UNIT 1

Chemistry and Cells

Chapter 2

The Chemical Context of Life

Chapter Focus

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. The chapter also focuses on the properties of water, which emerge from the polarity and hydrogen bonding capacity of this small, essential molecule.

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. **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* arising in higher levels of organization.

The Elements of Life Your body is composed of 25 different elements. The elements needed for an organism to live and reproduce are called **essential elements** (the list varies somewhat for different organisms). Carbon (C), oxygen (O), hydrogen (H), and nitrogen (N) make up 96% of living matter. Some elements, like iron (Fe) and iodine (I), may be required in very minute quantities and are called **trace elements**.

FOCUS QUESTION 2.1

Fill in the names beside the symbols of the following elements that, along with a few others, make up about 4% of an organism's mass.

Ca Calcium K Potassium

P phosphorus S Sulfur

Evolution of Tolerance to Toxic Elements Some plants exhibit evolutionary adaptations that allow them to grow in soils containing toxic elements.

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.

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. An electron distribution diagram shows the shared electrons in a molecule. In a *structural formula*, such as H—H, the line indicates a **single bond**. A *molecular formula*, such as O_2, indicates only the kinds and numbers of atoms. In an oxygen molecule, two pairs of valence electrons are shared between oxygen atoms, forming a double covalent bond, or simply a **double bond** (O=O). The **valence**, or bonding capacity, of an atom usually equals the number of electrons required to complete its valence shell.

FOCUS QUESTION 2.6

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

H = 1 O = 2 N = 3 C = 4

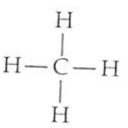
Electronegativity is the attraction of a particular atom for shared electrons. If the atoms in a molecule have similar electronegativities, the electrons remain equally shared, and the bond is said to be a **nonpolar covalent bond**. If one element is more electronegative, it pulls the shared electrons closer to itself, creating a **polar covalent bond**. This unequal sharing of electrons results in a "polarity" or separation of charges, with a slight negative charge ($\delta-$) associated with the more electronegative atom and a slight positive charge ($\delta+$) associated with the atom from which the electrons are pulled.

FOCUS QUESTION 2.7

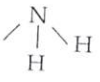
Explain whether the following molecules contain nonpolar or polar covalent bonds. (*Hint:* N and O both have high electronegativities. C and H have lower, and similar, electronegativities.)

a. nitrogen molecule $N \equiv N$

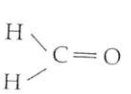
c. methane



b. ammonia



d. formaldehyde



a) Non-polar b) Polar c) Non-Polar d) C=O Polar C-H Non-polar

Ionic Bonds What happens when two atoms are very unequal 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.

Covalent molecules that are electrically charged are also referred to as *ions*.

FOCUS 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.** $CaCl_2$ Which atom becomes the cation? **b.** Ca^{2+}

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 another nearby electronegative atom. This attraction is called a **hydrogen bond**.

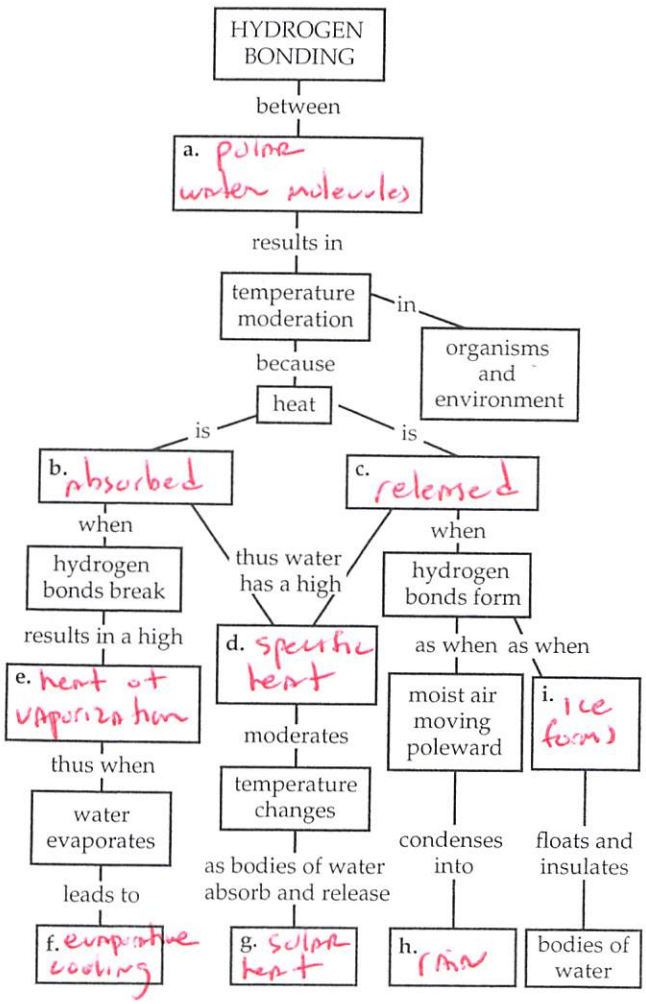
All atoms and molecules are attracted to each other when in close contact by **van der Waals interactions**. Momentary uneven electron distributions produce changing positive and negative regions that create these weak attractions.

Molecular Shape and Function A molecule's characteristic size and shape affect how it interacts with other molecules. A carbon atom bonded to four other atoms has a tetrahedral shape.

hydrogen-bonded to four other molecules, creating a crystalline lattice that spaces the molecules apart. Ice is thus less dense than liquid water and so it floats.

FOCUS QUESTION 2.11

The following concept map is one way to show how the breaking and forming of hydrogen bonds are related to temperature moderation. Fill in the blanks and compare your choice of concepts to those given in the answer section. Or, even better, create your own map to help you understand how water stabilizes temperature.



Water: The Solvent of Life A **solution** is a liquid homogeneous mixture of two or more substances; the dissolving agent is called the **solvent**, and the substance that is dissolved is the **solute**. Water is the solvent in an **aqueous solution**. The positive and negative regions of water molecules are attracted to oppositely charged ions or partially charged regions of polar molecules. Thus, solute molecules become surrounded by water molecules (a **hydration shell**) and dissolve into solution.

Ionic and polar substances are **hydrophilic**; they have an affinity for water due to electrical attractions and hydrogen bonding. Nonpolar and nonionic substances are **hydrophobic**; they will not easily mix with or dissolve in water.

Most of the chemical reactions of life take place in water. A **mole (mol)** is the amount of a substance that has a mass in *grams* numerically equivalent to its **molecular mass** (the sum of the mass of all atoms in the molecule). A mole of any substance has exactly the same number of molecules—6.02×10^{23}, called Avogadro's number. The **molarity** of a solution (abbreviated *M*) refers to the number of moles of a solute dissolved in 1 liter of solution.

FOCUS QUESTION 2.12

a. How many grams of lactic acid ($C_3H_6O_3$) are in 1 liter of a 0.5 *M* solution of lactic acid (^{12}C, ^{1}H, ^{16}O)? 45 g

b. How many molecules of lactic acid are in the solution in a?

3.01×10^{23}

Acids and Bases A water molecule can dissociate into a **hydrogen ion**, H^+ (which binds to another water molecule to form a **hydronium ion**, H_3O^+), and a **hydroxide ion**, OH^-. In pure water at 25°C, the concentrations of H^+ and OH^- are the same; both are equal to 10^{-7} *M*.

When acids or bases dissolve in water, the H^+ and OH^- balance shifts. An **acid** adds H^+ to a solution, whereas a **base** reduces H^+ in a solution by accepting hydrogen ions or by adding hydroxide ions (which then combine with H^+ and thus remove hydrogen ions). A strong acid or strong base dissociates completely when mixed with water. A weak acid or base reversibly dissociates, either releasing or binding H^+.

In an aqueous solution, the *product* of the $[H^+]$ and $[OH^-]$ is constant at 10^{-14}. Brackets, [ ], indicate molar concentration. If the $[H^+]$ is higher, then the $[OH^-]$ is lower, because the excess hydrogen ions combine with the hydroxide ions in solution and form water. Likewise, an increase in $[OH^-]$ causes an equivalent decrease in $[H^+]$.

The **pH** of a solution is defined as the negative log (base 10) of the $[H^+]$: pH = –log $[H^+]$. For a neutral aqueous solution, $[H^+]$ is 10^{-7} *M*, and the pH = 7. As the $[H^+]$ increases in an acidic solution, the pH value decreases. (This inverse relationship makes sense because the exponent becomes smaller: 10^{-4} indicates a higher $[H^+]$ than 10^{-7}.) The difference between each

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 (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. Fill in the following table, which summarizes the emergent properties of water that contribute to the fitness of the environment for life.

Property	Explanation of Property	Example of Benefit to Life
a. Cohesion Adhesion	Hydrogen bonds hold water molecules together and adhere them to a hydrophilic surface.	b. A water column is pulled up through plant vessels
High specific heat	c. Heat is absorbed or released when hydrogen bonds break or form.	Temperature changes in environment and organisms are moderated.
d. High heat of vaporization	Hydrogen bonds must be broken for water to evaporate.	e. Solar heat is dissipated by tropical seas.
f. evaporative cooling	Water molecules with high kinetic energy evaporate; remaining molecules are cooler.	g. evaporation of water cools surface of plants and animals
Less dense as a solid	h. hydrogen bonds in ice space water molecules further apart	i. Floating ice insulates bodies of H_2O so they don't freeze
j. Versatile solvent	k. Polar water molecules surround and dissolve ionic and polar solutes	Most chemical reactions in life involve solutes dissolved in water.

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. Which of the following is *not* a trace element in the human body?
   a. iodine
   b. zinc
   c. iron
   d. calcium
   e. fluorine

3. 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

4. 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.

5. Which of the following atomic numbers would describe the element that is least reactive?
   a. 1
   b. 8
   c. 12
   d. 16
   e. 18

6. An atom of argon has three electron shells, all of which are full. Its atomic mass is 40. How many neutrons does it have?
   a. 8
   b. 16
   c. 20
   d. 22
   e. 24

7. 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 drops to a lower electron shell and its potential energy increases.
   e. An electron of sunlight is transferred to chlorophyll, producing a chlorophyll ion with higher potential energy.

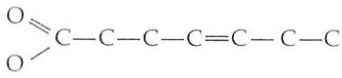
22. What is the molecular shape of methane (CH_4)?
    a. planar or flat, with the four H extending out from the carbon
    b. pentagonal, or a flat five-sided arrangement
    c. tetrahedral, with carbon in the center and H at each corner
    d. circular, with the four H attached in a ring around the carbon
    e. linear, since all the bonds are nonpolar covalent bonds

23. 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.

24. Which of the following molecules or compounds would you predict is capable of forming hydrogen bonds?
    a. CH_4
    b. CH_4O
    c. NaCl
    d. H_2
    e. **a**, **b**, and **d** can form hydrogen bonds.

25. 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

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



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

27. 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.

28. 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.

29. 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 reaction would stop because excess product is present.
    c. The reaction would slow down but still continue.
    d. The forward reaction would increase and more product would be formed.
    e. The reverse reaction would increase and more reactants would be formed.

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

$$C_5H_{12} + \_\_\_\_O_2 \rightarrow \_\_\_\_CO_2 + \_\_\_\_H_2O$$

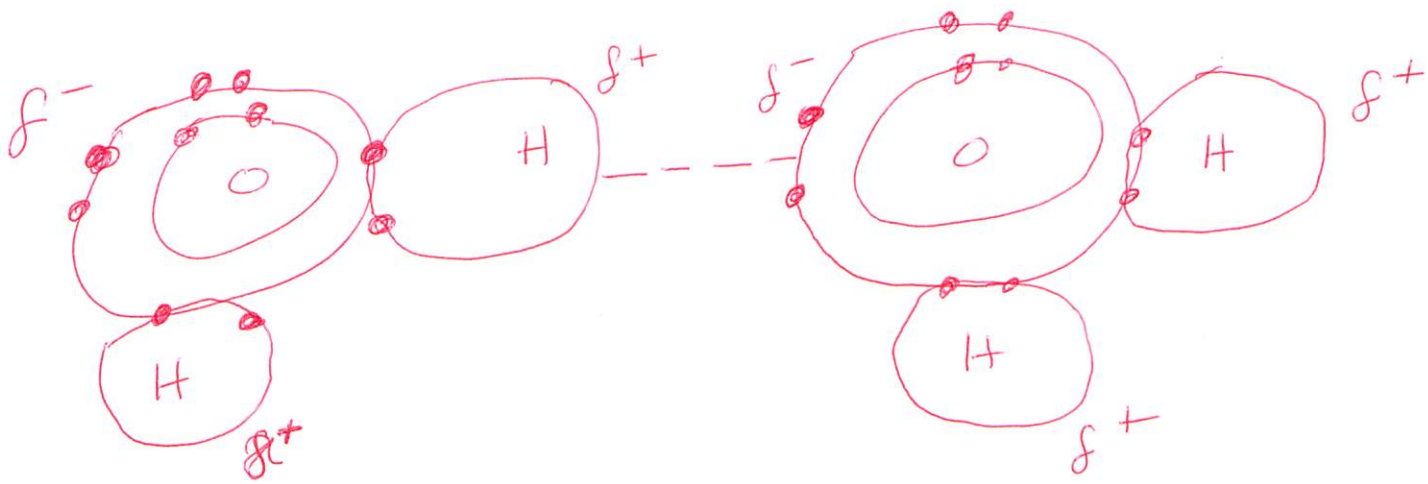
    a. 5; 5; 5
    b. 6; 5; 6
    c. 6; 6; 6
    d. 8; 4; 6
    e. 8; 5; 6

31. The polar covalent bonds of water molecules
    a. promote the formation of hydrogen bonds.
    b. help water to dissolve nonpolar solutes.
    c. lower the heat of vaporization and lead to evaporative cooling.
    d. create a crystalline structure in liquid water.
    e. do all of the above.

43. A buffer
    a. releases excess OH^-.
    b. releases excess H^+.
    c. is often a weak acid-base pair.
    d. always maintains a neutral pH.
    e. Both c and d are correct.

44. In the past century, the average temperature of the oceans has increased by 0.74°C. Would you consider this evidence of global warming?
    a. No, the rise in temperature is too small to be significant.
    b. No, global warming affects air temperature, not water temperature.
    c. No, the change of average temperature does not reflect the quantity of thermal energy in the oceans.
    d. Yes, because of the high specific heat of water and the huge volume of water in the oceans, a small rise in temperature would reflect a large amount of heat absorbed by the oceans.
    e. Yes, the decreased rate of calcification of reef-building organisms is directly related to this temperature increase.

2.9



2.12

$$\frac{0.5\ mol}{L}\ C_3H_6O_3\left(\frac{90\ g}{1\ mol}\right) = \boxed{45\ g/L}$$

$$\frac{0.5\ mol}{L}\ C_3H_6O_3\left(\frac{6.02\times10^{23}\ molecules}{1\ mol}\right) = \boxed{3.01\times10^{23}\ molecules/L}$$

2.14

carbonic acid: H_2CO_3 $\rightleftharpoons$ bicarbonate: HCO_3^- + hydrogen ion: H^+

H^+ donor

H^+ acceptor

a) Bicarbonate acts as a base to accept excess H^+ ions when the pH starts to fall; the reaction moves to the LEFT

b) When the pH rises, H^+ ions are donated by carbonic acid, and the reaction shifts to the RIGHT

2.15

a) $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+$

increasing $[CO_2]$ will drive the reactions to the RIGHT, increasing $[H^+]$

b) $HCO_3^- \rightleftharpoons CO_3^{2-} + H^+$

A lower pH means an increasing $[H^+]$, which will drive this reaction to the LEFT, thus decreasing $[CO_3^{2-}]$

c) $CO_3^{2-} + Ca^{2+} \rightleftharpoons CaCO_3$

with less CO_3^{2-} available to react with Ca^{2+}, calcification rate would be expected to decrease.