

CHAPTER 2 THE CHEMISTRY OF LIFE

Take Note: While the AP Biology exam does not test directly on this material, it is important to have a solid understanding of the concepts in this chapter in order to properly understand the biochemistry that is to follow. It is important that you have a working knowledge of the elements that are important for life, the role of isotopes in biology, and the different types of bonds that form between elements. The properties of water are extremely important, as well as the behavior of acids and bases.

2.1 Chemical Elements

Matter is defined as anything that has mass and takes up space. Both living and nonliving matter is composed of **elements**, the simplest forms of matter that cannot be broken down to simpler substances with different chemical or physical properties. Six of the elements that occur in nature—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (CHNOPS)—are important for life and make up 98% of the body weight of organisms.

Elements consist of tiny particles called **atoms**, the smallest unit of an element that displays the properties of the element. Atoms contain specific numbers of **protons**, **neutrons**, and **electrons**. Protons and neutrons are in the nucleus of an atom; electrons move around the nucleus. **Protons** are positively charged particles; neutrons have no charge. Both have 1 *atomic mass unit* (amu) of weight. **Electrons** are negatively charged particles located in orbitals outside the nucleus. Protons and neutrons in the nucleus determine the mass number of an atom. The atomic number indicates the number of protons and the number of electrons in electrically neutral atoms.

Isotopes are atoms of a single element that differ in their numbers of neutrons. A carbon atom with 8 rather than 6 neutrons is unstable; it releases energy and subatomic particles and is thus a **radioactive isotope**. Radioactive isotopes have many uses, including serving as tracers in biological experiments and medical procedures. An example is radioactive iodine that is used to detect tumors in the thyroid gland. High levels of radiation can destroy cells and cause cancer; careful use of radiation can sterilize products and kill cancer cells.

2.2 Compounds and Molecules

Ions form when atoms lose or gain one or more electrons. An ionic bond is an attraction between oppositely charged ions. It is formed when electrons are transferred from one atom to another atom. For example, sodium loses an electron, forming a positive charge, and chlorine gains an electron to give it a negative charge. The ionic bond that forms between them results in the formation of sodium chloride, NaCl.

Covalent bonds form when atoms share one or more pairs of electrons. There are single, double, and triple covalent bonds. In polar covalent bonds, the sharing of electrons is not equal. If the molecule is polar, the more electronegative atom carries a slightly negative charge and the other atom carries a slightly positive charge. In **nonpolar covalent bonds**, sharing of electrons is equal (i.e., the electrons are not attracted to either atom to a greater degree).

Take Note: *The properties of water are important in all of Biology. Be sure you fully understand the properties of water so that you can apply the knowledge gained in this section to other topics as you proceed through your study of Biology.*

2.3 Chemistry of Water

All living things are 70–90% water. The polarity of water molecules allows hydrogen bonding to occur between them. In a water molecule, the sharing of electrons by oxygen and hydrogen is not equal; the oxygen atom is more electronegative, attracting the electrons closer to it, and thus assuming a partial negative charge. As a result, the hydrogens develop a partial positive charge.

A hydrogen bond is a weak attraction between a slightly positive hydrogen atom and a slightly negative oxygen or nitrogen atom within the same or a different molecule. Many hydrogen bonds taken together are relatively strong and help maintain the structure and function of cellular molecules such as proteins and DNA. Water's polarity and hydrogen bonding account for its unique properties. These properties, described below, allow living things to exist and carry on cellular activities. Because of hydrogen bonding, water is liquid between 0° C and 100° C, which is essential for the existence of life.

1. *High heat capacity.* The temperature of liquid water rises and falls more slowly than that of most other liquids because the hydrogen bonds between water molecules hold more heat. This protects organisms from rapid temperature changes and helps them maintain homeostatic temperature.
2. *High heat of vaporization.* Hydrogen bonds between water molecules require a relatively large amount of heat to break. This property moderates Earth's surface temperature; permitting living systems to exist. When animals sweat, evaporation of the sweat removes body heat, thus cooling the animal.
3. *Water is a solvent.* Water dissolves a great number of substances (e.g., salts, large polar molecules). Ionized or polar molecules that are attracted to water are **hydrophilic** ("water loving"); whereas non-ionized and nonpolar molecules that cannot attract water are **hydrophobic** ("water fearing"). A **solution** contains dissolved substances called **solutes**.
4. *Cohesion and adhesion.* **Cohesion** allows water to flow freely without molecules separating. **Adhesion** is ability to adhere to polar surfaces. These characteristics allow water to rise up a tree from the roots to the leaves through small tubes. Adhesion of water to walls of vessels prevents water columns from breaking apart. Cohesion allows evaporation from leaves to pull water columns from roots.
5. *Water has a high surface tension.* Water is relatively difficult to break through at its surface. This property permits a rock to be skipped across a pond surface and supports insects walking on the surface of water.
6. *Ice is less dense than water.* Below 4° C, hydrogen bonding becomes more rigid but more open, causing expansion. Because ice is less dense, it floats; therefore, bodies of water freeze from the top down. If ice was heavier than water, ice would sink and bodies of water would freeze solid. This property allows ice to act as an insulator on bodies of water, thereby protecting aquatic organisms during the winter.

Take Note: A solid understanding of acids and bases is important for your understanding of the biochemistry presented in the next few chapters. Take time now to be sure you understand these concepts, so that you can properly understand the information that is to come.

2.4 Acids and Bases

A small fraction of water molecules dissociate to produce an equal number of hydrogen ions and hydroxide ions. The **pH scale** indicates acidity and basicity (alkalinity) of a solution. **pH** is the measurement of free hydrogen ions, expressed as a negative logarithm of the H^+ concentration ($-\log [H^+]$). Solutions with equal numbers of H^+ and OH^- are neutral. In acidic solutions, there are more hydrogen ions than hydroxide ions; these solutions have a pH less than 7. In basic solutions, there are more hydroxide ions than hydrogen ions; these solutions have a pH greater than 7. Cells are sensitive to pH changes.

Biological systems often contain buffers that help keep the pH within a normal range. **Buffers** keep pH steady and within normal limits in living organisms. Buffers stabilize pH of a solution by taking up excess hydrogen (H^+) or hydroxide (OH^-) ions, keeping the pH of the blood in a narrow range so that the body can maintain homeostasis. For example, carbonic acid helps keep blood pH within normal limits: $H_2CO_3 \rightarrow H^+ + HCO_3^-$.

Multiple Choice Questions

- Which of the following statements is NOT true regarding the properties of water?
 - Hydrogen bonds require a good deal of energy to break.
 - Water cools more slowly than other liquids.
 - The hydrogen bonds between water hold more heat energy.
 - Water reaches its boiling point more slowly than substances with a lower specific heat.
 - Water's surface tension arises due to hydrogen bonds between water molecules.
- In a molecule of DNA, the bonds holding the side chains must be very strong, whereas the bonds holding the rungs of the ladder between the nucleic acids must break during DNA replication. What types of bonds are present between adenine and thymine and cytosine and guanine in a DNA molecule?
 - nonpolar covalent
 - ionic
 - polar covalent
 - hydrogen
 - hydrophobic interactions
- Van der Waals interactions and hydrogen bonds and ionic bonds are weak interactions. Therefore,
 - their cumulative effects reinforce molecular structure, making them biologically significant.
 - they are not found in organic molecules.
 - they occur between molecules that are a long distance apart.
 - they occur when two atoms that are equally electronegative are attracted to one another.
 - they occur when cations and anions attract each other and transfer electrons.

4. Ionic bonds involve the
- equal sharing of electrons.
 - transfer of electrons.
 - uneven sharing of electrons.
 - asymmetric distribution in molecules.
 - hydrogen atom bonding of a hydrogen atom to one electronegative atom.
5. In the following reaction
- $$\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$$
- glucose is
- reduced.
 - an anion.
 - oxidized.
 - a cation.
 - electronegative.
6. One of the most common biological fluids which may be outside of the neutral pH range of 6–8 is
- saliva.
 - gastric juice.
 - mucus.
 - semen.
 - urine.
7. A buffer works by
- accepting hydrogen ions from the solution when they are in excess.
 - irreversibly combining with hydrogen ions to neutralize a base.
 - dissociating to yield OH^- ions to neutralize an acid.
 - donating hydrogen ions when they are in excess.
 - balancing the reaction between CO_2 and H_2O .
8. Evaporative cooling occurs because
- molecules with the greatest kinetic energy are the most likely to leave as a gas.
 - water's low heat of vaporization converts water to a gas.
 - when water is heated, the kinetic energy of molecules decreases and the liquid evaporates more rapidly.
 - molecules do not move fast enough to overcome attractions to other molecules.
 - hydrogen bonds form as water evaporates absorbing heat energy.
9. As water travels through xylem tissue
- hydrogen bonding attracts water to the walls of the cells to counteract gravity.
 - it forces water out of the root hairs as it travels from source to sink.
 - it is actively transported by the use of ATP.
 - it moves through aquaporins from one xylem cell to the next.
 - hydrogen bonds are not able to form because of the speed of the water molecules moving up the xylem.

10. It is improbable that the hydrogen atoms in two water molecules would be attracted to one another and the oxygen atoms would repel one another because
- hydrogen atoms have a partial negative charge and will be attracted to one another.
 - the slightly positive hydrogen of one molecule is attracted to the slightly negative oxygen of another molecule.
 - the opposite ends of water molecules have similar charges.
 - hydrogen is more electronegative than oxygen, and the electrons spend more time closer to the oxygen atom.
 - its two hydrogen atoms are joined to the oxygen atom by single covalent bonds.

Free Response Question

Water is a very unique molecule and is very important to biological systems. As an example, water striders, spiders, and other arthropods are able to walk across water.

- Discuss** three properties of water that make this possible.
- Explain** why humans are not able to walk across water.
- Propose** a hypothesis for the structure of arthropod legs to facilitate this phenomenon.

Annotated Answer Key (MC)

- C**; Hydrogen bonds do not hold heat energy, rather they require heat energy to be broken. They are strong enough to maintain the integrity of the DNA molecule.
- D**; Hydrogen bonds are readily broken and reformed, an ideal combination for the location between nucleic acids of the DNA strand.
- A**; Van der Waals forces are found in many organic molecules. These interactions usually occur between molecules that are a great distance apart and are not the same as covalent or ionic bonds, as represented by choices D and E. When viewed as a whole these interactions are very important biologically, especially in protein structure.
- B**; Ionic bonds involve attractions between ions of opposite charge. The charges of these atoms or compounds are acquired due to the loss or gain of one or more electrons. This transfer of electrons is a relatively weak bond as compared to the sharing of electrons in a covalent bond.
- B**; During aerobic respiration, a molecule of glucose is oxidized to produce ~38 molecules of ATP. When a molecule is oxidized, it loses electrons. Molecules that are reduced actually gain electrons.
- B**; Saliva, semen, urine, and mucus are all found within a relatively neutral pH range of 6–8. The pH scale ranges from 0–14, with 7 being neutral. Gastric juice has a very acidic pH, usually around 2, due to the presence of HCl in the stomach for chemical digestion.
- A**; Buffers function in pairs. When the weak acid dissolves in water it forms a weak base. The two work together to counter any small shift in pH to maintain a suitable environment for many biological processes to occur.
- A**; Water has a very high heat of vaporization. When water is heated, the kinetic energy of molecules actually increases and those water molecules are the most likely to leave. Hydrogen bonds actually break as water evaporates.

9. **A;** As water travels from the roots to the leaves, the force of gravity works against this upward movement. Adhesion (the attraction between water and the walls of the xylem) and cohesion (the attraction of water molecules to other water molecules in the xylem) create a string of water molecules that moves upward through the xylem by capillary action. This is a passive process requiring no energy or transfer of water molecules between cells.
10. **B;** A common misconception when describing hydrogen bonding is that it is a hydrogen atom bonded to a hydrogen atom. This is an unlikely probability due to the fact that the slightly positive hydrogen atom of one molecule will be attracted to slightly negative atoms of other molecules, NOT another positive hydrogen atom.

Answer to FRQ

Part A (MAX 8 POINTS)

One point identification, one point definition.

- Polarity: unequal distribution of electrons
- Cohesion: attraction of water molecules to water molecules
- Surface tension: property of water arising from cohesion of water molecules
- Hydrogen bonding: bond between hydrogen atom and an electronegative atom

Part B (MAX 2 POINTS)

- Discussion of weight (i.e., too heavy)
- Discussion of surface area (i.e., feet too small – low SA:V ratio)
- Other plausible explanations

Part C (MAX 4 POINTS)

- High surface area to volume ratio
- Webbing
- Fringes on toes
- Pressure of step (i.e., smacking)
- Circular motion (like the oar of a boat, creation of drag)
- Height of motion (creation of air pocket under the feet)
- Speed of movement
- Shallow movement