amino acid
Nucleic acid
Ribonucleic acid (RNA)
Nucleotide
Carbohydrate
Lipid
Hydrophobic
Hydrophilic

Review Questions

1. Using the periodic table shown in Figure 1.4, identify which atom is most likely to have properties similar to nitrogen.
   (A) Oxygen (O)
   (B) Bismuth (Bi)
   (C) Lead (Pb)
   (D) Carbon (C)

2. The element sodium (Na) has an atomic number of 11 and an atomic mass of 23. Calculate the number of protons and neutrons in Na.
   (A) 11 protons and 11 neutrons
   (B) 11 protons and 10 neutrons
   (C) 11 protons and 12 neutrons
   (D) 10 protons and 13 neutrons

3. Which type of bond is formed between a sodium ion and a chloride ion?
   (A) Ionic
   (B) Neutral
   (C) Polar covalent bond
   (D) Nonpolar covalent bond

4. Which type of bond is formed between two oxygen atoms?
   (A) Ionic
   (B) Neutral
   (C) Polar covalent bond
   (D) Nonpolar covalent bond

5. When two molecules undergo a chemical reaction, they
   (A) lose atoms.
   (B) keep the same bonding partners that they had as reactants.
   (C) establish new bonding partners.
   (D) incorporate atoms from the air and water as well as from the reactants.

6. Proteins, nucleic acids, and carbohydrates are all
   (A) information molecules.
   (B) signaling molecules.
   (C) polymers made up of repeating subunits.
   (D) monomers that combine to form polymers.

7. Two organic molecules that store energy for use by the cell are
   (A) carbohydrates and nucleic acids.
   (B) carbohydrates and lipids.
   (C) proteins and nucleic acids.
   (D) nucleic acids and lipids.

Module 1
AP® Practice Questions

PREP FOR THE AP® EXAM

Section 1: Multiple-Choice Questions

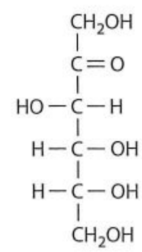
Choose the best answer for questions 1–5.

1. Identify the main source of energy that would sustain a shallow water aquatic community.
   (A) Carbon
   (B) Sunlight
   (C) Chemical compounds
   (D) Heat

2. Which is the best example of the flow of matter through a community?
   (A) Sunlight is necessary for trees to grow → leaves wash into a cave where they are colonized by fungi and bacteria → small mites graze on the bacteria for food → insects and spiders feed on the mites.
   (B) Deep-sea volcanic activity forms vents on the ocean floor → superheated water dissolves minerals and metals → bacteria use these minerals to survive → many organisms depend on the bacteria as a food source.
   (C) The decomposition of animals from millions of years ago formed oil → oil is used by humans as a fossil fuel → burning fossil fuels releases CO_2 into the atmosphere → CO_2 is used by plants to produce O_2 → O_2 is consumed by many living animals.
   (D) A meadow of wildflowers absorbs solar energy → each flower converts this into sugars → the flowers use the sugars to grow and reproduce.

3. Fluorine (F) is a strongly electronegative element with seven valence electrons in its outermost energy level. Compared to the less electronegative sodium (Na), which has one valence electron in its outermost level, fluorine
   (A) holds electrons loosely around its nucleus.
   (B) is not as greedy to gain electrons.
   (C) will have a partial positive charge when it bonds to other elements.
   (D) is likely to become an anion.

Questions 4 and 5 refer to the chemical structure of the sugar fructose shown below.



4. Identify the type of bond linking the oxygen and hydrogen atoms.
   (A) Covalent
   (B) Ionic
   (C) Electronegative
   (D) Double

5. Name the organic molecule that has this structure.
   (A) Protein
   (B) Nucleic acid
   (C) Carbohydrate
   (D) Lipid