UNIT 1

The Chemistry of Life

Chapter 2

The Chemical Context of Life

Key Concepts

2.1 Matter consists of chemical elements in pure form and in combinations called compounds

2.2 An element's properties depend on the structure of its atoms

2.3 The formation and function of molecules depends on chemical bonding between atoms

2.4 Chemical reactions make and break chemical bonds

Framework

This chapter considers the basic principles of chemistry that explain the behavior of atoms and molecules and that form the basis for our modern understanding of biology. You will learn how the subatomic particles—protons, neutrons, and electrons—are organized into atoms and atoms are combined by covalent or ionic bonds into molecules. Weak chemical bonds help to create the shapes and functions of molecules. Emergent properties are associated with each new level of structural organization in the hierarchy from atoms to life.

Chapter Review

2.1 Matter consists of chemical elements in pure form and in combinations called compounds

Elements and Compounds **Matter** is anything that takes up space and has mass. (Although sometimes used interchangeably, *mass* reflects the amount of matter in an object, whereas *weight* reflects gravity's pull on that mass.) The basic forms of matter are **elements,** substances that cannot be chemically broken down to other types of matter. A **compound** is made up of two or more elements combined in a fixed ratio. A compound usually has characteristics quite different from its constituent elements, an example of the emergence of novel properties in higher levels of organization.

Essential Elements of Life Carbon (C), oxygen (O), hydrogen (H), and nitrogen (N) make up 96% of living matter. The seven elements listed in Interactive Question 2.1 make up most of the remaining 4%. Some elements, like iron (Fe) and iodine (I), may be required in very minute quantities and are called **trace elements.**

■ **INTERACTIVE QUESTION 2.1**

Fill in the names beside the symbols of the following elements commonly found in living matter.

Symbol	Element
Ca	
P	
K	
S	
Na	
Cl	
Mg	

2.2 An element's properties depend on the structure of its atoms

An **atom** is the smallest unit of an element retaining the physical and chemical properties of that element.

Subatomic Particles Three stable subatomic particles are important to our understanding of atoms. Uncharged **neutrons** and positively charged **protons** are packed tightly together to form the **atomic nucleus** of an atom. Negatively charged **electrons** orbit rapidly about the nucleus.

Protons and neutrons have a similar mass of about 1.7×10^{-24} g or 1 **dalton** each. A dalton is the measurement unit for atomic mass. Electrons have negligible mass.

Atomic Number and Atomic Mass Each element has a characteristic **atomic number**, or number of protons in the nucleus of its atom. Unless indicated otherwise, an atom has a neutral electrical charge, and thus the number of protons is equal to the number of electrons. A subscript to the left of the symbol for an element indicates its atomic number; a superscript indicates mass number. The **mass number** is equal to the number of protons and neutrons in the nucleus and approximates the mass of an atom of that element in daltons. The term **atomic mass** refers to the total mass of an atom.

■ **INTERACTIVE QUESTION 2.2**

The difference between the mass number and the atomic number of an atom is equal to the number of __________. An atom of phosphorus, $^{31}_{15}P$, contains protons, electrons, and neutrons. The atomic mass of phosphorus is approximately __________.

Isotopes Although the number of protons is constant, the number of neutrons can vary among the atoms of an element, creating different **isotopes** that have slightly different masses but the same chemical behavior. Some isotopes are unstable, or **radioactive**; their nuclei spontaneously decay, giving off particles and energy.

Radioactive isotopes are important tools in biological research and medicine. Chemical processes can be located and monitored within an organism using radioactive tracers and PET (positron-emission tomography). Too great an exposure to radiation from decaying isotopes poses a significant health hazard.

The Energy Levels of Electrons **Energy** is defined as the ability to cause change. **Potential energy** is energy stored in matter as a consequence of the relative position of masses. Matter naturally tends to move toward a more stable lower level of potential energy and requires the input of energy to return to a higher potential energy.

The potential energy of electrons increases as their distance from the positively charged nucleus increases. Electrons can orbit in several different potential energy states, called **energy levels** or **electron shells**, surrounding the nucleus.

■ **INTERACTIVE QUESTION 2.3**

To move to a shell farther from the nucleus, an electron must __________ energy; energy is __________ when an electron moves to a closer shell.

Electron Configuration and Chemical Properties The chemical behavior of an atom is a function of its electron configuration—in particular, the number of **valence electrons** in its outermost electron shell, or **valence shell.** A valence shell of eight electrons is complete, resulting in an unreactive or inert atom. (The first shell holds only two electrons; thus $_2He$ is inert.) Atoms with incomplete valence shells are chemically reactive because of their unpaired electrons. The *periodic table of the elements* is arranged in order of the sequential addition of electrons to orbitals in the electron shells.

■ **INTERACTIVE QUESTION 2.4**

Draw the electron shell diagram for these atoms.

a. $_7N$

b. $_8O$

c. $_{12}Mg$

d. $_6C$

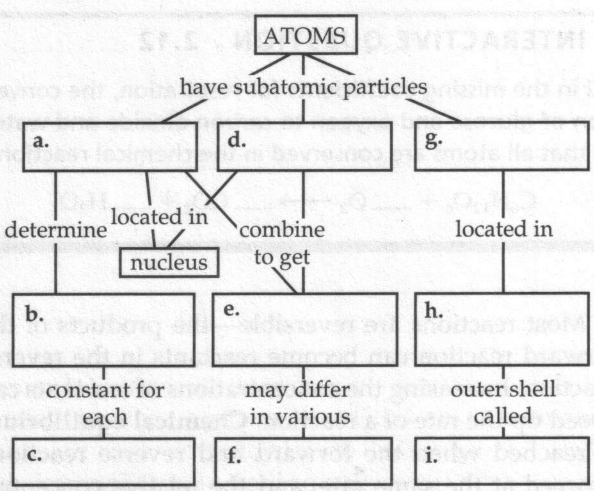
Electron Orbitals An **orbital** is the three-dimensional space or volume within which an electron is most likely to be found. No more than two electrons can occupy the same orbital. The first electron shell can contain two electrons in a single spherical orbital, called the 1s orbital. The second electron shell can hold a maximum of eight electrons in its four orbitals, which are a 2s spherical orbital and three dumbbell-shaped p orbitals located along the *x*, *y*, and *z* axes.

■ INTERACTIVE QUESTION 2.5

Look again at the electron shell diagram you drew for carbon (d.) in Interactive Question 2.4. Did you show the outer shell electrons unpaired? Why?

■ INTERACTIVE QUESTION 2.6

Fill in the blanks in the following concept map to help you review the atomic structure of atoms.



2.3 The formation and function of molecules depend on chemical bonding between atoms

Atoms with incomplete valence shells can either share electrons with or completely transfer electrons to or from other atoms such that each atom is able to complete its valence shell. These interactions usually result in attractions, called **chemical bonds,** that hold the atoms together.

Covalent Bonds When two atoms share a pair of valence electrons, a **covalent bond** is formed. A **molecule** consists of two or more atoms held together by covalent bonds. A **structural formula,** such as H—H, indicates both the number and type of atoms and also the bonding within a molecule. The dash indicates a **single covalent bond,** or just a **single bond.** A **molecular formula,** such as O_2, indicates only the kinds and numbers of atoms in a molecule. In an oxygen molecule, two pairs of valence electrons are shared between oxygen atoms, forming a **double covalent bond,** or simply a **double bond.**

The **valence,** or bonding capacity, of an atom equals the number of unpaired electrons in its valence shell. (Even though phosphorus has three unpaired electrons and a valence of three, it has a valence of five in some important biological molecules.)

■ INTERACTIVE QUESTION 2.7

What are the valences of the four most common elements of living matter?

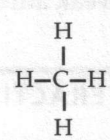
a. hydrogen c. nitrogen

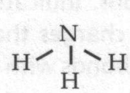
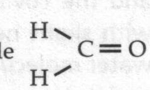
b. oxygen d. carbon

Electronegativity is the attraction of a particular type of atom for shared electrons. If the atoms in a molecule have similar electronegativities, the electrons remain equally shared between the two nuclei, and the covalent bond is said to be a **nonpolar covalent bold.** If one element is more electronegative, it pulls the shared electrons closer to itself, creating a **polar covalent bond.** This unequal sharing of electrons results in a slight negative charge (δ−) associated with the more electronegative atom and a slight positive charge (δ+) associated with the atom from which the electrons are pulled.

■ INTERACTIVE QUESTION 2.8

Explain whether the following molecules contain nonpolar or polar covalent bonds. (Hint: N and O both have high electronegativities.)

a. nitrogen molecule N≡N **c.** methane 

b. ammonia  **d.** formaldehyde 

Ionic Bonds If two atoms are very different in their attraction for the shared electrons, the more electronegative atom may completely transfer an electron from another atom, resulting in the formation of charged atoms called **ions.** The atom that lost the electron is a positively charged **cation.** The negatively charged atom that gained the electron is called an **anion.** An **ionic bond** may hold these ions together because of the attraction of their opposite charges.

Ionic compounds, called **salts,** often exist as three-dimensional crystalline lattice arrangements held together by electrical attractions. The number of ions present in a salt crystal is not fixed, but the atoms are present in specific ratios. Salts have strong ionic bonds when dry, but the crystal dissolves in water.

Ion also refers to entire covalent molecules that are electrically charged. Ammonium (NH_4^+) is a cation; this covalently bonded molecule is missing one electron.

■ INTERACTIVE QUESTION 2.9

Calcium ($_{20}Ca$) and chlorine ($_{17}Cl$) can combine to form the salt calcium chloride. Based on the number of electrons in their valence shells and their bonding capacities, what would the molecular formula for this salt be? a. ________ Which atom becomes the cation? b. ________

Weak Chemical Bonds Weak bonds, such as ionic bonds in water, form temporary interactions between molecules and are involved in many biological signals and processes. Weak bonds within large molecules such as proteins help to create the three-dimensional shape and resulting activity of these molecules.

When a hydrogen atom is covalently bonded with an electronegative atom, and thus has a partial positive charge, it can be attracted to another electronegative atom and form a **hydrogen bond.**

All atoms and molecules are attracted to each other when in close contact by **van der Waals interactions.** Momentary uneven electron distributions produce changing positive and negative regions that create these weak attractions.

■ INTERACTIVE QUESTION 2.10

Sketch a water molecule, showing oxygen's electron shells and the covalently shared electrons. Indicate the areas with slight negative and positive charges that enable a water molecule to form hydrogen bonds with other polar molecules.

Molecular Shape and Function A molecule's characteristic size and shape affect how it interacts with other molecules. When atoms form covalent bonds, their *s* and three *p* orbitals hybridize to form four teardrop-shaped orbitals in a tetrahedral arrangement. These hybrid orbitals dictate the specific shapes of different molecules.

■ INTERACTIVE QUESTION 2.11

Look at your diagram of a water molecule in Interactive Question 2.10. Why should its shape be roughly like a V?

2.4 Chemical reactions make and break chemical bonds

Chemical reactions involve the making or breaking of chemical bonds in the transformation of matter into different forms. Matter is conserved in chemical reactions; the same number and kinds of atoms are present in both **reactants** and **products,** although the rearrangement of electrons and atoms causes the properties of these molecules to be different.

■ INTERACTIVE QUESTION 2.12

Fill in the missing coefficients for respiration, the conversion of glucose and oxygen to carbon dioxide and water, so that all atoms are conserved in the chemical reaction.

$$C_6H_{12}O_6 + \_\_\ O_2 \longrightarrow \_\_\ CO_2 + \_\_\ H_2O$$

Most reactions are reversible—the products of the forward reaction can become reactants in the reverse reaction. Increasing the concentrations of reactants can speed up the rate of a reaction. **Chemical equilibrium** is reached when the forward and reverse reactions proceed at the same rate, and the relative concentrations of reactants and products no longer change.

Word Roots

an- = not (*anion:* a negatively charged ion)

co- = together; **-valent** = strength (*covalent bond:* an attraction between atoms that share one or more pairs of outer-shell electrons)

electro- = electricity (*electronegativity:* the tendency for an atom to pull electrons toward itself)

iso- = equal (*isotope:* an element having the same number of protons and electrons but a different number of neutrons)
neutr- = neither (*neutron:* a subatomic particle with a neutral electrical charge)
pro- = before (*proton:* a subatomic particle with a single positive electrical charge)

Structure Your Knowledge

Take the time to write out or discuss your answers to the following questions. Then refer to the suggested answers at the end of the book.

1. Fill in the following chart for the major subatomic particles of an atom.

Particle	Charge	Mass	Location

2. Atoms can have various numbers associated with them.
   a. Define the following and show where each of them is placed relative to the symbol of an element such as C: atomic number, mass number, atomic mass.
   b. Define valence.
   c. Which of these four numbers is most related to the chemical behavior of an atom? Explain.
3. Explain what is meant by saying that the sharing of electrons between atoms falls on a continuum from nonpolar covalent bonds to ionic bonds.

Test Your Knowledge

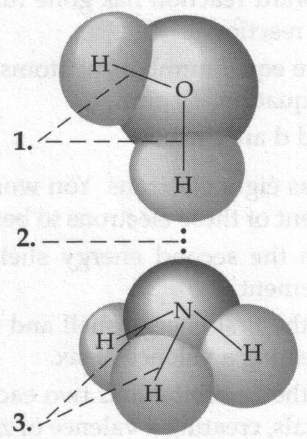
MULTIPLE CHOICE: *Choose the one best answer*

1. Each element has its own characteristic atom in which
   a. the atomic mass is constant.
   b. the atomic number is constant.
   c. the mass number is constant.
   d. two of the above are correct.
   e. all of the above are correct.
2. Radioactive isotopes can be used in studies of metabolic pathways because
   a. their half-life allows a researcher to time an experiment.
   b. they are more reactive.
   c. the cell does not recognize the extra protons in the nucleus, so isotopes are readily used in metabolism.
   d. their location or quantity can be experimentally determined because of their radioactivity.
   e. their extra neutrons produce different colors that can be traced through the body.
3. In a reaction in chemical equilibrium,
   a. the forward and reverse reactions are occurring at the same rate.
   b. the reactants and products are in equal concentration.
   c. the forward reaction has gone further than the reverse reaction.
   d. there are equal numbers of atoms on both sides of the equation.
   e. a, b, and d are correct.
4. Oxygen has eight electrons. You would expect the arrangement of these electrons to be:
   a. eight in the second energy shell, creating an inert element.
   b. two in the first energy shell and six in the second, creating a valence of six.
   c. two in the 1*s* orbital and two each in the three 2*p* orbitals, creating a valence of zero.
   d. two in the 1*s* orbital, one each in the 2*s* and three 2*p* orbitals, and two in the 3*s* orbital, creating a valence of two.
   e. two in the 1*s* orbital, two in both the 2*s* and 2*px* orbitals, and one each in the 2*py* and 2*pz* orbitals, creating a valence of two.
5. A covalent bond between two atoms is likely to be polar if
   a. one of the atoms is much more electronegative than the other.
   b. the two atoms are equally electronegative.
   c. the two atoms are of the same element.
   d. the bond is part of a tetrahedrally shaped molecule.
   e. one atom is an anion.

6. A triple covalent bond would
   a. be very polar.
   b. involve the bonding of three atoms.
   c. involve the bonding of six atoms.
   d. produce a triangularly shaped molecule.
   e. involve the sharing of six electrons.

7. A cation
   a. has gained an electron.
   b. can easily form hydrogen bonds.
   c. is more likely to form in an atom with seven electrons in its valence shell.
   d. has a positive charge.
   e. Both c and d are correct.

8. What types of bonds are identified in the following illustration of a water molecule interacting with an ammonia molecule?



   a. Bonds 1 are polar covalent bonds, bond 2 is a hydrogen bond, and bonds 3 are nonpolar covalent bonds.
   b. Bonds 1 and 3 are polar covalent bonds, and bond 2 is a hydrogen bond.
   c. Bonds 1 and 3 are polar covalent bonds, and bond 2 is an ionic bond.
   d. Bonds 1 and 3 are nonpolar covalent bonds, and bond 2 is a hydrogen bond.
   e. Bonds 1 and 3 are polar covalent bonds, and bond 2 is a nonpolar covalent bond.

9. Which of the following weak bonds may form between any closely aligned molecules?
   a. nonpolar covalent
   b. polar covalent
   c. ionic
   d. hydrogen
   e. van der Waals interactions

10. The ability of morphine to mimic the effects of the body's endorphins is due to
   a. a chemical equilibrium developing between morphine and endorphins.
   b. the one-way conversion of morphine into endorphin.
   c. molecular shape similarities that allow morphine to bind to endorphin receptors.
   d. the similarities between morphine and heroin.
   e. hydrogen bonding and other weak bonds forming between morphine and endorphins.

Use this information to answer questions 11 through 16.

The six elements most common in living organisms are:

$^{12}_{6}C$ $^{16}_{8}O$ $^{1}_{1}H$ $^{14}_{7}N$ $^{32}_{16}S$ $^{31}_{15}P$

11. How many electrons does phosphorus have in its valence shell?
   a. 3
   b. 5
   c. 7
   d. 15
   e. 16

12. What is the atomic mass of phosphorus?
   a. 15
   b. 16
   c. 31
   d. 46
   e. 62

13. A radioactive isotope of carbon has the mass number 14. How many neutrons does this isotope have?
   a. 2
   b. 6
   c. 8
   d. 12
   e. 14

14. How many covalent bonds is a sulfur atom most likely to form?
   a. 1
   b. 2
   c. 3
   d. 4
   e. 5

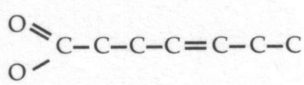
15. Based on electron configuration, which of these elements would have chemical behavior most like that of oxygen?

a. C
b. H
c. N
d. P
e. S

16. How many of these elements are found next to each other (side by side) on the periodic table?

a. one group of two
b. two groups of two
c. one group of two and one group of three
d. one group of three
e. all of them

17. Taking into account the bonding capacities or valences of carbon (C) and oxygen (O), how many hydrogen (H) must be added to complete the structural diagram of this molecule?



a. 9
b. 10
c. 11
d. 12
e. 13

18. A sodium ion (Na^+) contains 10 electrons, 11 protons, and 12 neutrons. What is the atomic number of sodium?

a. 10
b. 11
c. 12
d. 23
e. 33

19. What type of bond would you expect potassium (K) to form?

a. ionic; it would donate one electron and carry a positive charge
b. ionic; it would donate one electron and carry a negative charge
c. covalent; it would share one electron and make one covalent bond
d. covalent; it would share two electrons and form two bonds
e. none; potassium is an inert element

20. What is the molecular shape of methane (CH_4)?

a. planar or flat, with the H arranged around the C
b. pentagonal, or a flat five-sided arrangement
c. tetrahedral, due to the hybridization of the *s* and three *p* orbits of the C
d. circular, with the four H attached in a ring around the C
e. linear, since all the bonds are nonpolar covalent

21. Which of the following is a molecule capable of forming hydrogen bonds?

a. CH_4
b. H_2O
c. NaCl
d. H_2
e. a, b, and d can form hydrogen bonds.

22. Chlorine has an atomic number of 17 and a mass number of 35. How many electrons would a chloride ion have?

a. 16
b. 17
c. 18
d. 33
e. 34

23. What is the difference between a molecule and a compound?

a. There is no difference; the terms are interchangeable.
b. Molecules contain atoms of a single element, whereas compounds contain two or more elements.
c. A molecule consists of two or more covalently bonded atoms; a compound contains two or more atoms held by ionic bonds.
d. A compound consists of two or more elements in a fixed ratio; a molecule has two or more covalently bonded atoms of the same or different elements.
e. Compounds always consist of molecules, but molecules are not always compounds.

24. Which of the following atomic numbers would describe the element that is least reactive?

a. 1
b. 8
c. 12
d. 16
e. 18

25. What coefficients must be placed in the blanks to balance this chemical reaction?

$$C_5H_{12} + \_\_ O_2 \longrightarrow \_\_ CO_2 + \_\_ H_2O$$

a. 5; 5; 5
b. 6; 5; 6
c. 6; 6; 6
d. 8; 4; 6
e. 8; 5; 6