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 depend 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. You will learn how the subatomic particles—protons, neutrons, and electrons—are organized in atoms, how atoms are connected by covalent bonds, and how ions are attracted to each other in ionic bonds. Weak chemical bonds help to create the shapes and functions of molecules.

Chapter Review

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

Matter is anything that takes up space and has mass. (Although sometimes the terms are used interchangeably, *mass* is the amount of matter in an object, whereas *weight* reflects gravity's pull on that mass.)

Elements and Compounds **Elements** are 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. The characteristics of a compound differ from those of its constituent elements, an example of emergent properties in higher levels of organization.

The Elements of Life **Essential elements** are those needed for an organism to live and reproduce. 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, such as 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.

Ca	Na
P	Cl
K	Mg
S	

Evolution of Tolerance to Toxic Elements Serpentine soil contains toxic elements. Some plants exhibit evolutionary adaptations that enable them to grow in such soils.

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

Each element has its own type of **atom**, the smallest unit of matter retaining the properties of that element.

Subatomic Particles Three stable *subatomic particles* are important to your understanding of atoms. Uncharged **neutrons** and positively charged **protons** are packed tightly together to form the **atomic nucleus** of an atom. Negatively charged **electrons** form a large cloud around the positively charged nucleus.

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

Atomic Number and Atomic Mass What makes the atoms of different elements unique? Each element has a characteristic **atomic number,** or number of protons in each of its atoms. Unless otherwise indicated, 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 its 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; the nuclei of **radioactive isotopes** spontaneously decay, giving off particles and energy. Radioactive isotopes are important tools in biological research and medicine. Too great an exposure to radiation from decaying isotopes poses a significant health hazard.

Each radioactive isotope has a fixed rate of decay—its **half-life,** which is the number of years it takes for 50% of the "parent" isotope to decay into its "daughter" isotope. In a process called **radiometric dating,** scientists use the ratio of different isotopes to estimate how many half-lives (in years) have passed since a fossil or rock was formed.

The Energy Levels of Electrons **Energy** is defined as the capacity to cause change—to do work. **Potential energy** is energy stored in matter as a consequence of its position or structure. The potential energy of electrons increases as their distance from the positively charged nucleus increases. Electrons can be located in different **electron shells,** each with a characteristic energy level and distance from the nucleus.

INTERACTIVE QUESTION 2.3

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

Electron Distribution and Chemical Properties What determines the chemical behavior of an atom? It is a function of the distribution of its electrons—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, however, can hold only two electrons.) Atoms with incomplete valence shells are chemically reactive. The elements in each row, or *period*, of the *periodic table of the elements* have the same number of electron shells and are arranged in order of increasing number of electrons.

INTERACTIVE QUESTION 2.4

Draw an electron distribution diagram for the following atoms. *(Note that electrons do not pair up in the second and third shells until after 4 electrons are present.)*

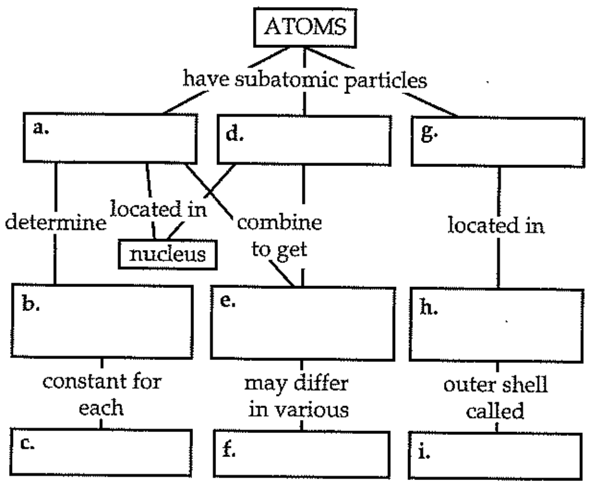
a. $_1H$ **c.** $_8O$

b. $_6C$ **d.** $_{11}Na$

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 1*s* 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

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,** which hold the atoms close 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 *molecular formula,* such as H_2, indicates only the kinds and numbers of atoms. Both an electron distribution diagram and a *Lewis dot structure* show the shared electrons in a molecule. A *structural formula,* such as H—H, uses a dash to indicate the shared electrons of a **single bond.** In an oxygen molecule (O_2), two pairs of valence electrons are shared between oxygen atoms, forming a **double bond** (O=O). The **valence,** or bonding capacity, of an atom usually equals the number of unpaired electrons in its valence shell.

INTERACTIVE QUESTION 2.6

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

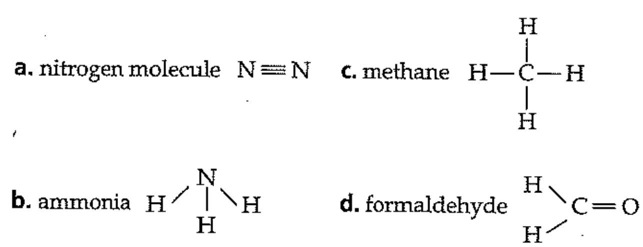
b. Draw the Lewis dot structures for the following molecules.

H_2 O_2 N_2 CH_4

Electronegativity is the attraction of a particular atom for shared electrons. If the atoms in a molecule have similar electronegativities, the electrons remain equally shared, and the bond is said to be a **nonpolar covalent bond.** If one element is more electronegative, it pulls the shared electrons closer to itself, creating a **polar covalent bond.** This unequal sharing of negatively charged electrons results in a "polarity" or separation of charges, with 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 2.7

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



Ionic Bonds If two atoms are very different in their attraction for valence electrons, the more electronegative atom may completely transfer an electron from the other 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, or **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.

Molecules that are electrically charged are also referred to as *ions*.

INTERACTIVE QUESTION 2.8

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 formula for this salt be? **a.** _____ Which atom becomes the cation? **b.** _____

Weak Chemical Bonds Ionic bonds and other weak bonds may form temporary interactions between molecules. Weak bonds within many large molecules help to create those molecules' three-dimensional functional shapes.

A hydrogen atom that is covalently bonded to an electronegative atom has a partial positive charge and can be attracted to a different nearby electronegative atom. This attraction is called 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 2.9

Draw the structural formula of a water molecule, showing in which direction the shared electrons are pulled. Indicate the areas with slight negative and positive charges that enable a water molecule to form hydrogen bonds with other polar molecules. Then draw a second water molecule and indicate a hydrogen bond between the two.

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 2.10

Look at your sketch of a water molecule in Interactive Question 2.9. Why is it roughly V shaped?

2.4 Chemical reactions make and break chemical bonds

Chemical reactions involve the making or breaking of chemical bonds. 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 2.11

Fill in the missing coefficients for respiration—the conversion of glucose and oxygen to carbon dioxide and water, with the release of energy. Make sure that all atoms are conserved in the chemical reaction.

$C_6H_{12}O_6$ + _____O_2 → _____CO_2 + _____H_2O

Chemical 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:* a type of strong chemical bond in which two atoms share one or more pairs of valence electrons)

electro- = electricity (*electronegativity:* the attraction of a given atom for the electrons of a covalent bond)
iso- = equal (*isotope:* one of several forms of an element, each with the same number of protons but a different number of neutrons, thus differing in atomic mass)
neutr- = neither (*neutron:* a subatomic particle having no electrical charge, found in the nucleus of an atom)
pro- = before (*proton:* a subatomic particle with a single positive electrical charge, found in the nucleus of an atom)

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 concerning 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 relation to the symbol of an element such as C (use the most common isotope, C-12): 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 how ionic bonds and the two types of covalent bonds can be arranged in an order that reflects the degree of electron sharing.

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.
2. Which of the following is *not* a trace element in the human body?
   a. iodine
   b. zinc
   c. iron
   d. calcium
3. A sodium ion (Na^+) contains 10 electrons, 11 protons, and 12 neutrons. What is the mass number of sodium?
   a. 11 c. 23
   b. 12 d. 33
4. Radioactive isotopes can be used in studies of metabolic pathways because
   a. their half-lives allow 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.
5. Which of the following atomic numbers would describe the element that is least reactive?
   a. 8 c. 16
   b. 12 d. 18

Use this information to answer questions 6 through 11.

Six of the elements most common in living organisms are

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

6. How many electrons does phosphorus have in its valence shell?
   a. 3 c. 7
   b. 5 d. 15
7. What is the approximate atomic mass of sulfur?
   a. 16 c. 48
   b. 32 d. 64
8. A radioactive isotope of carbon has the mass number 14. How many neutrons does this isotope have?
   a. 2 c. 8
   b. 6 d. 14

9. How many covalent bonds is a nitrogen atom most likely to form?
   a. 1   c. 3
   b. 2   d. 4

10. Based on electron configuration, which of the following elements would have chemical behavior most like that of oxygen?
   a. C   c. S
   b. N   d. P

11. How many of the elements listed above 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

12. Which of the following describes what happens as a chlorophyll pigment absorbs energy from sunlight?
   a. An electron moves to a higher electron shell and the electron's potential energy increases.
   b. An electron moves to a higher electron shell and its potential energy decreases.
   c. An electron drops to a lower electron shell and releases its energy as heat.
   d. An electron of sunlight is transferred to chlorophyll, producing a chlorophyll ion with higher potential energy.

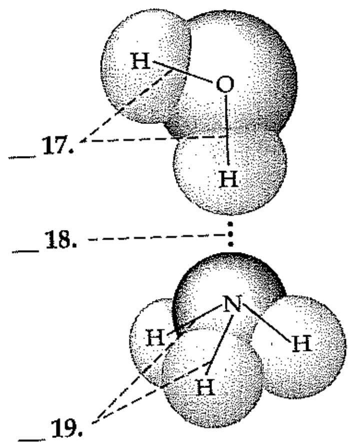
13. An atom of argon has three electron shells, all of which are full. Its mass number is 40. How many neutrons does it have?
   a. 16   c. 22
   b. 20   d. 24

14. A covalent bond between two atoms is likely to be nonpolar if
   a. one of the atoms is much more electronegative than the other.
   b. the two atoms are about equally electronegative.
   c. the two atoms are of the same element.
   d. Both **b** and **c** are correct.

15. A triple covalent bond would
   a. not be possible.
   b. involve the bonding of six atoms.
   c. produce a triangularly shaped molecule.
   d. involve the sharing of six electrons.

16. A cation
   a. has gained an electron.
   b. is more likely to form in an atom with seven electrons in its valence shell.
   c. has a positive charge.
   d. Both **b** and **c** are correct.

For questions 17–19, choose from the following answers to identify the types of bonds in this diagram of a water molecule interacting with an ammonia molecule.
   a. nonpolar covalent bond
   b. polar covalent bond
   c. ionic bond
   d. hydrogen bond



20. Which of the following explains how geckos can walk up walls?
   a. polar covalent bonds
   b. ionic bonds
   c. hydrogen bonds
   d. van der Waals interactions

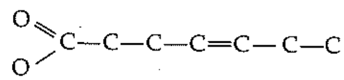
21. What is the molecular shape of methane (CH_4)?
   a. planar or flat, with the four H extending out from the carbon
   b. tetrahedral, due to the hybridization of the *s* and three *p* orbitals of carbon
   c. circular, with the four H attached in a ring around the carbon
   d. linear, because all the bonds are nonpolar covalent bonds

22. Which of the following molecules would you predict is capable of forming hydrogen bonds?
   a. CH_4
   b. CH_4O
   c. N_2
   d. H_2

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

a. 16 **c.** 18
b. 17 **d.** 34

24. Taking into account the valences of carbon (C) and oxygen (O), how many hydrogen (H) must be added to complete the following molecule?



a. 9 **c.** 11
b. 10 **d.** 12

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

a. There is no difference; the terms are interchangeable.
b. A molecule consists of two or more covalently bonded atoms; a compound contains two or more atoms held together by ionic bonds.
c. 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.
d. Compounds always consist of molecules, but molecules are not always compounds.

26. Which of the following is true of 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 to completion.
d. There are equal numbers of atoms on both sides of the equation.

27. What would be the probable effect of adding more product to a reaction that is in equilibrium?

a. There would be no change because the reaction is in equilibrium.
b. The forward reaction would stop because excess product is present.
c. The forward reaction would increase and more product would be formed.
d. The reverse reaction would increase and more reactants would be formed.

28. What coefficients must be placed in the blanks to balance the following chemical reaction?

C_5H_{12} + _____ O_2 → _____ CO_2 + _____ H_2O

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