Lecture Outline: Water and Life

I. **The Specialness of Water**

A. **Water's Essential Role for Life**

1. No life would have evolved without water's specialness.

B. **The Basis of Water's Specialness: Polarity**

1. Recall: Molecules and Covalent Compounds

a. Covalent compounds form molecules.

b. Ionic compounds form crystals of indeterminate size.

c. A covalent bond is the sharing of a pair of electrons.

(1) Covalent bonds are stronger than ionic bonds.

e. Non-polar covalent bonds involve equal sharing of electrons.

f. Polar covalent bonds involve unequal sharing of electrons.

(1) Unequal sharing results in partial charges (slightly negative where electrons spend more time, slightly positive at the other end).

(2) Partial charges are denoted by lowercase Greek delta (delta minus and delta positive).

2. Hydrogen Bonds

a. Form between any polar molecules.

b. In pure water, hydrogen bonds occur between adjacent water molecules.

c. Hydrogen bonds are **not chemical bonds** because they do not change the substance.

d. They are attractive forces due to opposing partial charges.

e. Reason for unequal sharing: **Electronegativity**

(1) If two atoms are of the same element, sharing is equal.

(2) If two atoms are different elements, sharing may be unequal.

(3) Electronegativity is an atomic property that determines unequal sharing.

(4) Electronegativity values increase from lower left to upper right on the periodic table.

(5) Oxygen has high electronegativity and attracts shared electrons more strongly than hydrogen.

(6) Electrons spend more time around the more electronegative atom, creating a partial negative charge.

I. Contrast with Non-polar Molecules (e.g., Oxygen Gas, O2)

(1) Oxygen atoms are unstable alone and form O2 molecules.

(2) Oxygen has a valence of two, meaning it needs two more electrons to fill its outer shell and forms two covalent bonds.

(3) In O2, both oxygen atoms have equally high electronegativity, leading to equal sharing of electrons and no partial charges.

(4) Non-polar molecules do not orient or attract each other; water molecules do due to partial charges.

(5) Water molecules exhibit more order in a population compared to non-polar molecules.

II. **Special Properties of Water Attributed to Polarity and Hydrogen Bonding**

A. **Capillary Attraction and Transpiration**

1. Capillary attraction is the movement of water against gravity in narrow tubes.
2. Examples:
    a. Blood moving up a glass capillary tube.
    b. Transpiration in plants: directional movement of water from soil to roots, up through the plant, and out the leaves.

(1) This uphill movement is driven by a pulling force from hydrogen bonding.

(2) Water molecules form a "train" in xylem tubes, linked by hydrogen bonds.

3. Two types of sticky forces caused by hydrogen bonds:
   a. **Cohesion**: Attraction between particles of the same type (e.g., water molecules attracting other water molecules).
   b. **Adhesion**: Attraction between particles of different types (e.g., water molecules attracting the walls of vessels).
4. Mechanism of Transpiration: Water leaving the leaves turns into gas, leaving a space. Adhesive forces pull the leading water molecule up the tube wall, and cohesive forces drag the rest of the water column behind it.
5. Individual hydrogen bonds are weak, but their cumulative effect from trillions of bonds is significant.
6. This process enables water to be pulled to the tops of the tallest trees without external pumps.

B. **Surface Tension**
1. Surface tension makes the water surface appear to have a "skin" that is tougher to pierce.
2. Explanation:
   a. Water molecules at depth are pulled in all directions by surrounding molecules.
   b. Water molecules at the surface are only pulled downwards by molecules below them (no molecules above).
   c. This downward force compresses the top layer of molecules, making it denser and harder to penetrate.
3. This property allows certain animals to walk on the surface of water.

C. **High Specific Heat Capacity**
1. Specific heat capacity is the amount of energy required to change the temperature of one gram of a substance by one degree Celsius.
2. It indicates how easy or difficult it is to heat up or cool down a substance.
3. Water has a comparatively **high specific heat capacity**, meaning it takes a lot of energy to heat or cool it.
4. Implication for bodies of water: They warm and cool more slowly than

land masses.

   a. Oceans experience less extreme temperature fluctuations than land, even with the same solar energy input.

5. Biological significance: Life originated in the ocean due to the stable temperature conditions provided by water's high specific heat capacity.

D. **High Latent Heat of Vaporization**

1. Latent heat of vaporization is the amount of energy required to transform one gram of a substance from a liquid into a gas (evaporate it).
2. Vaporization is a physical change where particles move farther apart.
3. Water has a **high latent heat of vaporization**, meaning evaporating water requires a lot of heat.
4. Biological significance: Sweating cools the body.
   a. The evaporation of water from sweat takes heat from the body, leading to cooling.
   b. Evaporation cools both the liquid water from which it occurs and the air into which it evaporates.
5. Explanation of Cooling during Evaporation:
   a. **Temperature vs. Heat:**

      (1) Heat is an **extensive property**, dependent on the amount of substance (e.g., a swimming pool has more heat than a glass of water at the same temperature).

      (2) Temperature is an **intensive property**, representing the average speed of particles (e.g., a pool and a glass of water can have the same temperature if their average particle speeds are equal).

   d. Evaporation preferentially removes the **fastest-moving water molecules** from the liquid phase.
   e. Removing the fastest molecules lowers the average speed of the remaining liquid molecules, thus decreasing the liquid's temperature.
   f. The evaporated water molecules, though fast for a liquid, are

generally slower than the average particles in the air. Their addition lowers the average speed (and thus temperature) of the air.

g. This phenomenon explains cooler temperatures experienced in coastal areas where air blows inland from the ocean.

h. The presence of hydrogen bonds in water impedes molecules from escaping, contributing to the high energy required for vaporization.

E. **Water is Denser as a Liquid than as a Solid (Ice Floats)**

1. This property is unusual; most substances are denser as solids than as liquids.
2. In most solids, particles are tightly packed and locked in place (vibrating). In liquids, they are close but slipping past each other.
3. Reason (due to Hydrogen Bonding):
    a. When water freezes, molecules swivel into a specific three-dimensional "soccer ball" arrangement due to the angles of hydrogen bonds.
    b. This arrangement creates significant open space between molecules, making ice less dense than liquid water.
    c. In liquid water, the faster motion of molecules continuously breaks and reforms hydrogen bonds, preventing this rigid, spacious arrangement and allowing molecules to pack more closely.
4. Biological significance:
    a. If ice were denser and sank, bodies of water would freeze from the bottom up.
    b. This would lead to complete freezing over time, making it impossible for aquatic life to survive.
    c. Floating ice acts as a protective, insulating layer on the surface, preventing the water below from getting even colder and reflecting sunlight.
    d. This allows aquatic organisms to survive through colder seasons.

F. **Water is an Excellent Solvent**

1. A solution is a mixture where a **solvent** dissolves a **solute**.
2. Water dissolves a wide variety of solutes.

3. Reason: Water is **polar**. It effectively dissolves other polar or fully charged substances (like ionic compounds).
4. Water does not dissolve non-polar substances (e.g., oil) because they do not have partial charges for interaction.
5. Mechanism for dissolving ionic compounds (e.g., table salt, NaCl):
    a. Small, polar water molecules interact with the charges on the surface of an ionic crystal.
    b. Water molecules "pick off" individual ions from the crystal lattice.
    c. Water molecules surround each separated ion in a three-dimensional "shroud."
    d. They orient themselves so their partial charges face the opposite charge of the ion (partially positive hydrogens face negative chloride ions; partially negative oxygen faces positive sodium ions).
    e. This keeps the ions independently dissolved in the water.
6. Biological significance: This property is fundamental to life and metabolism.
    a. All chemical reactions within cells occur in "aqueous solution," meaning water is the solvent.
    b. Life fundamentally involves aqueous solution chemistry.
7. Water also dissolves other polar molecules, such as proteins:
    a. Proteins are polymers made of amino acids, some of which carry charge.
    b. Proteins fold into specific three-dimensional shapes (confirmations) that expose partial charges on their surface.
    c. Water molecules swivel to align their opposite partial charges with the protein's surface charges, effectively shrouding and dissolving the large protein molecule.

G. **Autoionization of Water and the pH Scale**

1. **Autoionization**: Pure water molecules spontaneously ionize themselves.
    a. In a population of pure water, a tiny fraction of molecules are constantly undergoing this process.

b. One water molecule transfers a proton (H^+) to another.

c. A proton (H^+) is equivalent to a hydrogen ion.

d. This process forms two types of ions:

(1) A **hydroxide ion** (OH^-): A water molecule that lost a proton, retaining the electron.

(2) A **hydronium ion** (H_3O^+): A water molecule that gained a proton. (Hydronium ions quickly lose the proton, making it equivalent to a free hydrogen ion).

g. This is a reversible reaction.

h. In pure water, equal concentrations of hydrogen ions (H^+) and hydroxide ions (OH^-) are formed.

i. Therefore, pure water is considered **neutral** (neither basic/alkaline nor acidic).

2. **The pH Scale**: Measures acidity and basicity.

a. It is a **logarithmic scale (base 10)**, meaning each whole number step represents a 10-fold difference in hydrogen ion concentration, not a linear difference.

b. It is a **negative logarithmic scale**, designed to handle very small numbers conveniently.

c. **Definition of pH**: The negative base 10 logarithm of the hydrogen ion concentration, symbolized as $[H^+]$.

d. **Neutral pH (7)**:

(1) The concentration of hydrogen ions in pure water is reliably 1×10^{-7} molar.

(2) Therefore, $pH = -\log(10^{-7}) = 7$.

(3) The value of 7 for neutrality is a direct consequence of water's properties, not an arbitrary choice.

h. **Acids**:

(1) Substances that dissociate in water, releasing additional hydrogen ions (H^+).

(2) This increases the concentration of H^+ relative to OH^-.

(3) **Lower pH values (below 7) indicate increasing acidity**.

(4) A decrease of one pH unit means a 10-fold increase in hydrogen ion concentration (e.g., pH 6 is 10 times more acidic than pH 7; pH 5 is 100 times more acidic than pH 7).

m. **Bases (Alkaline)**:

(1) Substances that dissociate in water, releasing additional hydroxide ions (OH-).

(2) This increases the concentration of OH- relative to H+.

(3) **Higher pH values (above 7) indicate increasing basicity (alkalinity)**.

q. The pH scale typically ranges from 0 to 14, but pH values can theoretically be below 0 (for very strong acids) or above 14 (for very strong bases).

3. **Biological Significance of pH Maintenance**:

a. Most cells in the human body maintain a pH very close to 7 (slightly basic).

b. Even small shifts in pH, either up or down, can be detrimental to cellular function and life.

c. The stomach is an exception, having a very low pH (2 or lower) due to hydrochloric acid secretion. This acidity is important for digestion and kills harmful bacteria.

d. **Acid Rain**:

(1) Acid rain (or acid precipitation) occurs when industrial pollutants (e.g., sulfur compounds from factories or diesel engines) mix with air and water to form acids (e.g., sulfuric acid).

(2) It significantly affects the pH of receiving environments.

(3) The primary harm to organisms (like trees) is the **denaturation of proteins**.

(4) **Protein denaturation**: A change in a protein's three-dimensional shape (confirmation) in response to environmental changes (like pH or temperature).

(5) When proteins denature, they lose their specific function (e.g., as enzymes), which can quickly kill an organism.

(6) Humans are indirectly affected by acid rain through its impact on producers (plants) in the food chain.