Solution Manual for Biological Science 6th Edition by Freeman Quillin Allison Black Taylor Podgorski Carmichae ISBN 9780321976499 0321976495

CHAPTER
2

Water and Carbon: The Chemical Basis of Life

Learning Objectives: *Students should be able to...*

- Describe the structure of an atom and the role of electrons in forming bonds and interactions between atoms that form molecules.
- Explain how the structure of water molecules relates to water's unusual properties and to its importance to life.
- Define a chemical reaction and the role of energy and entropy in determining if a reaction will be spontaneous or not.
- Describe the chemical evolution theory and evaluate the two models proposed to explain the process component.
- Describe the six major functional groups attached to carbon atoms, their structural formulas, and their basic characteristics.

Lecture Outline

- Scientific explanation of how life on Earth began:
  1. Pattern component—Both small molecules and complex carbon-containing molecules are required for life.
  2. Process component—Simple chemical compounds combined to make more complex chemicals and compounds that eventually led to the first life-form (evolution).
  3. This entity became the first life-form from which all life has descended.
- Switch from chemical evolution to biological evolution, which is governed by natural selection.

I. Atoms, Ions, and Molecules: The Building Blocks of Chemical Evolution

A. Four atoms make up 96 percent of every organism:

1. Carbon, hydrogen, oxygen, and nitrogen
2. Physical structure of these atoms (C, H, O, and N) affects the function of the molecules that they form.
3. Small molecules formed (water, carbon dioxide, etc.) are building blocks for more complex structures required for chemical evolution and, ultimately, life.

B. Basic atomic structure

  1. Structure of an atom **(Fig. 2.1a)**

    a. Nucleus

        - **(1)** Protons: large, in nucleus, positive charge
            - **(i)** The number of protons gives an atom its chemical identity.
            - **(ii)** Number of protons does not vary = atomic number. **(Fig. 2.2)**
        - **(2)** Neutrons: large, in nucleus, no charge
            - **(i)** The number of neutrons does not affect the atom's chemical identity but affects its mass.
            - **(ii)** Number of neutrons can vary in an element, and these are called isotopes. (Example: ^{14}C has 6 protons and 8 neutrons and is considered an unstable isotope that decays into ^{14}N when one neutron decays to a proton making 7 protons and 7 neutrons.)
            - **(iii)** Number of protons + number of neutrons = atomic mass (based on average of all naturally occurring isotopes of an atom).
    - **b.** Orbitals
        - **(1)** Electrons: travel in orbital, have negligible mass and a negative charge
        - **(2)** Most of an atom's volume is empty space found in the orbitals.
        - **(3)** Atoms that have the same number of electrons as protons have no charge (electrically neutral).
- **2.** Measuring mass of electrons, protons, and neutrons
    - **a.** Dalton—mass of one proton or one neutron equals approximately one Dalton; electrons are so small they are considered to have no mass.
    - **b.** Carbon has 6 protons and 6 neutrons and an atomic mass of ≈12 daltons (^{12}C).
    - **c.** If carbon had 6 protons and 7 neutrons, it would have an atomic mass of 13 (^{13}C); ^{12}C and ^{13}C are isotopes.
- **3.** Movement of electrons around the nucleus of an atom
    - **a.** Electrons move around the nucleus in orbitals.
    - **b.** Each orbital has two electrons.
    - **c.** Orbitals are organized into shells numbered 1, 2, 3, etc.
    - **d.** Orbitals are more distant from the nucleus as the shell number increases.
    - **e.** Each shell has a specific number of orbitals (a shell with one orbital can thus hold two electrons, while a shell with four orbitals can hold eight electrons).
    - **f.** Electrons fill the shells closest to the nucleus first before filling any outer shells.
- **4.** The outermost shell is called the valence shell and contains valence electrons.
    - **a.** Electrons in the outermost shell of the highlighted atoms in **Figure 2.3** have unpaired electrons (at least one) in their valence shell.
    - **b.** Number of unpaired electrons = atom's valence. (Example: Carbon has four valence electrons.)
    - **c.** An atom is most stable when its valence shell is filled with electrons.
    - **d.** Filling outer shells can be accomplished by formation of chemical bonds that bind atoms together.
    - **e.** Sharing electrons between atoms results in the formation of a covalent bond.

C. How does covalent bonding hold molecules together?

  1. How does a hydrogen atom, with one unpaired valence electron, become stable? The outer shell can only hold a total of two electrons.

    a. By pairing together two hydrogen atoms, each atom can share its electron with the other atom's valence shell.

    b. By sharing, both outer shells are now full.

    c. Sharing of electrons between two hydrogens results in H–H or H_2, a molecule of hydrogen. **(Fig. 2.4)**

    d. A molecule results when covalent bonds are formed by sharing electrons between atoms (two or more).

    e. Covalent bonds result from the attraction between protons in the atom's nucleus and the surrounding electrons; the attraction must be stronger than the repulsion of positively charged nuclei to each other or repulsion of electrons by one another to make a covalent bond.

  2. Equal sharing of electrons between atoms results in a covalent bond that is nonpolar. Examples: H−H bonds and C−H bonds. **(Fig. 2.5a)**

  3. Unequal sharing of electrons (if the electrons are pulled closer to one of the atom's nuclei) results in a covalent bond that is polar. **(Fig. 2.5b)**

    a. The tendency of an atom to hold electrons tightly is referred to as electronegativity and results from the number of protons in the nucleus and the distance of the shells from the nucleus.

    b. Atoms with increasing electronegativity are observed on the periodic table when moving from left to right in any given row (more electrons).

    c. Atoms decrease in electronegativity on the periodic table going down any column (increasing distance from nucleus).

    d. Polar covalent bonds result in partial charges (δ) on certain parts of the molecule. (Example: water) **(Fig. 2.5b)**

  4. Single bonds share one pair of electrons, double bonds share two pairs, and triple bonds share three pairs. **(Fig. 2.8b, c)**

D. Ionic bonding, ions, and the electron-sharing continuum

  1. In an ionic bond, the electron(s) is lost entirely from one atom and donated to the other atom, usually resulting in a filled outer shell for each atom. **(Fig. 2.6a)**

  2. The donor atom carries an extra (+) charge (cation); the recipient atom carries one less (–) charge (anion). (Example: sodium chloride) **(Fig. 2.6b, c)**

  3. A sodium chloride molecule, where the sodium ions and the chloride ions pack together tightly, results from the strong attraction between the ions that create the salt crystals.

  4. The degree of sharing of electrons exists on a continuum; equal sharing of covalent nonpolar bonds, unequal sharing of polar covalent bonds, and complete sharing of ionic bonds. **(Fig. 2.7)**

E. Some simple molecules formed from C, H, N, and O

  1. There are four atoms required for most of life molecules.

  2. Valence shells of each show how many covalent bonds each atom can form.

        - **a.** H = 1
        - **b.** O = 2
        - **c.** N = 3
        - **d.** C = 4
    - **3.** Molecules form from single, double, and triple bonds between atoms. **(Fig. 2.8)**
        - **a.** Methane—CH_4 (single bonds)
        - **b.** Ammonia—NH_3 (single bonds)
        - **c.** Water—H_2O (single bonds)
        - **d.** CO_2 (double bonds)
        - **e.** N_2 (triple bonds)
    - **4.** ***Students should be able to draw arrows between the atoms in each molecule shown in* Figure 2.8 *to indicate the relative position of the shared electrons. If the electrons are equally shared, then students should draw a double-headed arrow.***
- **F.** The geometry of simple molecules
    - **1.** The shape of molecules depends on the atoms bound to one another and the shapes of the electron orbitals for each bound atom.
    - **2.** CO_2 and N_2 are linear.
    - **3.** Methane (CH_4) is tetrahedral, with the electron pairs in each C–H orbital trying to get as far away from one another as possible. **(Fig. 2.9a)**
    - **4.** Water is a bent two-dimensional structure. **(Fig. 2.9b)**
        - **a.** Four orbitals are in oxygen’s outer valence shell.
        - **b.** Two orbitals have pairs from the oxygen atom.
        - **c.** Two orbitals have mixed shared pairs from oxygen and hydrogen.
        - **d.** All four orbitals repel each other.
- **G.** Representing molecules **(Fig. 2.10)**
    - **1.** Molecular formula shows types and numbers of atoms but nothing about shape.
    - **2.** Structural formula display which atoms are bound to one another and what types of bonds bind the atoms together; geometry is also displayed.
    - **3.** Ball-and-stick models show a 3-dimensional representation of molecules and the relative size and shape of the overall structure.
    - **4.** Space-filling model is the most accurate 3-dimensional spatial depiction of a molecule.
    - **5.** Specific colors in models denote particular atoms, with black representing carbon, blue representing oxygen, and red representing nitrogen.
    - **6.** Building blocks for chemical evolution existed in volcanic gases, in deep-sea hydrothermal vents, and in the atmospheres of nearby planets.
    - **7.** Chemical evolution hypothesis suggests that these building blocks combined into more complex molecules in an aqueous (water-based) environment that facilitated the reactions necessary for this evolution.

II. Properties of Water and the Early Oceans

- **A.** Life is based on water.
    - **1.** Life arose in an aqueous environment.
    - **2.** Every cell is approximately 75 percent water (volume), making it the most abundant molecule in living organisms. **(Fig. 2.11)**

3. Humans can survive weeks without eating, but only three to four days without drinking water.

B. Water is an efficient solvent—an agent for dissolving substances into a solution.

1. O–H bonds are polar due to high electronegativity of oxygen and display partial positive and negative charges.
2. H_2O is a bent molecule because the partial negative charge on oxygen points away from the partial positive charges on the hydrogen atoms.
3. Weak electrical interactions between two water molecules allow the partially negative charge of the oxygen atom of water to be attracted to the partially positive charges on a hydrogen atom on an adjoining water molecule, forming a hydrogen bond. **(Fig. 2.12)**
4. ***Students should understand why the shape of the water molecule results in hydro-gen bonding that is stronger than if the water molecule were to be linear.***
5. ***Students should be able to (a) draw a fictional version of*** **Figure 2.12b** ***that shows water as a linear (not bent) molecule with partial charges on the oxygen and hydro-gen atoms and (b) explain why electrostatic attractions between such water mole-cules would be much weaker as a result.***
6. Hydrogen bonding in water allows for most charged and polar molecules to form hydrogen bonds and dissolve in water (hydrophilic).
7. Uncharged and nonpolar molecules do not interact with water and are called hydrophobic. **(Fig. 2.13)**
8. Hydrogen bonds are not as strong as covalent or ionic bonds, but they are critical to life because of the sheer number of them that form between water and hydrophilic molecules.

C. What properties are correlated with water's structure?

1. Cohesion is the attraction between like molecules. **(Fig. 2.14a)**
   - **a.** The meniscus in a tube of water displays water at the bottom of the meniscus that is lower than the sides because of the attraction of water molecules to one another (pulling one another down).
2. Adhesion is the attraction between unlike molecules; the sides of the meniscus with a tube of water results from cohesion between the water molecules and the tube's walls, pulling the water at the sides up toward the tube.
3. Water displays surface tension due to cohesion; hydrogen bonding between water molecules or with other hydrophilic substances resists forces that would increase surface area, creating an "elastic membrane." **(Fig. 2.14b)**
4. Water is denser as a liquid than a solid (there are more water molecules in a given volume of liquid water than the same volume of solid water, or ice).
   - **a.** Number of hydrogen bonds per water molecule in ice is four, which is more than in liquid water; as such, water molecules in the liquid phase can pack more densely together.
   - **b.** Ice is less dense than water and floats. Ice stays on top of the water, providing a layer of insulation for the water below; if ice did not float, it would fall to the bottom of lakes and oceans and would never melt. **(Fig. 2.15)**
5. Water has a high capacity to absorb energy; this means that as heat hits water molecules, it takes a lot of heat to break the hydrogen bonds of the water molecules

before those molecules can begin moving more quickly (heat becomes kinetic energy to move the water molecules faster); specific heat is the amount of energy required to raise the temperature of 1 gram of a substance 1˚C. **(Table 2.1)**

- **a.** The amount of hydrogen bonding of a molecule correlates with the molecule’s specific heat; polar molecules display higher specific heat values than nonpolar molecules because it requires more energy to break the increased number of hydrogen bonds.
- **b.** Water has a high heat of vaporization because of hydrogen bonding, which prevents the conversion of water from liquid to gas; heat of vaporization is the amount of heat required to change 1 gram of a liquid substance to gas.
- **c.** Evaporation of water from your body, when you sweat or put water on your body when it is hot, removes heat as it changes from the liquid to gas phase.

6. The protection of forming molecules in Earth’s ocean during chemical evolution from the high energy of the sun’s radiation is critical to the evolution of higher-order molecules.

7. **Table 2.2** summarizes the key properties of water.

D. The role of water in acid–base reactions

1. Water molecules continuously undergo a chemical reaction (when one substance is combined with others or broken down into another substance; or when atoms undergo rearrangements, usually with chemical bonds being broken and made).

- **a.** Water can undergo dissociation: $H_2O \leftrightarrows H^+ + OH^-$.
- **b.** The dissociation of water is completely reversible, denoted by the double arrows.
- **c.** Water dissociates into hydrogen (H^+) ions and hydroxide ions (OH^-); but protons (H^+) do not exist by themselves and instead associate with a water molecule to form a hydronium ion (H_3O^+) in the following reaction: $H_2O + H_2O \leftrightarrows H_3O^+ + OH^-$.

2. Acids donate protons during a chemical reaction; bases accept protons; water acts as both an acid and a base; however, it is a weak base with very few water molecules donating protons to make hydronium ions.

3. Strong acids readily give up a proton, such as hydrochloric acid (HCl): $HCl + H_2O \leftrightarrows H_3O^+ + Cl^-$.

4. Strong bases readily accept protons, such as sodium hydroxide (NaOH): $NaOH(aq) \rightarrow Na^+ + OH^-$and $OH^- + H_3O^+ \leftrightarrows 2\ H_2O$. Determining the concentration of protons:

- **a.** There is no way to count the actual number of protons.
- **b.** A mole is 6.022×10^{23}.
- **c.** A mole of a substance is equal to its molecular weight in grams; example of water = 1+1+16 = 18 approximately; thus, 18 g of water would be approximately 6.02×10^{23} molecules, or 1 mole.
- **d.** Substances dissolved in water have a concentration based on molarity; number of moles of a substance in 1 L of water is molarity; 1 mole of protons (H^+) in a liter of water would be a 1 molar solution of protons. A 1 L sample of pure water has $1.0 \times 10^{-7 M\ H+}$.

5. The pH of a solution determines whether it is acidic or basic.

- **a.** Concentration of protons is so small, chemists and biologists use the logarithmic notation, $pH = -\log [H^+]$; solving the equation for $[H^+] = \text{antilog} (-pH) = 10^{-pH}$. **(Fig. 2.16)**

- **b.** Solutions with proton concentrations > 1×10^{-7} M are acidic (pH<7); solutions with proton concentrations <1×10^{-7} M are basic (pH>7).
- **c.** ***Students should understand that a change of pH from 7 to 5 represents a solution that has 100-fold more protons and is 100 times more acidic.***
- **d.** ***Students should be able to calculate the concentration of protons in a solution that has a pH of 8.5.***
- **e.** Pure water is a standard on the pH scale, and living cells have a pH of approximately 7 (neither acidic or basic, but neutral).
- **f.** Living organisms are sensitive to changes in pH.
- **g.** Compounds that minimize changes in pH are buffers (weak acids); buffers protect cells and maintain homeostasis.
- **h.** Buffers are usually weak acids, willing to give up protons in solution; when many protons are present, acids are regenerated.
- **i.** Carbonic acid dissociates to bicarbonate and a proton: $CH_2O_3 \leftrightarrows CHO_3^- + H^+$.
- **j.** If carbonic acid and bicarbonate are in equal concentrations, they act as a buffer; when protons are incrementally increased, they combine with bicarbonate and form carbonic acid and the pH does not change; when protons are slightly decreased, carbonic acid dissociates and the pH does not change.
- **k.** ***Students should be able to predict what would happen to the concentration of bicarbonate ions if a base like sodium hydroxide (NaOH) were added to the solution of carbonic acid.***

III. Chemical Reactions, Energy, and Chemical Evolution

- **A.** Theory of chemical evolution suggests that simple molecules combined to create complex organic (carbon-containing) molecules—proteins, nucleic acids, sugars, and lipids.
  - **1.** Environments where chemical evolution occurred
    - **a.** Atmosphere—gases ejected from volcanoes (CO_2, N_2) with water vapor, H_2, and CO.
    - **b.** Deep-sea hydrothermal vents—rich in CO_2 and H_2 and minerals such as nickel and iron.
- **B.** How do chemical reactions happen?
  - **1.** In a chemical reaction, reactants are converted into products.
    - **a.** Most common reaction in gases from volcanoes is water and CO_2 to produce carbonic acid (acid rain).
    - **b.** Balanced equation: $CO_2\ (g) + H_2O\ (l) \leftrightarrows CH_2O_3\ (aq)$ demonstrating the conservation of mass in closed system.
  - **2.** Most reactions are reversible, denoted by $\leftrightarrows$.
  - **3.** Chemical equilibrium:
    - **a.** Rate of forward reaction equals rate of reverse reaction; equilibrium is dynamic but stable; quantities of reactants and products are not necessarily equal.
    - **b.** Equilibrium can be disturbed by adding or removing reactant or product or by altering the temperature.
  - **4.** Reactions that absorb heat are endothermic; reactions that release heat are exothermic.

C. What is energy?

- **1.** Energy is the capacity to do work or supply heat.
- **2.** Examples of different forms of energy:
  - **a.** Potential energy = stored energy **(Fig. 2.17)**
    - **(1)** The potential energy in chemical bonds is called chemical energy and derives from electrons in outer shells trying to occupy the shell closest to the nucleus of the atom possible; an electron in an outer shell far from the nucleus has more potential energy than one close to the nucleus.
  - **b.** Kinetic energy = energy of motion
    - **(1)** The kinetic energy of molecular motion is called thermal energy.
    - **(2)** Temperature equals the amount of thermal energy possessed by a molecule (cold objects have slowly moving molecules; hot objects have quickly moving molecules).
    - **(3)** Heat—the transfer of energy between two molecules when they meet.
- **3.** First law of thermodynamics: Energy is not created or destroyed; it just changes form or is transferred.
  - **a.** Chemical evolution resulted from the transfer of energy during the early Earth years, with energy input from radiation, electricity in lightning, and energy stored in chemical bonds.

D. What makes chemical reactions spontaneous?

- **1.** Spontaneous chemical reactions are those that proceed on their own without any added energy.
  - **a.** Reactions tend to be spontaneous if the products are less ordered than the reactants; example is explosion of nitroglycerin into CO_2, N_2, and H_2O with the release of heat.
    - **(1)** Amount of disorder is called entropy.
    - **(2)** Entropy increases when products of reaction are more disordered than reactants.
    - **(3)** Second law of thermodynamics states that entropy increases in a closed system.
  - **b.** Reactions tend to be spontaneous if the products have a lower potential energy than reactants.
    - **(1)** If electrons are held more tightly in products than in the reactants, then the product has lower potential energy.
    - **(2)** Equal sharing of electrons in molecules such as H_2 or O_2 results in higher potential energy than in H_2O, where the electronegative oxygen holds the electrons tighter than in O_2.
    - **(3)** In the reaction of $H_2 + O_2 \rightarrow H_2O$, entropy decreases, but the potential energy of the products is much lower than the reactants, and a large drop in potential energy as heat results in the reaction occurring spontaneously. **(Fig. 2.18)**
    - **(4)** Spontaneous processes result in lower potential energy, increased disorder, or both. **(Fig. 2.19)**

IV. Model Systems for Investigating Chemical Evolution

A. To probe the kinds of reactions that have set chemical evolution in motion, researchers focus on small molecules that were present on early Earth.

    1. Prebiotic soup model—molecules were synthesized from gases in atmosphere or on meteorites; these molecules ended up in the oceans upon condensation; additional reactions resulted in more complex molecules.
    2. Surface metabolism model—surface gases contacted minerals near deep-sea ocean vents and resulted in reactions generating more complex molecules.
- **C.** Early origin-of-life experiments
    1. Stanley Miller, a graduate student, designed prebiotic soup experiment by simulating early Earth's atmosphere and conditions. **(Fig. 2.20)**
        - **a.** Large flask with "mini atmosphere" containing CH_2, NH_3, and H_2
        - **b.** Connected to small flask containing boiling water (ocean)—added water vapor
        - **c.** Collected water vapor that cooled and condensed and sent it back into boiling water (mimicking rain)
        - **d.** Nothing happened without the addition of energy as electrical charges (simulating lightning bolts).
        - **e.** Solution turned pink to dark red and cloudy due to formation of hydrogen cyanide and formaldehyde.
- **D.** Recent origin-of-life experiments
    1. Miller experiment criticized for including CH_4 and NH_3
    2. Synthesis of molecules (precursors of life) using light energy
    3. Synthesis of formaldehyde from carbon dioxide and hydrogen (CO_2 (g) + 2 H_2 (g) → CH_2O (g) + H_2O (g)) may have played a large role in chemical evolution.
        - **a.** Heating formaldehyde can result in higher-order molecules being formed, such as sugars (requiring a large input of energy). Early Earth was probably bombarded with high-energy photons, which can break molecules apart to form highly reactive free radicals. **(Fig. 2.21)**
        - **b.** Ozone was not present in appreciable amounts in early atmosphere and did not protect Earth from high-energy photons.
        - **c.** Free radicals resulting from high-energy photons hitting molecules are thought to be responsible for some of the key reactions in early chemical evolution; they contain unpaired electrons in their outermost shells, making them highly reactive.
    4. Experiments modeling conditions on early Earth indicate that formaldehyde (H_2CO) would have formed.
    5. Experiments also showed that HCN (hydrogen cyanide) would have formed—another precursor for life.
        - **a.** Thus, key intermediates in forming larger organic molecules would have formed and rained down into oceans. **(Fig. 2.22a)**
    6. Chemical energy and chemical evolution
        - **a.** During chemical evolution, the energy in sunlight was converted to chemical energy (the potential energy stored in chemical bonds).
    7. This allowed for larger, more organized molecules to be formed from smaller, simpler ones.
    8. Hydrothermal vents
        - **a.** Surface metabolism model to account for the potential dilution of formaldehyde and hydrogen cyanide in Earth's early oceans

        - **(1)** Reactants recruited to defined space—reactive minerals present on walls of deep-sea vent chimneys **(Fig. 2.22b)**
        - **(2)** Minerals play a critical role in rate of reactions as catalysts.
        - **(3)** Catalysts influence only the rate of reactions and does not provide energy for reactions.
        - **(4)** Example reaction: Carbon dioxide and hydrogen react to synthesize acetic acid ($2\ CO_2\ (aq) + 4\ H_2\ (aq) \rightarrow CH_3COOH\ (aq) + 2\ H_2O\ (l)$).
            - **(i)** Spontaneous—driven by energy in reactants
        - **(5)** Acetic acid can form under the conditions present at hydrothermal vents.
        - **(6)** Acetic acid is important in the synthesis of Acetyl CoA (important throughout the tree of life).
        - **(7)** Data suggests that minerals from thermal vents are the original source of catalysts used in modern reactions.
        - **(8)** Precursors for synthesis of nucleotides (molecules of inheritance) also found in experiments mimicking the surface metabolism conditions

V. The Importance of Organic Molecules

- **A.** Carbon atoms provide the structural framework for important compounds for life (excluding water).
    - **1.** Carbon atoms can be linked together in long chains such as octane in gasoline. **(Fig. 2.23a)**
    - **2.** Carbon atoms can be linked together in rings, such as in the sugar glucose. **(Fig. 2.23b)**
- **B.** Functional groups
    - **1.** Carbon atoms create the framework for a molecule's overall shape.
    - **2.** Addition of H-, N-, O-, P- —or S-containing groups, which are functional groups—to a carbon skeleton imparts a variety of chemical reactivities to carbon molecules. **(Table 2.3)**
    - **3.** There are six major functional groups:
        - **a.** Amino groups function as bases, attracting protons in solution.
        - **b.** Carboxyl groups function as acids, dropping protons in solution.
            - **(1)** Important amino- and carboxyl-containing molecules are amino acids.
            - **(2)** NOTE: More than one functional group may occur on any molecule.
            - **(3)** Covalent bonds can form between amino- and carboxyl-groups.
            - **(4)** Amino- and carboxyl-groups participate in H–bonding.
        - **c.** Carbonyl groups are found on aldehydes and ketone molecules.
        - **d.** Hydroxyl groups are highly soluble in water and act as weak acids; hydroxyl groups are polar, tend to form H–bonds, and are soluble in water.
        - **e.** Phosphate groups have two negative charges and can affect the shape of the molecule or a molecule to which they are transferred; large amounts of chemical energy are stored in phosphate bonds.
        - **f.** Sulfhydryl groups can link two molecules via disulfide bonds.
    - **4.** Functional groups attached to a carbon framework decide how a molecule is going to "behave." When examining new compounds, do the following:

a. Look at the overall shape based on carbon atoms.

b. Note where covalent bonds localize and where polarities exist.

c. Identify functional groups to predict functions associated with the molecule.

Chapter Vocabulary

To emphasize the functional meanings of these terms, the list is organized by topic rather than by first mention in the chapter. It includes terms that may have been introduced in earlier chapters but are important to the current chapter as well. It also includes terms other than those highlighted in bold type in the chapter text.

H
S
acetaldehyde
acid
acid–base reaction
acidity
adhesion
alcohol
aldehyde
alkalinity
amino group
anion
aqueous
atom
atomic number
atomic weight
ball-and-stick model
base
buffer
carbon
carbonyl group
carboxyl group
carboxylic acid
catalyst
cation
chemical bond
chemical energy
chemical equilibrium
chemical evolution
chemical reaction
cohesion
concentration
covalent bond
dalton
disulfide bond
double bond
electron
electron shell
electronegativity
element
endergonic
endothermic
energy
entropy
evolution
exergonic
exothermic
first law of thermodynamics
formaldehyde
free radicals
functional groups
Gibbs free energy
heat
heat of vaporization
homeostasis
hydrogen
hydrogen bond
hydrogen ion
hydrophilic
hydrophobic
hydrophobic interactions
hydroxide ion
hydroxyl group
inorganic molecules
ion
ionic bond
isotope
ketone
kinetic energy
LUCA
mass number
mechanical energy
meniscus
molarity
mole
molecular formula
molecular weight
molecule
neutron
nitrogen
nonpolar covalent bond
nonspontaneous chemical reactions
nucleus
orbital
organic compounds
organic molecules
organic phosphate
oxygen
ozone
pH
pH scale
phosphate group
photons
polar covalent bond
polarity
potential energy
prebiotic soup model
product
proton
radioactive isotope
reactant
second law of thermodynamics
single bond
solute
solution
solvent
space-filling model

specific heat
spontaneous chemical reactions
structural formula
sulfhydryl group
surface metabolism model
surface tension
system
temperature
thermal energy
triple bond
valence
valence electron
valence shell

Lecture Activities

Student-Led Concept Illustrations

Estimated duration of activity: A few minutes as you lecture

Often, getting students involved is as simple as having them illustrate a phenomenon in their own terms. The following questions can be presented to students, allowing them to explain these concepts in terms that their peers can understand.

Types of chemical bonds: After describing hydrogen, covalent, and ionic bonds, ask the students to come up with nonbiological analogies to these types of bonds. You can start their thinking by comparing the molecules in covalent bonds to partners in a three-legged race. Another chemical-bond analogy that students tend to identify with is different levels of interpersonal relationships: Hydrogen bonds are analogous to acquaintances, ionic bonds are analogous to dating relationships, and covalent bonds are analogous to marriages. Ask the students to explain why each type of bond can be represented by each type of interpersonal relationship.

The properties of water: After explaining water's unique properties, ask students to explain the following phenomena:

- A leaf can land on the water's surface, but a rock sinks.
- There is less variation between day and night temperatures at the beach than between day and night temperatures in the desert.
- Salt dissolves in water, but gasoline does not.
- All mammals that live in hot environments keep themselves cool using only two mechanisms: sweating and/or panting.

Energy: After introducing different forms of energy, ask students what sort of energy transformation is occurring in the following common daily activities. (Once they have the idea, you may challenge them to come up with additional examples.)

- Rubbing hands together to get warm (mechanical energy to thermal energy)
- Hearing (sound energy to mechanical energy; sound waves cause our eardrums to vibrate)
- A plant growing (electromagnetic energy to chemical energy; photosynthesis)
- A person riding a bicycle (chemical energy to mechanical energy)

Practicing BioSkills: Using Logarithms (BioSkills 5)

Estimated duration of activity: 15 minutes

Many introductory students are not familiar with the concepts of logarithms, scientific notation, and molarity. The pH scale is a good opportunity to review all three concepts.

First, model for students how to convert a concentration of hydrogen ions (e.g., 0.001 mole of hydrogen ions per liter) to scientific notation (1×10^{-3}) and then to pH (3). Ask students why there is a 3 in the first number (i.e., in the number 0.001, the 1 is three places away from the decimal point). Then write the formal pH equation:

$$\mathrm{pH} = -\log[\mathrm{H}^+]$$

It may be useful to "translate" this mathematical equation into English, such as: "*Log* is a formal way of asking, What's the exponent?"

When students understand the basic concepts of logarithms and scientific notation, have pairs of students work on these questions:

- What is the pH of a solution that has 0.01 mole of hydrogen ions per liter?
- What is the pH of a solution that has 0.0000001 mole of hydrogen ions per liter?
- A solution has a pH of 4. What is the molarity of H^+ ions?
- As the pH gets *higher*, does the concentration of hydrogen ions get lower or higher?
- A solution changes from pH 1 to pH 2. How much did the hydrogen-ion concentration change?

Allow 5 to 10 minutes, and then poll the class about their results, review the correct answers, and correct any misconceptions. Remind students that they can consult **BioSkills 5** for further practice with logarithms.

Concept-Processing Pairs

Estimated duration of activity: 10 to 20 minutes (depending on the level of student understanding and the number of items used)

This activity has two parts. Students are divided into pairs. One member of each pair is designated A and the other B.

Part 1, Paired review: Give students 3 to 5 minutes to clarify with each other the basic concepts of the chapter, such as:

- Types of chemical bonds
- Polarity
- Properties of water
- Solubility

Part 2, Elaborative questions: Have students take turns asking each other questions that test understanding. Designate who will attempt to answer the first question (i.e., pick either student A or student B to start; this saves time for the student pairs with too much inertia to decide for themselves who will start). The number of questions asked depends on the length of time allotted for the activity. Make sure adequate time is provided for each question. Students will need time to process their answers, hear your optimal answer, and then discuss their understanding. The purpose of the exercise is to help students recognize and repair misconceptions and holes in their understanding.

A typical agenda for this activity:

1 to 2 minutes: Student A explains the answer to the question (as best as s/he can).

1 to 2 minutes: Student B assesses and amends the answer (as best as s/he can).

1 minute: Instructor shares the optimal answer with the class.

1 to 2 minutes: Student pairs discuss their answer relative to the answer.

1 to 3 minutes: Instructor entertains questions from the class.

Repeat the process with another question.

Sample questions:

- A molecule of octane contains about six times the mass of a molecule of water. Neverthe-less, if one pours liquid octane onto liquid water, the octane floats on top of the water. How can this be?
- A salt crystal dropped into a beaker of water becomes smaller and eventually seems to disappear. However, the same salt crystal remains intact at the bottom of a beaker of octane. Explain.
- A beaker of water is allowed to sit underneath another, larger beaker placed upside down over it (thereby trapping air above the water). After a long period of time, a few air molecules are found in the water and a few water molecules are present in the air above the beaker. However, the air and the water mostly remain separated. Why?
- (Follow-up to the preceding question) Air contains mostly nitrogen (N_2) and oxygen (O_2). Explain how the structures of these two gases contribute to the observation in the preceding question.
- One liter of water is mixed with 0.2 L of table salt. After the salt is dissolved, the new volume is slightly greater than 1 L but much less than 1.2 L. Why?

Discussion Idea: Calories and Body Temperature

Students like to relate what they are learning to the processes that occur in their own bodies. While discussing Gibbs free energy and the laws of thermodynamics, you can relate these concepts to nutrition and body temperature. Begin by asking students these two questions:

- Why do you heat up when you exercise?
- Why is exercising said to “burn calories”?

Give students two hints: (1) In the field of nutrition, the calorie is a unit of energy; that is, if one serving of a food contains 50 “calories,” that food will release 50 kilocalories of energy when broken down by cells. (2) In any spontaneous reaction, at least some of the energy is converted into heat and is “lost” (cannot be captured in chemical bonds). With those two hints, students should be able to reach the following conclusions:

- The oxidation of food releases energy that is captured by cells in the bonds of ATP; that is, chemical energy in food molecules is converted into chemical energy in ATP molecules. Some energy is lost as heat.
- When you exercise, the energy in the bonds of ATP is used to fuel muscle contraction. Again, some of this energy is lost as heat.
- The more molecules of ATP a muscle uses, the more energy is lost as heat. Muscles rapidly heat up. They also rapidly “run out” of ATP molecules and soon need more food molecules to produce more molecules of ATP. (Students may be interested to learn that at maximum contraction, a muscle will run out of ATP molecules in just a few seconds. This is why athletes can sustain a maximum contraction such as in Olympic weight lifting for only a few seconds.)

Notes to Instructors

Chapter 2 Water and Carbon: The Chemical Basis of

Life What is the focus?

Living organisms function in the real world, so they are subject to all the laws of chemistry and physics. In addition, biological organisms and systems are variable. No two organisms are exactly alike, and no two systems are identical in form or function. As a result, our analysis of such systems tends to deal with statistical averages or probabilities. This means it is difficult to understand biological systems without having a good basic understanding of chemistry, physics, and math (including probability and statistics).

The vast majority of introductory biology students have studied inorganic chemistry in their high school and first-year college chemistry courses. Many students compartmentalize their knowledge, however. In some cases, the compartmentalization is so extreme that the students feel uncomfortable dealing with chemical formulas and ideas outside of chemistry classes. Therefore, it is generally useful to review some of the basic ideas in chemistry and, at the same time, demonstrate how they can be applied to understanding biological systems.

Activity 2.1 A Quick Review of Elements and

Compounds What is this activity designed to do?

The questions in this activity are designed to help students review and understand:

- atomic/molecular number, mass number, and atomic/molecular weight and how they can be used to determine the reactivity of elements
- various types of chemical bonds and how they affect the structure and energetics of molecules
- the difference between a mole and a molar equivalent and how knowledge of these can be used in biological applications

What misconceptions or difficulties can this activity reveal?
Question 1: Many students don’t understand that nutrients for plants are inorganic and most nutrients for animals (heterotrophs) are organic.

Questions 2 and 3: Most students know how to balance a chemical equation. Fewer understand the relationship between molecules of a substance and moles of that substance. Similarly, most students can recite what a mole is; however, the majority have not thought about how that knowledge can be applied. Therefore, much of this first

activity is devoted to making it clear that a balanced equation indicates not only the number of molecules required but also the number of moles required. It also explains why moles can be substituted for molecules in such equations.

Question 4: Some students have difficulty understanding that a solution's concentration or molarity does not change if you aliquot or subdivide the solution into smaller volumes. To test this, ask your students: "There is 10% sugar in this solution. If I pour half of it into one beaker and the other half into another beaker, what percent sugar will I have in each beaker?" More than half of the students will automatically answer 5%.

Questions 5 and 6: These questions are designed to help students understand how knowledge of balanced equations and molar equivalents can be useful in biology.

Questions 7 and 8: The answers go into a little more detail than *Biological Science*, 6th edition. Students obviously shouldn't be asked to know the specific electronegativity of each of the elements. However, using concrete numbers may help students understand how their electronegativity is related to the type of bonds formed between elements.

Activity 2.2 A Quick Review of the Properties of Water

What is this activity designed to do?

The questions in this activity are designed to help students review and understand the properties of water and how they support life. Students are asked to review these key properties:

- H_2O molecules are cohesive; they form hydrogen bonds with each other.
- H_2O molecules are adhesive; they form hydrogen bonds with polar surfaces.
- Water is a liquid at normal physiological (or body) temperatures.
- Water has a high specific heat.
- Water has a high heat of vaporization.
- Water's greatest density occurs at 4°C.

In addition, students review pH and how it is related to both the ionization constant of pure water and the concentration of H^+ ions in a solution.

What misconceptions or difficulties can this activity reveal?

Most students have no difficulty stating the properties of water and the definition of pH. On the other hand, not all of them have a good understanding of how these properties are related to biological and other phenomena. Therefore, some questions ask students to relate pH values to actual concentrations of H^+ ions in solution and to relate the properties of water to common experiences they have had in class or in life.

Extend Your Understanding

Activity 2.3 Are Silicon-based Life Forms Possible?

What is this activity designed to do?

This activity is a way to get students to think about biochemistry as the foundation for life on Earth.

What misconceptions or difficulties can this activity reveal?

This activity requires students to think in a new way about the building blocks of life and allows them to look at additional resources, evaluate those resources, and form an educated opinion about a question most of them would consider to be in the realm of science fiction.

Answers

Activity 2.1 A Quick Review of Elements and Compounds

1. Figure 2.3 (page 57 of *Biological Science*, 6th ed.) lists the chemical elements that occur naturally in the human body. Similar percentages of these elements are found in most living organisms.

a. In what abiotic (nonlife) chemical forms are these elements often found in nature?	b. In what chemical form(s) do animals need to obtain these elements?	c. In what chemical form(s) do plants need to obtain these elements?
These elements are most commonly found as CO_2, N_2, and O_2 in the atmosphere and as H_2O, PO_4, and S compounds• on Earth.	With the exception of oxygen and water, animals obtain most of these elements in the form of organic compounds.	Plants can obtain C as CO_2, N as ammonia or nitrates, phosphorus as phosphates, sulfur as sulfates, and so on. In other words, plants obtain these elements as inorganic compounds.

2. A chemical element cannot be broken down to other forms by chemical reactions. Each element has a specific number of protons, neutrons, and electrons.

   a. What is the name of the following element, and how many protons, neutrons, and electrons does it have?

11
Na
23

Name	Number of protons	Number of neutrons	Number of electrons
Sodium	11	11	12

b. What information do you need to calculate or determine the following?

The atomic number of an element	The mass number of an element	The weight in atomic mass units (daltons) of one atom of an element
The atomic number is equal to the number of protons (or electrons).	The mass number is equal to the number of protons plus the number of neutrons.	You can estimate the weight in amus as 1 amu per proton or neutron. Therefore, the weight in amus of an element is approximately• equal to the number of protons plus the number of neutrons.

c. What are the atomic number, mass number, and weight in atomic mass units (daltons) of the element shown in part a?

Atomic number	Mass number	Weight in atomic mass units
11	23	23

3. One mole of an element or compound contains $6.02 * 10^{23}$ atoms or molecules of the element or compound. One mole of an element or compound has a mass equal to its mass number (or molecular weight) in grams. For example, 1 mole of hydrogen gas (H_2) contains $6.02 * 10^{23}$ molecules and weighs 2 g.

a. What is the weight of 1 mole of pure sodium (Na)?	b. How many molecules of Na are in 1 mole of Na?
23 g	$6.02 * 10^{23}$

c. How would you determine how many grams are in a mole of any chemical element or compound?

A mole of any chemical element or compound is equal to the mass number in grams of that mole or compound. For example, the mass number of Na is 23; therefore, a mole of Na has a mass of 23 g. The mass number of water is 18; therefore, a mole of water has a mass of 18 g.

4. One atom of Na can combine with one atom of Cl (chlorine) to produce one molecule of NaCl (table salt).

a. If Cl has 17 electrons, 17 protons, and 18 neutrons, what is its mass number?	b. What is the mass number of NaCl?	c. How many grams of NaCl equal a mole of NaCl?
35	23+35=58	58 g

d. If you wanted to combine equal numbers of Na and Cl atoms in a flask, how much Cl would you have to add if you added 23 g of Na? (Explain the reasoning behind your answer.)

Twenty-three g of Na is equal to 1 mole of Na. A mole contains $6.02 * 10^{23}$ molecules of the substance. To add an equal number of molecules of Cl, you need to add 1 mole of Cl, or 35 g.

e. To make a one-molar (1 *M*) solution of NaCl, you need to add 1 mole of NaCl to distilled water to make a final volume of 1 L (1000 ml). A 1 *M* solution is said to have a molarity of 1. If you added 2 moles of NaCl to distilled water to make a final volume of 1 L, you would make a 2 *M* solution and its molarity would equal 2.

You make up a 1 *M* solution of NaCl.

How many molecules of NaCl are in the 1 *M* NaCl solution?	How many molecules of NaCl are there per ml of the solution?
You would have $6.02 * 10^{23}$ molecules in the liter.	To calculate the number of molecules per ml, divide $6.02*10^{23}$ by 1000 = $6.02 * 10^{20}$ molecules/ml.

f. Next, you divide this 1 *M* solution of NaCl into four separate flasks, putting 250 ml into each flask.

How many grams of NaCl are in each flask?	How many molecules of NaCl are in each flask?	How many molecules of NaCl are there per ml of distilled water?	What is the molarity of NaCl in each of the four flasks?
58/4 = 14.5 g	$6.02 * 10^{23}$ divided by 4 = $1.51 * 10^{23}$	$6.02 * 10^{20}$	1 *M*

5. The summary formula for photosynthesis is

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

a. How many molecules of carbon dioxide and water would a plant have to use to produce 3 molecules of glucose ($C_6H_{12}O_6$)?	b. How many moles of carbon dioxide and water would a plant have to use to produce 2 moles of glucose?
For each molecule of glucose produced, 6 molecules of carbon dioxide and 6 molecules of water are consumed. Therefore, the plant would need to use 18 molecules of each.	Because a mole of anything contains the same number of molecules, the plant would need to use 6 times as many moles of carbon dioxide and water, or 12 moles of each.

c. Refer to the summary formula for photosynthesis. If you know the number of molecules or moles of any of the reactants used (or products produced), how would you calculate the number of molecules or moles of all of the other reactants needed and products produced?

If the formula is balanced and if it is a true representation of the overall reactions that occur, then the numbers in front of each reactant and product indicate the molecular or molar equivalents required for the reactions.

Note: To represent the actual reactants required and products produced, the overall formula for photosynthesis is more correctly stated as:

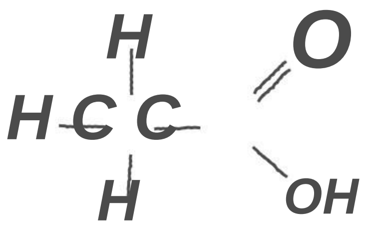
$$6\,CO_2 + 12\,H_2O \;S\; C_6H_{12}O_6 + 6\,O_2 + 6\,H_2O$$

In most texts, however, this is reduced to $6\,CO_2 + 6\,H_2O \;S\; C_6H_{12}O_6 + 6\,O_2$.

6. A biologist places a plant in a closed chamber. A sensor in the chamber maintains the carbon dioxide level at the normal atmospheric concentration of 0.03%. Another sensor allows the biologist to measure the amount of oxygen produced by the plant over time. If the plant produces 0.001 mole of oxygen in an hour, how much carbon dioxide had to be added to the chamber during that hour to maintain the atmospheric concentration of 0.03%?

   For every mole of oxygen produced, 1 mole of carbon dioxide had to be consumed. Therefore, 0.001 mole of carbon dioxide had to be added to maintain a constant level of CO_2 in the chamber.

7. Refer to pages 57–61 of your textbook for a description of these types of chemical bonds: nonpolar and polar covalent bonds, ionic bonds, and hydrogen bonds. (The molecule diagrammed here can also be represented by the formula CH_3COOH.)



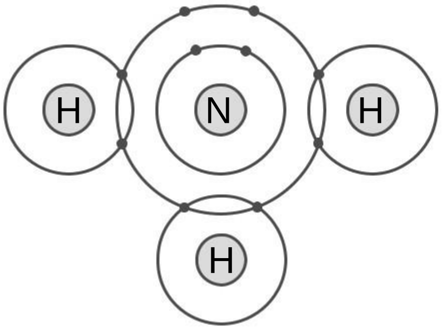
Explain how you could determine which of the bonds between elements in this molecule are polar or nonpolar covalent bonds, ionic bonds, and hydrogen bonds, and van der Waals interactions.

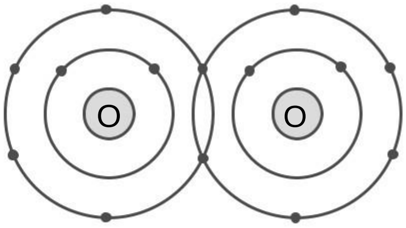
The best way to determine the type of bond is to determine each atom’s electronegativity, or its attraction for electrons. As a general rule, the more filled the outer electron shell of an atom, the higher its electronegativity. In addition, the fewer electron shells, the greater the electronegativity. As a result, an atom’s attraction for electrons increases as you go from left to right in the periodic table. Electronegativity values tend to decrease as you go from top to bottom of the periodic table. To determine whether bonds are ionic, polar covalent, or nonpolar covalent, you need to determine the difference in electronegativity between the atoms that make up a molecule. If the difference in electronegativity is small, the bond is likely to be nonpolar covalent. If the difference is very large, the bond is likely to be ionic. Intermediate differences produce polar covalent bonds. The table lists specific electronegativity values for selected elements.

H=2.1						
Li = 1.0	Be = 1.5	B=2.0	C=2.5	N=3.0	O=3.5	F=4.0
Na = 0.9	Mg = 1.2	Al = 1.5	Si = 1.8	P=2.1	S=2.5	Cl = 3.0

Using specific electronegativity values, you can determine the type of bond: If the difference in electronegativity between two atoms in a compound is less than 0.5, the bond is nonpolar covalent. If the difference is between 0.5 and 1.6, the bond is polar covalent. If the difference is greater than 1.6, the bond is ionic.

8. O_2 and NH_3 are both small covalent molecules found in cells. NH_3 is extremely soluble in the aqueous environment of the cell, whereas O_2 is relatively insoluble. What is the basis for this difference in solubility between the two molecules? In reaching your answer, draw the structures of the molecules as valence shell diagrams (as in Figure 2.8, page 60). Given these diagrams, consider the types of interactions each molecule could have with water.

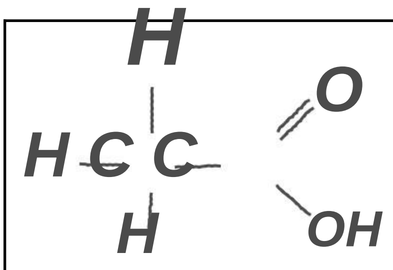




Ammonia is a polar molecule much like water. The N in it is relatively negative, and the H’s are relatively positive. Polar substances tend to be more soluble in water. O_2, on the other hand, is not polar.

Activity 2.2 A Quick Review of the Properties of Water

1. Compounds that have the capacity to form hydrogen bonds with water are said to be hydrophilic (water loving). Those without this capacity are hydrophobic (water fearing).

	Is the molecule on the left hydrophilic or hydrophobic? Explain your answer. This molecule is acetic acid. The –COOH group is polar, which makes this molecule hydrophilic.

2. In addition to being polar, water molecules can dissociate into hydronium ions (H_3O^+, often described simply as H^+) and hydroxide ions (OH^-). The concentration of each of these ions in pure water is 10^{-7}. Another way to say this is that the concentration of hydronium ions, or H^+ ions, is one out of every 10 million molecules. Similarly, the concentration of OH^- ions is one in 10 million molecules.

   a. The H^+ ion concentration of a solution can be represented as its pH value. The pH of a solution is defined as the negative $\log_{10}$ of the hydrogen ion concentration. What is the pH of pure water?
   The hydrogen ion concentration of pure water is 10^{-7}. The $\log_{10}$ of 10^{-7} is –7. The negative $\log_{10}$ of 10^{-7} is therefore 7.

   b. Refer to the diagram of the molecule of acetic acid in question 1. The –COOH group can ionize to release an H^+ ion into solution. If you add acetic acid to water and raise the concentration of H^+ ions to 10^{-4}, what is the pH of this solution?
   The pH of a solution with an H^+ ion concentration of 10^{-4} is 4.

3. Life as we know it could not exist without water. All the chemical reactions of life occur in aqueous solution. Water molecules are polar and are capable of forming hydrogen bonds with other polar or charged molecules. As a result, water has the following properties:

A. H_2O molecules are cohesive; they form hydrogen bonds with each other.
B. H_2O molecules are adhesive; they form hydrogen bonds with polar surfaces.
C. Water is a liquid at normal physiological (or body) temperatures.
D. Water has a high specific heat.
E. Water has a high heat of vaporization.
F. Water's greatest density occurs at 4°C.

Explain how these properties of water are related to the phenomena described in parts a–h below. More than one property may be used to explain a given phenomenon.

a. During the winter, air temperatures in the northern United States can remain below 0°C for months; however, the fish and other animals living in the lakes survive.

Water is most dense at 4°C. In a lake, the 4°C water sinks below water that is colder or warmer. In addition, as it freezes, water takes on a crystalline structure and becomes ice. Ice has a density of about 0.92 g/cm^3, pure water at 0°C has a density of about 0.99 g/cm^3, and pure water at 4°C has a density of 1.0 g/cm^3. The ice on top of a lake acts like insulation and, as a result, most deep lakes do not freeze all the way to the bottom.

b. Many substances—for example, salt (NaCl) and sucrose—dissolve quickly in water.

Water is very polar. The attraction of the polar water molecules for the Na^+ and Cl^- ions of NaCl is strong enough to allow them to dissociate and interact with water molecules (dissolve).

c. When you pour water into a 25-ml graduated cylinder, a meniscus forms at the top of the water column.

Water is attracted to the polar molecules that make up the glass (or plastic) cylinder. At the same time, they are attracted to each other. As a result, some of the water molecules associate with the polar molecules of the cylinder and are apparently “pulled up” the inside edge of the cylinder.

d. Sweating and the evaporation of sweat from the body surface help reduce a human’s body temperature.

Water has a high specific heat. The specific heat of water is 1 cal/g/°C. In other words, it takes 1 calorie of heat to change the temperature of 1 g of water 1°C. In addition, water has a high latent heat of vaporization (540 cal/g at 100°C). This can be thought of as the additional heat required to break apart polar water molecules so that they can move from the liquid to the gaseous state. As a result, evaporation (change of water from liquid to gaseous state) carries with it large amounts of heat.

e. A bottle contains a liquid mixture of equal parts water and mineral oil. You shake the bottle vigorously and then set it on the table. Although the law of entropy favors maximum randomness, this mixture separates into layers of oil over water.

The oil molecules are nonpolar and hydrophobic. The water molecules are polar and cohesive. As a result, the water molecules tend to interact strongly with each other and exclude the oil molecules. The oil layers on top of the water because it is less dense than water.

f. Water drops that fall on a surface tend to form rounded drops or beads.

Water molecules are cohesive and form hydrogen bonds with each other. As a result, a drop of water tends to bead up or become rounded.

g. Water drops that fall on your car tend to bead or round up more after you polish (or wax) the car than before you polished it.

The wax (or polish) is hydrophobic and therefore less polar than the surface was likely to be before you polished it. Because the adhesion between the surface and the water molecules is lower, the cohesion of the water molecules for each other appears to be even more dramatic.

h. If you touch the edge of a paper towel to a drop of colored water, the water will move up into (or be absorbed by) the towel.

The polar water molecules adhere to the cellulose in the paper towel and cohere to each other. As a result, they are drawn up into the towel. The same mechanism accounts for the movement of water molecules up capillary tubes.

Extend Your Understanding

Activity 2.3 Are silicon-based life forms possible?

Silicon is very similar to carbon in its chemical properties. For example, both are in the same group of the periodic table, and both Si and C have 4 electrons in their outer shells. Based on these similarities, some science fiction writers have suggested that life forms on other planets could be silicon-based. Given what you know about the two elements, their reactivity or electronegativity, and the types of compounds they form, indicate whether it is possible that life could be Si-based as well as C-based. Feel free to use additional resources to make an argument for or against a world where silicon forms the building blocks of life.

Most students will recognize that Si and C both have 4 valance electrons, which allows Si to make a similar number and type of bonds as carbon. However, students who do additional research will find the following types of information:

On the surface, silicon seems like an ideal substitute for carbon in another living system. Theoretically, silicon has bonding chemistry identical to that of carbon, and, like carbon, silicon can combine with four other elements to construct an incredible range of different macromolecules. So why not silicon-based life?

First, let's look at the competition. Carbon, the MVP in all known biological molecules from sugar to DNA and even squid ink, is unique in that its bonding versatility allows it to take on many forms: long side chains that make up fatty acids and cell membranes, ring structures that compose hormones and sugars, and even simple gaseous molecules like methane (CH_4) or carbon dioxide (CO_2). Can silicon compete?

The short answer is probably not. Although carbon can form a variety of structures (rings, long chains, multi-ring chains, and double-bonded carbon catenations), silicon's analogous structures are comparatively unstable and sometimes highly reactive. Additionally, such analogous silicon compounds may never occur in nature; the largest silicon molecule ever observed had only six silicon atoms. In contrast, some carbon-based molecules contain tens of thousands of carbon atoms in their structure!

Silicon also has the formidable disadvantage of being less abundant in the universe. The birthplaces of all heavier elements—older stars—tend to produce far more carbon than silicon. Thus, the likelihood of a living system to evolve based on silicon is low based on the sheer rarity of naturally produced silicon compared to carbon. In fact, astronomical observations of the spectra of various stars and nebulae reveal that organic carbon ring structures (also known as polycyclic aromatic hydrocarbons, or PAHs) exist even in the far reaches of space.

Another chemical property unique to carbon chemistry that silicon lacks is chirality, or "handedness." All organic carbon molecules may be found naturally in left- or right-handed conformations. However, life as we know it utilizes only the right-hand form of sugars, integral components in DNA structure, and the left-hand form of amino acids, the building blocks of proteins. Very few silicon compounds have handedness. The biochemical reactions of life are incredibly specific; in fact, many larger biomolecules are so precise that a single conformational change (right to left) around one carbon atom would block the reaction. Without chirality, the number of different reactions available and achievable by a silicon-based system is limited.

Although the chances for silicon-based life may be slim, silicon may have played a role in emergence of life on Earth. One of the unsolved mysteries in the origin of life is why life came to employ one chiral version of a molecule (left vs. right) in its reactions and not the other. Some chemists believe that the chiral selection process in the prebiotic "soup" might have been aided by a "handed" silica (SO_2) surface. Both left- and right-handed molecules could have interacted with the chiral surface, and they were aligned according to handedness. In this manner, chiral molecules were separated and sorted in preparation for prebiological selection. So even if silicon is an unlikely participant in the biological reactions of life, it could have certainly lent a helping hand to the origin of life.

(From http://nai.nasa.gov/astrobio/feat_questions/silicon_life.cfm)

Notes to Instructors

Chapter 3 Protein Structure and Function
Chapter 4 Nucleic Acids and the RNA World
Chapter 5 An Introduction to Carbohydrates
Chapter 6 Lipids, Membranes, and the First Cells

What is the focus?

The activities associated with Chapter 2 provided students with a review of some of the basics of inorganic chemistry. The activities associated with Chapters 3 through 6 deal with organic chemistry and biochemistry. Although most introductory biology students have had some exposure to inorganic chemistry, many fewer have had courses in organic chemistry or biochemistry. Therefore, these activities are designed with these goals in mind:

- Help students identify the major differences among the four main types of biological macromolecules: carbohydrates, lipids, proteins, and nucleic acids.
- Recognize what functional groups are and how they can modify the general properties and functions of organic compounds.
- Use their understanding from the goals above to predict how various structural modifications can affect the behavior of macromolecules.

Activity 3.1 What Properties Do Proteins Have?

What is this activity designed to do?

In this activity, students examine the general properties of amino acids and proteins. In particular, they examine the properties of functional groups and how these can modify the behavior of macromolecules. This includes how modifying functional groups can affect the water solubility and the chemical reactivity of molecules.

At the end of this activity, students are asked to predict how various macromolecules could react if placed in specific environments or if modified in specific ways. Answering these questions requires students to integrate and use understanding they have gained from Chapters 2 and 3.

What misconceptions or difficulties can this activity reveal?

Question 1: This table asks students to evaluate the properties of functional groups that modify the behavior of organic macromolecules. As students learn what the different types of organic macromolecules are through subsequent chapters and learn how to identify the different types of macromolecules, an understanding of the functional groups will help students identify what to look for when they evaluate a chemical structure.

Question 2: The table asks students to look at different possible characteristics of R-groups.

R-Group	Basic, acidic, or neutral	Polar or nonpolar	Hydrophilic or hydrophobic

This question helps students understand, for example, that something that is polar is also hydrophilic; that is, these designations are not mutually exclusive. In addition, by learning the characteristics of key functional groups, students will have a better understanding of how modifications in macromolecular structure can lead to modifications in function.

Questions 3 and 4: These questions require students to begin applying their understanding of how protein structure affects function and how that structure might change under a different set of conditions. The experimental scenarios give students an opportunity to begin thinking about their knowledge in an experimental context to predict the outcome of a given set of conditions. Students may have difficulty with these questions at first, but the ability to practice application of understanding will ultimately improve their critical-thinking skills.

Activity 3.2 What Factors Affect Chemical Reactions in Cells?

What is this activity designed to do?

This activity asks the students to construct a concept map that integrates their understanding of protein structure, enzyme function, and general energy transformations in metabolic reactions. It requires them to have a general understanding of enzyme structure and function.

What misconceptions or difficulties can this activity reveal?

If done in small groups in class, the concept-mapping activity can be used to reveal the students' levels of understanding as well as any misconceptions they may have. Doing this activity helps many students understand how the tertiary (or quaternary) structure of an enzyme can be modified by modifying a side group on an amino acid. In addition, understanding the impact of changes in the physical or chemical conditions surrounding the enzyme can help students understand why organisms expend so much energy in maintaining homeostasis.

Question 1: Because they tend to memorize terms and definitions separately, many students don't recognize that a single reaction can simultaneously be spontaneous, catabolic, and exergonic and have a negative ΔG. Question 1 will give students the opportunity to see what an exam question for this content might test and allows them to justify their answer to solidify their thought process. Practice with justifying answers to

exam questions will improve test-taking skills and help students with test anxiety better manage the testing situation.

Question 2: For years, the dogma held that all enzymes were proteins. This question can be used to point out that we now know that some enzymes are made of RNA.

Question 3: This question points out the types of factors that can affect enzyme function. Students need to make the logical leap that for cells to maintain their metabolism at optimal levels; they must be able to regulate their internal environment. Many students do not make this connection without additional help or suggestions.

Activity 3.3 How Can Changes in Experimental Conditions Affect Enzyme-mediated Reactions?

What is this activity designed to do?

This activity asks students to apply their general understanding from Activity 3.2 to specific experimental situations. They must understand how enzyme function (and therefore metabolism) can be affected by changes in substrate and/or product concentration and by changes in the enzyme itself.

What misconceptions or difficulties can this activity reveal?

This set of experimental situations gives students practice in making the connection between "knowing something" (for example, knowing the definitions of competitive and noncompetitive inhibitors) and understanding how to use that information to interpret results or to predict results if their understanding is correct. Many students are not comfortable doing this, especially in situations that have more than one possible answer depending on the assumptions the student makes. Therefore, these questions give them practice with developing assumptions as well as predictions based on those assumptions.

Activity 4.1 What Makes a Compound a Nucleic Acid?

What is this activity designed to do?

This activity requires students to understand the basic components of nucleic acids and work through the experimental procedure Watson and Crick used to determine the structure of DNA. Students must use their knowledge of the structure of DNA and RNA as well as their understanding of the RNA world hypothesis.

What misconceptions or difficulties can this activity reveal?

This activity requires students to work through Watson and Crick's experimental procedure and evaluate the evidence they used to make each of a set of conclusions about the structure of DNA. Some students may have difficulty connecting experimental results to conclusions because they do not fully understand the experimental procedure or the results themselves. Question 4 requires students to use their knowledge of the structure of

DNA, RNA, and five nitrogenous bases, as well as an understanding of the 3′ and 5′ ends of ribose and deoxyribose, to identify the nucleic acid and nucleotide sequence.

Activity 5.1 How Does Structure Affect Function in Carbohydrates?

What is this activity designed to do?

This activity allows students to organize the most important information about polysaccharides and lipids and connect this information to living organisms. Students are also asked to connect structure to function in polysaccharides and lipids.

What misconceptions or difficulties can this activity reveal?

This activity is primarily an organizational tool for students to manage a large amount of content. The activity requires students to make connections between structure and function, based on the information in the organizational chart.

Activity 6.1 What Roles Do Lipids Play in Organisms?

What is this activity designed to do?

These questions allow students to organize the most important information about polysaccharides and lipids and connect this information to living organisms. Students are also asked to connect structure to function in polysaccharides and lipids.

What misconceptions or difficulties can this activity reveal?

These questions are primarily organizational tools for students to manage a large amount of content. They require students to make connections between structure and function, based on the information in the organizational chart.

Activity 6.2 What Controls the Movement of Materials Into and Out of the Cell?

What is this activity designed to do?

These questions are designed to help students begin to understand

- the physical and chemical factors that affect the transport of substances into and out of cells (as well as into and out of organelles)
- how the size of solute molecules affects osmotic potential

What misconceptions or difficulties can this activity reveal?

Question 1: Many students visualize the phospholipid bilayer as a static structure rather than as a fluid structure. As a result, they have a difficult time understanding how anything could move across a membrane made of phospholipids alone.

The difficulty in understanding the fluid nature of membranes isn't that surprising. After all, how does something that is fluid act as a boundary layer? If it is so fluid, why do red

blood cells in hypotonic solution swell so much before they burst or lyse? Why don't the membranes just separate into individual phospholipid units under this pressure? Many of us have similar difficulty understanding how the various chemical elements can be so hard when each atom is composed of electrons orbiting around a central core of protons and neutrons.

Although it doesn't answer these questions, it helps to remind students of the size differences that exist among cells, phospholipids, and the substances that can move through them. For example, a molecule of oxygen, carbon dioxide, or water is at least 50 times smaller than a phospholipid molecule. In addition, the distances that individual phospholipid molecules move per unit time are very small. For example, *Biological Science*, 6th edition, notes that phospholipids can move about 2 µm/second. By comparison, the diffusion rate for substances in water is about 40 µm/second. This means that the movement of phospholipids in the membrane is about 20 times slower than the movement of water molecules in diffusion. In other words, phospholipid membranes are fluid but nowhere near as fluid as water.

Question 2: Many students don't understand how molecular size affects osmotic potential. Once they understand this, it will be easier for them to understand why systems don't store ATP or sugar molecules but instead store energy in the form of starches and fats.

Activity 6.3 How Is the Structure of a Cell Membrane Related to Its Function?

What is this activity designed to do?

These questions are designed to help students begin to understand

- the physical and chemical factors that affect the transport of substances into and out of cells (as well as into and out of organelles)
- how the size of solute molecules affects osmotic potential

What misconceptions or difficulties can this activity reveal?

Modeling the different types of transport as they occur in a single membrane allows students to recognize that all three types of transport can be going on simultaneously in different parts of the membrane.

Extend Your Understanding

Activity 6.4 Effects of Missing or Nonfunctional Ion Channels in Cell Membranes

What is this activity designed to do?

This activity is designed to take understanding about membrane transport and apply it to a new, hypothetical situation that parallels a disease scientists understand very

well—cystic fibrosis. This question also requires students to approach the new situation experimentally, as if they are doing research. This exercise is an extension of the CF essay in Chapter 6 of *Biological Science*, 6th edition.

Extend Your Understanding

Activity 6.5 What Effect Does Cholesterol Have on Phospholipid Membrane Permeability?

What is this activity designed to do?
This activity requires students to interpret results that are contrary to those shown in the text and revise their conclusions based on the data shown. This activity also tries to convey the idea that research usually results in more questions and asks students to ask new questions or propose new experiments in light of these new data.

Integrate Your Understanding

Chapters 3–6 What do Carbohydrates, Lipids, Proteins, and Nucleic Acids Have in Common? How Are They Different?

What is this activity designed to do?
Parts A and B. This activity is designed to help students easily recognize carbohydrates, lipids, proteins, and nucleic acids when viewed as chemical structures. Students develop some simple rules to make it easier for them to recognize differences among the general chemical structures of carbohydrates, lipids, proteins, and nucleic acids. This type of activity is especially important for the many introductory biology students who have not yet had organic chemistry or biochemistry.

Part C. These questions require students to apply their understanding of the four basic types of macromolecules to a few situations they may have never considered before. These types of questions will challenge students with only a basic understanding of the content.

Part D. In this activity, students are asked to predict how various macromolecules could react if placed in specific environments or if modified in specific ways. Answering these questions requires students to integrate and use understanding they have gained from Chapters 3–6.

What misconceptions or difficulties can this activity reveal?
Part A, Question 1: This question asks for the C:H:O ratio of the various macromolecules. For carbohydrates, it is approximately 1:2:1. For many lipids, it is approximately 1:2:very few. And for proteins and nucleic acids, there is no reliable ratio of C:H:O. Many students become upset that the answer for proteins and nucleic acids is “no reliable ratio of C:H:O.” Remind them that they would not have known the C:H:O ratio was not a good predictor for these molecules unless they investigated it. Answers like this just mean we

need to look for other ways of identifying these molecules. Some of these other ways include looking for specific functional groups, for example, amino and carboxyl groups in amino acids and ribose versus deoxyribose and specific nucleotides to identify RNA versus DNA.

Part B: After developing their own rules for identifying macromolecules, most students won’t have difficulty identifying these structures as carbohydrate, protein, lipid, or nucleic acid. It is best to present this activity in that light; that is, let students know that the purpose of the activity is to help them prove it is possible to categorize complex macromolecules using only a few simple rules.

Part D: Experiments a, b, and c ask students to examine how phospholipids (and glucose) will distribute themselves in different kinds of aqueous environments. Many students have memorized the concept that phospholipids can form bilayers or micelles in aqueous environments, and they have the misconception that phospholipids will organize into micelles or bilayers under any circumstance.

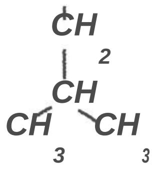
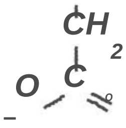
Answers

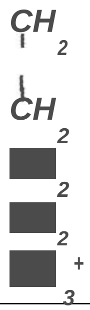
Activity 3.1 What properties do proteins have?

1. Functional groups can modify the properties of organic molecules. In the table below, indicate whether each functional group is polar or nonpolar and hydrophobic or hydrophilic. Which of these functional groups are found in proteins and lipids? Use Table 2.3 on page 57 and Figure 3.2 on page 80 of *Biological Science*, 6th edition, to fill in the table.

Functional group	Polar or nonpolar?	Hydrophobic or hydrophilic?	Found in all proteins?	Found in many proteins?
–OH	Polar	Hydrophilic	No	In some R-groups
–CH_2	Nonpolar	Hydrophobic	No	Yes, in side groups
–COOH	Polar	Hydrophilic	Yes	
–NH_2	Polar	Hydrophilic	Yes	
–SH	Polar	Hydrophilic	No	Found in cysteine
–PO_4	Polar	Hydrophilic	No	Only if they have been phosphorylated

2. Twenty amino acids are commonly utilized in the synthesis of proteins. These amino acids differ in the chemical properties of their side chains (also called R-groups). What properties does each of the following R-groups have? (*Note:* A side chain may display more than one of these properties.)

R-group	Basic, acidic, or neutral	Polar or nonpolar	Hydrophilic or hydrophobic
a. 	Neutral	Normal	Hydrophobic
b. 	Acidic	Polar	Hydrophilic

R-group	Basic, acidic, or neutral	Polar or nonpolar	Hydrophilic or hydrophobic
c. 	Basic	Polar	Hydrophilic
d. 	Neutral	Polar	Hydrophilic

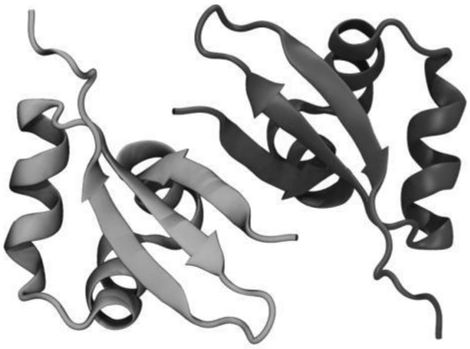
3. Polypeptides and proteins are made up of linear sequences of amino acids. In its functional form, each protein has a specific three-dimensional structure or shape. Interactions among the individual amino acids and their side chains play a major role in determining this shape.

   a. How are amino acids linked together to form polypeptides or proteins? What is this type of bond called?

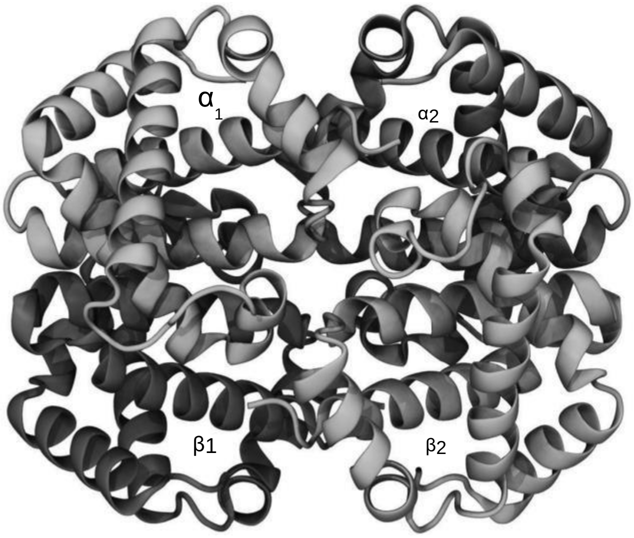
   Amino acids are covalently linked together via peptide bonds to form polypeptides or proteins. (See Figure 3.6 in your textbook.)

b. Define the four structures of a protein.	c. What kinds of bonds hold each of these together?
Primary: The linear sequence of amino acids in a polypeptide or protein	Covalent peptide bonds formed by dehydration reactions hold the individual amino acids together in the polypeptide chain.
Secondary: α-helix or β-pleated sheet conformations occurring at regular intervals along the polypeptide	The secondary structure results from H bonding relationships set up between the H attached to the N in one amino acid and the O attached to the C of another amino acid.
Tertiary: The folded or functional conformation of a protein	Hydrogen and covalent bonds between side chains (R-groups) of various amino acids contribute, as do hydrophobic interactions and van der Waals interactions.
Quaternary: The folded or functional conformation of a protein made up of more than one polypeptide	Hydrogen and covalent bonds between side chains (R-groups) of various amino acids contribute, as do hydrophobic interactions and van der Waals interactions.

d. On the figures below, label at least one of each of the following characteristics of proteins: α-helix, β-pleated sheet, H-bonding along peptide-bonded backbone, and van der Waals interaction.



(a) Cro protein, a dimer



(b) Hemoglobin, a tetramer

The Cro protein is composed of α-helices connected by a β-pleated sheet. Hydrogen bonds hold the coils of the α-helices together. Hemoglobin is composed of four sets of α-helices. The folding of the α-helices is controlled by van der Waals interactions.

e. Describe how the structures above might change if denatured by high heat or by a chemical that can denature protein.

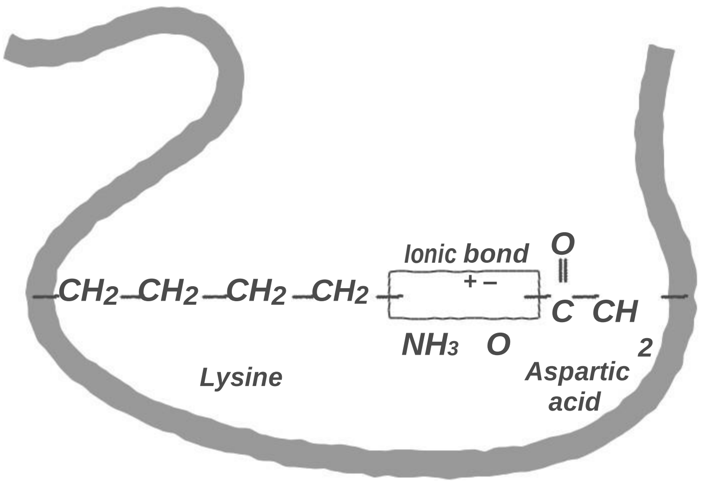
As shown in Figure 3.13 of *Biological Science*, 6th edition, when a protein is denatured, the hydrogen and disulfide bonds break, thereby causing the protein to uncoil the α-helix structure and unfold where there were previously disulfide bonds.

4. Use your understanding of the proteins in living organisms to predict the outcome of the following experiments. Be sure to explain your reasoning.

Experiment a: A globular protein ordinarily found in aqueous solution has these amino acids in its primary structure: glutamic acid, lysine, leucine, and tryptophan. Predict where you would find each amino acid: in the interior portion of the protein (away from water) or on the outside of the protein (facing water). (Refer to Figure 3.10 on page 85 of the textbook.)

Glutamic acid and lysine are electrically charged and will therefore be on the outside of the protein. Leucine and tryptophan are nonpolar and will be inside the protein.

Experiment b: Drawn below is part of the tertiary structure of a protein showing the positions of two amino acids (aspartic acid and lysine). Replacing lysine with another amino acid in the protein may change the shape and function of the protein. Replacing lysine with which type(s) of amino acid(s) would lead to the least amount of change in the tertiary structure of this protein? (Refer to Figure 3.11a on page 86 of the textbook.)



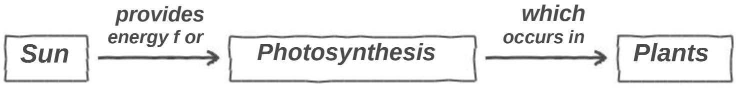
Aspartic acid has a negatively charged R-group. Lysine has a positively charged side group. To cause the least amount of change in the tertiary structure of this protein, you have to replace lysine with an amino acid that contains a positively charged side group, such as arginine or histidine.

Activity 3.2 What factors affect chemical reactions in cells?

Construct a concept map of general metabolism using the terms in the list below, according to the following guidelines:

- Keep in mind that there are many ways to construct a concept map.
- Begin by writing each term on a separate Post-it note or piece of paper.
- organize the terms into a map that indicates how the terms are associated or related.
- Draw lines between terms and add action phrases to the lines to indicate how the terms are related.
- If you are doing this activity in small groups in class, explain your map to another group when you finish it.

Here is an example:



Terms

peptide bonds
proteins
α-helix
primary structure
secondary structure
tertiary structure
β-pleated sheet
R-groups
hydrogen bonds
substrate or reactant (ligand)

activation energy
ΔG / free energy
endergonic
exergonic
enzymes
catalysts
competitive inhibitor
noncompetitive inhibitor
active site
product

allosteric regulation
activator
four-step enzyme-mediated reaction sequence or metabolic pathway (A¡B¡ C¡D)
intermediate compound
end-product
feedback inhibition

Use the understanding you gained from doing the concept map to answer the following questions.

1. Reduced organic compounds tend to contain stored energy in C–H bonds. As a general rule, the greater the number of C–H bonds, the greater the amount of potential energy stored in the molecule. Answer each question in the chart as it relates to the two reactions shown at the top. Be sure to explain the reasoning behind your answers.

	Reaction 1: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$ (methane)	Reaction 2: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
a. Is the reaction exergonic or endergonic?	Exergonic	Endergonic
b. Is the reaction spontaneous?	Yes	No
c. Is the reaction anabolic or catabolic?	Catabolic	Anabolic
d. Is Δ*G* (the change in free energy) positive or negative?	Negative	Positive

2. All metabolic reactions in living organisms are enzyme mediated. Each enzyme is specific for one (or only a very few similar types of) reaction. Given this, there are approximately as many different kinds of enzymes as there are reactions.

   a. What characteristics do all enzymes share?
   All enzymes contain a reactive site. All have a specific conformation that fits them to their substrate(s). All serve to reduce the activation energy of reactions.

   b. What characteristics can differ among enzymes?
   Before ribozymes were discovered, biologists thought all enzymes were composed of protein. Some enzymes include cofactors, which can be ions or other organic compounds. If a cofactor is organic, it is called a coenzyme. Many vitamins are coenzymes.

3. How can enzyme function be mediated or modified? To answer, complete columns a and b below.

a. What factors can modify enzyme function?	b. What effect(s) can each of these factors have on enzyme function?
Temperature	Each enzyme has a range of temperatures in which it functions.
pH	The same is true for pH. At temperatures and pHs outside this range, protein enzymes can become denatured. This changes their 3-D configuration and therefore their ability to function.
Molecules may compete for the active site.	The action of some enzymes can be inhibited by molecules that compete for the active site (competitive inhibition). Other inhibitors can bind at another site and alter the configuration of the active site (noncompetitive inhibition).
Molecules may stabilize the 3-D form of the enzyme.	In some cases, activators are required to stabilize the active 3-D form of the enzyme.

c. What role(s) can modification of enzyme function play in the cell?
To maintain optimal levels of enzyme activity and therefore metabolism, cells must maintain a relatively constant internal environment (homeostasis). On the other hand, cells can control or modify enzyme function to inhibit or enhance the function of a specific enzyme (as noted in part b). As a result, cells can maintain tight control over the levels of various cellular components. For example, an end-product of a reaction series can serve as an allosteric inhibitor of the first enzyme in the pathway. This type of control has the effect of quickly and efficiently turning off the entire pathway when the end-product is present in excess (or of turning it on when the end-product concentration decreases).

Activity 3.3 How can changes in experimental conditions affect enzyme-mediated reactions?

1. You set up a series of experiments to monitor the rates of a reaction. The reaction is an enzyme-mediated reaction in which A ¡ B + C. For each experiment in this series, you continuously add the reactant A and monitor its concentration so that the amount of A remains constant over time.
   For each group of experiments, explain how the differences in experimental conditions could affect the reaction.

   a. You compare two side-by-side experiments. In experiment 1, you use *x* amount of the enzyme. In experiment 2, you use 2*x* amount of the same enzyme.

   If you double the amount of enzyme present, you double the rate of accumulation of the product. The rate at which any specific enzyme operates to make A S B + C does not change. However, the apparent rate at which C accumulates appears to double. For example, if one enzyme can complete the reaction A S B + C in 1 msec, then at the end of 1000 msec (1 second) we would expect 1000 A to be converted to 1000 B + 1000 C. If two enzymes were working simultaneously, then within 1 second, 2000 A could be converted to 2000 B + 2000 C. (*Note:* This answer assumes that the amount of A is much greater than the amount of B + C.)

   b. You compare two side-by-side experiments. In both, you use equal amounts of the enzyme. In experiment 3, you allow the products to accumulate over time. In experiment 4, you remove the products from the system as they are produced.

   Recall that most metabolic reactions are reversible, and for these reactions, the same enzyme that catalyzes the forward reaction can generally catalyze the reverse reaction. As a result, in experiment 4, the apparent rate of the reaction will be constant over time. In other words, to use the example above, each enzyme will break down a unit of A into B and C every millisecond. In experiment 3, however, as the reaction reaches equilibrium levels of A versus B + C, the apparent rate of the reaction will decrease. Each enzyme will still be operating at the same rate (1 reaction per millisecond); however, some will be catalyzing the forward reaction and some the reverse reaction. At equilibrium, the numbers of enzyme molecules catalyzing the forward versus reverse reactions per unit time should be equal.

c. In the next two experiments, you use equal amounts of the enzyme. You run experiment 5 at 20°C and experiment 6 at 25°C.

   Each type of enzyme is functional within a set range of temperatures. The temperature at which the enzyme has its greatest rate of activity or reaction rate is called its optimal temperature. On either side of the optimal temperature (positive or negative), the rate of the enzyme-catalyzed reaction decreases. As a result, exactly how the enzyme in this system will react depends on both its optimal temperature and the range of temperatures over which it is active. For example, if we assume the enzyme's range of temperature is 0° to 50°C and its optimal temperature is about 35°C, then the rate at which the enzyme works at 25°C will be faster than its rate at 20°C. On the other hand, if the range of temperatures for this enzyme is 40° to 90°C, then at both 20° and 25°C, we will see no activity.

d. In two final experiments, you use equal amounts of the enzyme. You run experiment 7 at pH 6 and experiment 8 at pH 8.

   Similar to part c, each enzyme has an optimal pH and a range of pH in which it is active. As above, exactly how the enzyme will react at pH 6 versus pH 8 will depend on its optimal pH and range of pH.

2. Enzyme function can be inhibited or regulated by the presence of chemicals that mimic either the reactants or the products.

   a. How do competitive and noncompetitive inhibition of an enzyme differ?

      A competitive inhibitor can bind at the active site of an enzyme and prevent the substrate from binding. A noncompetitive inhibitor binds at a different site on the enzyme and changes the shape of the active site, which then prevents the substrate from binding.

   b. What are allosteric enzymes? What function(s) can they serve in reaction sequences?

      Allosteric enzymes are usually made up of more than one polypeptide. The activity of these enzymes is often controlled by enhancers and inhibitors, which bind at different sites on the enzyme. Binding of an enhancer changes the enzyme's shape and makes its active site(s) available for catalysis. Binding of an inhibitor also causes a shape change, but one that makes the active site(s) unavailable.

3. An enzyme catalyzes the reaction X ¡ Y + Z. In a series of experiments, it was found that substance A inhibits the enzyme.

- When the concentration of X is high and A is low, the reaction proceeds rapidly and Y and Z are formed.
- As the concentration of A increases, the reaction slows regardless of whether X is present in high or low concentration.
- If the concentration of A is high (relative to X), the reaction stops.
- If the concentration of A again decreases, the reaction will ultimately resume.

What type of enzyme regulation is described here? Explain or justify your answer.
The enzyme in the reaction described, X S Y + Z, is most likely an enzyme that has a site for a noncompetitive inhibitor molecule. If this were a case of competitive inhibition, then the higher the concentration of X (relative to A), the faster the reaction rate should be. The inhibition described is also reversible, as evidenced by the ability of the reaction to resume if the concentration of A decreases.

4. In an enzymatic pathway, A, B, and C are intermediates required to make D, and 1, 2, and 3 are enzymes that catalyze the designated reactions:

1 2 3
A¡B¡C¡D

E

This is analogous to what happens in a factory. In a leather goods factory, for example, the leather (A) is cut into the parts needed for shoes (B). The shoe parts are sewn together (making C), and C is packaged for shipping as D. Now shoe sales are dropping and backpack sales are increasing. As a result, the manager of the factory decides to switch production from shoes to backpacks (E).

a. Where should the shoe-making process be shut down—at step 1, 2, or 3? Explain.
The shoe-making process should be shut down at step 1. It makes no sense to produce any of the parts to make shoes if you don’t need them.

b. In a cell, if an excess of a chemical product D arises, where should this synthetic pathway be shut down in the cell? Explain your reasoning.
If we use the same logic as in part a, then the synthetic pathway A S B S C S D should also be shut down at the first step.

c. What type(s) of enzyme regulation is/are most likely to occur in the cell in this type of feedback system? Explain your reasoning.
Allosteric enzymes are frequently involved in this type of feedback regulation of synthetic pathways.

Activity 4.1 What makes a compound a nucleic acid?

1. Closely related macromolecules often have many characteristics in common. For example, they share many of the same chemical elements and functional groups. Therefore, to separate or distinguish closely related macromolecules, you need to determine how they differ and then target or label that difference.

   a. What makes RNA different from DNA?

   RNA contains ribose sugar, whereas DNA contains deoxyribose sugar. In addition, RNA contains uracil and not thymine. DNA contains thymine but not uracil.

   b. If you wanted to use a radioactive or fluorescent tag to label only the RNA in a cell and not the DNA, what compound(s) could you label that is/are specific for RNA? You could label either ribose or uracil.

   c. If you wanted to label only the DNA, what compound(s) could you label? You could label either deoxyribose or thymine.

2. You want to use a radioactive tracer that will label only the protein in an RNA virus. Assume the virus is composed of only a protein coat and an RNA core. Which of the following would you use? Be sure to explain your answer.

   a. radioactive P b. radioactive N c. radioactive S d. radioactive C

   To distinguish between protein and RNA in a virus, you could use radioactively labeled S compounds. If you grew viruses on cells with radioactively labeled S compounds, the sulfhydryl groups in the virus's protein would become labeled but the RNA would not become labeled.

3. Watson and Crick used modeling to determine the structure of DNA. What information led them to determine the following:

   a. DNA is double stranded.

   X-ray crystallography completed by Rosalind Franklin and Maurice Wilkins showed that the structure of DNA was helical or spiral. Watson and Crick's modeling efforts revealed that a double-stranded helical model (rather than a single-stranded looping structure) made sense with the measurements of distances of groups of atoms in the molecule, given that according to Chargaff's rule #A's = #T's, and #C's = #G's.

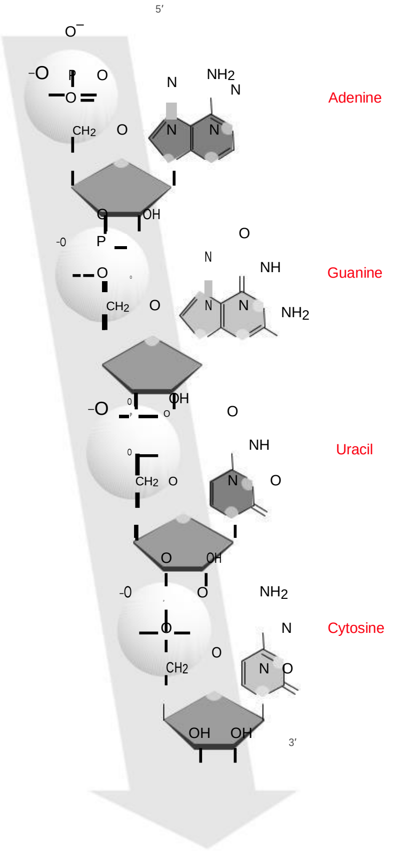
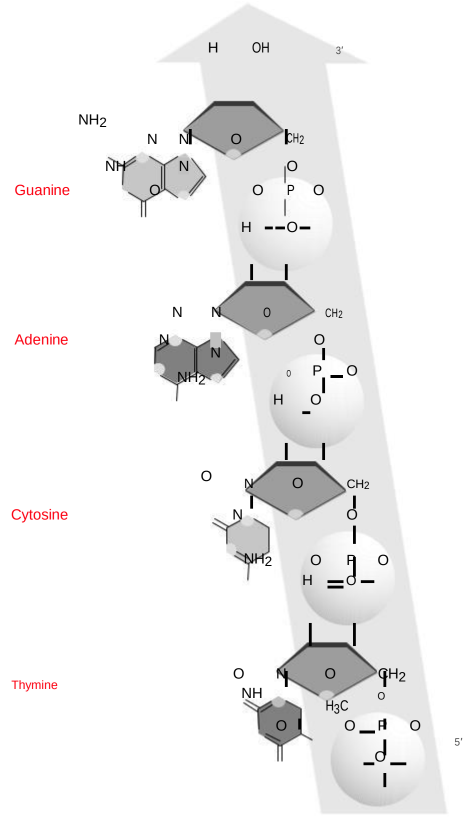
b. The two strands of nucleotides in DNA run antiparallel.

Watson and Crick’s modeling efforts showed that the only way to keep the distances correct was to pair up the nucleotides and run the strands opposite one another, or antiparallel.

c. The nucleotides in the two antiparallel strands are arranged such that a purine is always paired with a pyrimidine.

As in part b, the only way to keep the distances correct was to pair up the nucleotides purine with pyrimidine. Adenine pairs with thymine and guanine with cytosine, because of Chargaff’s finding that #A’s = #T’s, and #C’s = #G’s.

4. For each nucleic acid strand shown below, indicate whether it is DNA or RNA, label each of the bases, and write out the nucleotide sequence, starting at the 5′ end. For assistance, refer to Figure 4.1 on page 94 in *Biological Science*, 6th edition.

a. Type of nucleic acid: ______________RNA______________ Nucleotide sequence as A, G, C, etc.: 5′ A___G ___ U___ C__3′	b. Type of nucleic acid: DNA___ _ Nucleotide sequence as A, G, C, etc.: 5′ _T__ C___A ___G___3′
	

5. Many scientists believe that RNA molecules were the first macromolecules that emerged to allow some of the fundamental processes of life to be conducted. Indicate which of the following statements supports the RNA world hypothesis, and be sure to justify your answer.

   a. RNA includes the base uracil (U) instead of thymidine (T).

   b. DNA is more stable than RNA.

   c. Unlike DNA, RNA can catalyze chemical reactions.

   d. Because RNA uses ribose instead of deoxyribose, RNA can be used as an energy source.

   Statement c supports the RNA world hypothesis. The fact that RNA can catalyze chemical reactions supports the theory of chemical evolution—that life began as a naked self-replicator. It is possible that life began with RNA because it has the ability to catalyze reactions that could link nucleic acid monomers into a copy of itself, thereby self-replicating. Although this process has not yet been achieved in the laboratory, considerable progress has been made to indicate that it may have once been possible.

   Choices a and b have no bearing on the RNA world hypothesis, even though they are true.

   Choice d is false; both sugars can be used as energy sources.

Activity 5.1 How does structure affect function in carbohydrates?

1. Polysaccharides, complex carbohydrates, have a wide range of structures that affect how these macromolecules can function in organisms. Fill out the chart below to help you understand the characteristics of different polysaccharide structures and the roles they play in living organisms. (Refer to Summary Table 5.1 on page 112 of *Biological Science*, 6th edition.)

	Structural components	3-D structural arrangement	Role(s) the polysaccharide play(s) in organisms	Type(s) of organisms in which compound is found
Starch	α-Glucose monomers with glycosidic linkages	Mixture of unbranched helix called amylase and branched helix called amylopectin	Stores sugars	Plants
Glycogen	α-Glucose monomers with glycosidic linkages	Highly branched helices; branches every 10 monomers	Stores sugars	Animals
Cellulose	β-Glucose monomers with glycosidic linkages and hydrogen bonds	Long, parallel strands joined into sheets with multiple hydrogen bonds	Provides structure to the plant cell wall	Plants
Chitin	*N*-acetyl glucosamine monomers with glycosidic linkages and hydrogen bonds	Long, parallel strands joined into stiff sheets with multiple hydrogen bonds	Strengthens cell wall of fungi and algae; component of exoskeleton of insects and crustaceans	Animals—e.g., fungi, algae, insects, and crustaceans

Peptidoglycan	*N*-acetyl-glucosamine and *N*-acetyl-muramic acid monomers with an amino acid chain Glycosidic linkages between monomers and peptide bonds between adjacent amino acid chains	Long, parallel strands joined into sheets with multiple peptide bonds	Provides strength to bacterial cell walls	Bacteria

2. Compare the structures of starch and glycogen. Compare the structures of cellulose, chitin, and peptidoglycan. How are each of these suited to their functions?

   Starch and glycogen have very similar structures and very similar functions. Because both starch and glycogen are stored for later use, they need to be relatively easily broken down into their component monomers, which is why they are connected by only simple glycosidic linkages.

   Cellulose, chitin, and peptidoglycan all exist as sets of long parallel strands linked together into sheets. This makes them ideal to function in a structural role because many hydrogen and/or peptide bonds provide strength and the ability to withstand forces pushing in or pulling out. Cellulose and peptidoglycan provide structural support, but chitin's monomers and hydrogen bonds form a tough sheet that is used for protection as well as structural support.

[redacted]