Unit Four: The Chemistry of Life and the Properties of Water

Part Two: The Properties of Water
Water is an important biological molecule
Water covers 75% of the Earth’s Surface
Water and Life

- Most cells are surrounded by water, and cells themselves are about 70-95% water.
- All living organisms require water more than any other substance.
  - Makes up 65-75% of our bodies.
  - 82% of our blood is water.
Water is Unique!

- Water’s unique properties make the external environment fit for living organism and the internal environment of organisms fit for the chemical and physical processes of life.

- All metabolic processes necessary for life take place in water.

- THEREFORE IT IS VERY IMPORTANT TO UNDERSTAND THE STRUCTURE OF THE WATER MOLECULE AND ITS UNIQUE PROPERTIES!
The Water Molecule
The Water Molecule

- **The structure of water** is the basis for its unique properties.
  - Chemical Formula: $H_2O$
  - Covalently bonded molecule
  - Neutral molecule
    - 10 protons
    - 10 electrons
    - Shape is called “bent”
The Water Molecule

Bohr Model of $\text{H}_2\text{O}$
Covalent Molecules

- Covalent molecules can be polar or non-polar
  - In non-polar covalent molecules, atoms share electrons equally.
  - In **polar covalent molecules**, atoms **DO NOT** share electrons equally.

- Molecules develop slightly positive sides and a slightly negative side.
The Water Molecule is Polar

- Water is a polar covalent molecule.
  - 8 protons in oxygen nucleus and only 1 proton in the nuclei of each hydrogen.
  - 8 electrons around the oxygen atom and 1 each around the hydrogen atom.
  - Remember, the electrons can move around!
  - The 8 protons of the oxygen atom attract the shared electrons from the hydrogen atoms more strongly than the individual protons in each of the hydrogen atoms.
  - The electrons move closer to the oxygen atom.
The Water Molecule is Polar

- The oxygen atom gains a partial negative charge.
- They hydrogen atoms gain partial positive charges.
- This uneven distribution of electrons between the oxygen and each hydrogen atom give water its polarity.
  - Electronegativity is the tendency for one atom to pull the electrons of another atom.
Hydrogen Bonds
The Water Molecule is Polar

- The water molecule is a polar covalent molecule
- The opposite ends have opposite charges resulting in water’s polarity.
- Polarity allows the opposite charges of water molecules to interact to form hydrogen bonds with each other.
- The ability of water to form hydrogen bonds is the basis for the many important properties of water.
Hydrogen Bonds

- **Hydrogen bonds** are attractions between a hydrogen atom and an atom such as oxygen, nitrogen, or fluorine that is either part of another molecule or located at a distant site on the same molecule.

- Both the hydrogen atom and the other atom must be involved in a polar covalent bond.
Hydrogen Bonding of Water

- **Hydrogen bonds** between water molecules are weak attractions between the partially negative oxygen of one water molecule and the partially positive hydrogen of a *different* water molecule.

- Hydrogen bonds can form between water molecules or between water and another charged molecule.
  - Weaker than true bonds
    - Ionic > covalent > hydrogen.
Hydrogen Bonding of Water

- The attraction between the hydrogen atom on one water molecule and the oxygen molecule on another water molecule forms a hydrogen bond.

- **Intermolecular forces** are forces between molecules.

- One water molecule can have 4 hydrogen bonds.
Hydrogen Bonding
Hydrogen Bonding in Ice
The polarity of water causes it to bond to itself... and to other molecules.
Hydrogen Bonding

Water molecule

Hydrogen atom

δ+ δ-

Hydrogen bond

Oxygen atom

An organic molecule

Hydrogen atom

Hydrogen bond

δ+ δ-

Oxygen atom
The Properties of Water
The Properties of Water

- 6 properties of water that facilitate an environment for life
  - External environment of Earth
  - Internal environment of organisms
- All six properties are a direct result of the polarity of water and its ability to form hydrogen bonds with other water molecules as well as other polar molecules!
The Properties of Water

- **Cohesion**
  - Creates surface tension

- **Adhesion**
  - Combined with cohesion, creates Capillary Action

- **High Specific Heat**
  - Results in resistance to temperature change

- **High Heat of Vaporization**
  - Evaporative cooling

- **Density Anomaly**
  - Ice floats

- **Universal Solvent**
  - Solutions
Cohesion
Cohesion

- Cohesion is the attraction of a substance to itself
  - The attraction of water to another water molecules
  - It results from hydrogen bonding
- Surface tension is a measure of how hard it is to break the surface of a liquid.
  - Surface tension is a result of cohesion.
Surface Tension

- Surface tension

- Because of the hydrogen bonding, water acts as if it were coated with a film. This surface tension (the tough “Skin” formed on the surface of water) causes water to “bead-up” on a hard, unwettable surface. Surface tension allows us to skip rocks on water and it allow small organisms like the water strider to “walk on water”.

Averett

11/15/2013
Surface Tension
Adhesions
Adhesion

- Adhesion is the attraction of different substance to one another.
  - The attraction of water to different substances.
MENISCUS OF WATER & MERCURY
Nonpolar liquid mercury forms a convex meniscus in a glass tube, whereas polar water with a strong adhesion to (polar) glass forms a concave meniscus.

- The water’s surface is curved down because water has greater adhesion than cohesion.
- The surface of mercury is curved up because mercury has greater cohesion than adhesion.
Cohesion, Adhesion and Capillary Action

- Cohesion and adhesion work together to allow capillary action.
  - The ability of water to spread through fine pores or to move upward through narrow tubes against the force of gravity
  - The rise in height being inversely proportional to the tub’s radius.
Transpiration

- Capillary action allows water to be transported against gravity in plants without using energy!!!
- This is called transpiration.
High Specific Heat
High Specific Heat

- Specific heat is the amount of heat that must be absorbed or lost for 1 gram of that substance to change by 1°C

  - Calorie – the amount of heat energy it takes to raise the temperature of 1 gram of water 1°C
    - Kilocalorie – the amount of heat energy required to raise the temperature of 1 kg of water by 1°C
      - *calories on food packages are actually kilocalories

- The specific heat of water is 1 cal/g/°C
  - This sets the standard of comparison for all substances
High Specific Heat

The high specific heat of water is due to hydrogen bonding.

- Heat is absorbed when hydrogen bonds break
  - When water is heated, most of the heat energy is used to break hydrogen bonds and not much is left over to raise the temperature of the water.

- Heat is released when hydrogen bonds form. (liquid to solid....)
High Specific Heat

Example:

- A greater input of energy is required to raise the temperature of water than the temperature of air.

- This is why we see a different in water temperature versus air temperature when we are swimming....

- Water absorbs heat from warmer air and releases stored heat to cooler air.

- Water can absorb or release a large amount of heat with only a slight change in its own temperature.
The high specific heat of water minimizes temperature fluctuations to within limits that permit life and help maintain stability.

Because water can absorb a lot of heat with little change in temperature, it acts as a thermal buffer.

The world is covered mostly by water.

Large bodies of water resist changes in temperature and provide stable environmental temperatures for organisms as well moderate the climate of the nearby land.

Large bodies of water can absorb and store huge amounts of heat from the sun during the daytime and summer while warming up only a few degrees.

Then, the water gradually cools in the evening and warms the air.

This creates a more stable environment because it keeps the air cooler in the day and warmer at night. Compare coasts to desserts.
High Specific Heat

- Organisms are made primarily of water, so these same properties help to maintain body temperatures.
  - Water in a cell can absorb much heat with little change in temperature.
  - This is vital because many biologically important chemical reactions take place in a very narrow temperature range.
High Heat of Vaporization
Heat of Vaporization

- The transformation from a liquid to a gas is called vaporization or evaporation.
- Heat of Vaporization is the quantity of heat a liquid must absorb for 1 gram of it to be converted from the liquid to the gas state.
High Heat of Vaporization

- The amount of heat energy needed to change 1 gram of 100°C boiling water to 100°C steam is 540 cal/g.
  - this is double the amount needed for alcohol or ammonia
- This is due to hydrogen bonding
  - Hydrogen bonds make it difficult for water molecules to escape the liquid state and are responsible for water’s high heat of vaporization
    - The hydrogen bonds must be broken before water can evaporate and this requires considerable energy.
Evaporative Cooling

- As a liquid evaporates, heat is taken away and the surface of the remaining liquid cools down.
  - This process is called evaporative cooling.
  - Evaporative cooling of water helps stabilize temperatures in organism and bodies of water.
Evaporative Cooling

- In organisms, evaporative cooling helps moderate body temperature through sweating
  - As the molecules of water change into a gas, they can float away from the body
  - When sweat evaporates and becomes a gas, it not only changes its state, but it also takes a small amount of heat with it when it floats away from your body.
  - Multiply this by millions of sweat molecules, and our body begins to feel cooler. The sweat literally takes the heat away from your body.
**Evaporative Cooling**

- **More Humidity**
  - Sweat stays on your skin
  - Little to no relief from the heat

- **Less Humidity**
  - Sweat evaporates
  - More relief from the heat
Evaporative Cooling

- Evaporative cooling helps moderate Earth’s climate by absorbing solar radiation and dissipating the heat by evaporation of surface water.
- Much of the solar heat absorbed by tropical seas is consumed during evaporation of surface water.
- Then the moist tropical air circulates poleward and it releases the heat as it condensed to form rain.
- This property also contributes to the stability of temperature in lakes and ponds.
Evaporative Cooling
Evaporative Cooling

HEAT ENERGY TAKEN FROM ENVIRONMENT

Sublimation

Solid Water (Ice)

Melting 335 kJ/kg

Freezing

Liquid Water

Evaporation 2257 kJ/kg

Condensation

Deposition

Water Vapor

HEAT ENERGY RELEASED TO ENVIRONMENT
Density Anomaly
Density Anomaly

• Most substances increase in density as temperature decreases because the molecules making up the substance begin to move more slowly and get closer together.

• Conversely, in most substances, density decreases as temperature increases
• This is true for water until it reaches 4°C Celsius!

• As water cools below 4°C, it expands and its density begins to decrease as the temperature decreases and approaches 0°C, the freezing point of water.

• At 4°C things change – the water molecules come so close together that every one of them can form hydrogen bonds simultaneously with 4 other molecules.

• Water’s density then begins to decrease due to the crystal like structures that form when hydrogen bonds form!!!
Density Anomaly

• Due to the geometry of the water molecule, water molecules must move slightly apart to maintain the max number of hydrogen bonds in a stable structure.

• At 0° Celsius, an open network is formed, allowing air in and ice becomes less dense than liquid water
  • This is why ice floats on top of water!!!!
  • If water continued to contract as it froze, it would be heavier than liquid water
Density Anomaly

- Water
- Benzene
Density Anomaly

Ice

Hydrogen bonds are stable

Hydrogen bond

Liquid water

Hydrogen bonds constantly break and re-form

Copyright © Pearson Education, Inc., publishing as Benjamin Cummings.
Density Anomaly

(a) In ice, water molecules form a crystal lattice.

(b) In liquid water, no crystal lattice forms.

(c) Liquid water is denser than ice. As a result, ice floats.
Density Anomaly

• This effects the environment!
  • If water continued to contract as it froze, it would be heavier than liquid water.
    • Bodies of water would freeze from the bottom up, not melt, and all life would be destroyed!!!
  • Instead, layers of ice insulate water below it, keeping temperatures at or above the freezing point of water and allowing life to exist beneath the frozen surface during cold seasons.
    • When ice freezes, it releases heat to surroundings, so ice and snow act at temperature stabilizers.
Density Anomaly

• This also causes spring overturn.
• Ice covers surfaces of bodies of water in winter causing stratification of layers
• Ice melts in spring, becomes denser water, and sinks to the bottom of the lake, causing water to circulate throughout the lake.
• Oxygen from the surface is returned to the depths, and nutrients released by bottom dwelling bacteria are carried to the upper layers of the lake.
• This is the life cycle of a lake.
Property of Water #6

- Universal Solvent
Universal Solvent

- Water is the solvent of life, often called the *universal solvent* due to the fact that many substances both polar and ionic will dissolve in water.
  - This is due to its polarity!
  - Will dissolve both ionic and polar substances!
Universal Solvent

- A **solution** is a liquid homogeneous mixture of two or more substances.
  - The dissolving agent is called the **solvent**
  - The solvent is always present in greater amounts than the solute
  - The substance that is dissolved is called the **solute**

When water is the solvent, the solution is an aqueous solution.
Universal Solvent

- Water is the Universal Solvent
  The positive and negative regions of water molecules are attracted to oppositely charged ions or partially charged regions of polar molecules
  - Solute molecules become surrounded by water molecules and *dissolve* into solution.

**IONIC COMPOUNDS DISSOLVE IN WATER**
The partial charges of the water molecules attract the full charges of the ions. The water molecules surround each ion and pulls the compound apart.
NaCl dissolving in H₂O
Universal Solvent

• POLAR MOLECULES DISSOLVE IN WATER - Attraction between the water molecules and the solute molecules is greater than the attraction among the molecules of the solute.
• CO₂ is a polar molecule
• Sugar is a polar molecule - Carbohydrates (sugar) have polar hydroxyl (OH) groups that can hydrogen bond to water molecules. As weak hydrogen bonds form, energy is released and this is used to break up the sugar crystal allowing it to dissolve. The sugar molecules are surrounded by water molecules and then carried off into solution.
Universal Solvent

Lysozyme molecule in a nonaqueous environment

(b) Lysozyme molecule (purple) in an aqueous environment

Ionic and polar regions on the protein’s surface attract water molecules.
• NONPOLAR MOLECULES WILL NOT DISSOLVE IN WATER! They do not have charged or partially charged regions.
  • Lipids (fats and oils) will not dissolve in water.
    • This is why “oil and water don’t mix”
  • A crystal of iodine (I$_2$) is added to water (left) and to carbon tetrachloride (right).

Both have had the same amount of time and stirring but the purple iodine crystal remains undissolved in the water but has dissolved in the carbon tetrachloride.

Iodine molecules are nonpolar. Is carbon tetrachloride polar or nonpolar?
• Ionic and polar substances are hydrophilic
  • They have an affinity for water due to electrical attractions and hydrogen bonding

• Nonpolar and non-ionic compounds are hydrophobic
  • They will not mix with or dissolve in water
Universal Solvent and Solubility

• Molecules and ions cannot take part in chemical processes inside cells unless they dissolve in water!
• Important materials cannot be transported within an organism unless they are dissolved in water or water-based fluids.
• However, nonpolar substances will only dissolve in other nonpolar substances.
  - Nonpolar vitamin E will dissolve in nonpolar fat in your cells – therefore you do need some fat in your diet.
Blood is mostly water
  - Plasma, the liquid part of your blood, is 95% water
    - Plasma’s solvent is water
    - Plasma’s solutes are sugars, protein, and other polar molecules

It is both – a solution and a suspension
  - $O_2$ is dissolved in the water in the blood
    - Therefore it is a solution
  - Cells and platelets are not dissolved
    Therefore it is a suspension
A mosquito injects a solution containing a protein solute that prevents blood from clotting.

The mosquito sucks in blood which is a solution containing solutes such as ions, sugars, and proteins.
Matter Flowchart

MATTER

Can it be physically separated?

MIXTURE

Is the composition uniform?

Homogeneous Mixture (solution)

Colloids

no

go to PURE SUBSTANCE

Can it be chemically decomposed?

Compound or Molecule

Suspensions

yes

no

no

go to PURE SUBSTANCE

no

Element

yes

Heterogeneous Mixture

no

yes

no

no

no
• Mixture
  • 2 or more substances that are physically mixed together but not chemically combined
  • 2 types of mixtures
    • Solutions
      • Homogeneous mixture – one substance completely dissolves in another so components are evenly distributed. Particles are so small they do not settle, therefore there is no Tyndell effect. (rubbing alcohol)
    • Suspensions and colloids
      • Heterogeneous mixtures
        • suspensions – A fluid containing solid particles that are sufficiently large for sedimentation. The solid is dispersed throughout the fluid through agitation. Unlike colloids, suspensions will eventually settle. (oil and water)
        • Colloids – a fluid containing medium sized solid particles that will not settle but are large enough to cause Tyndell effect. (milk)
The Tyndall Effect is caused by reflection of light by very small particles in suspension in a transparent medium. It is often seen from the dust in the air when sunlight comes in through a window, or comes down through holes in clouds. It is seen when headlight beams are visible on foggy nights, and in most X-File episodes when Moulder and Scully check out some dark place with flashlights.
Concentration of a solution

- The amount of solute dissolved in a certain amount of solvent is a solution’s concentration
  - There is a point where no more solute can be dissolved in a solvent… it is saturated
Acids, Bases and the pH Scale
Acids, Bases and pH

- Some compounds break up into hydrogen ions (H⁺) or hydroxide ions (OH⁻) when they dissolve in water.
  - These ions can make the solution acidic or basic.
  - Examples: carbonic acid
    - Example: water

\[
\text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^-
\]

- Carbonic acid
- Hydrogen ion or proton
- Bicarbonate ion

\[
\text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^-
\]

- Water
- Hydrogen ion or proton
- Hydroxide ion
Acids, Bases and pH

• A compound that releases or donates a proton when added to, or dissolved in, water is an **Acid**
  
  • **Remember!** A hydrogen ion (H\(^+\)) is simply a proton.
    • Releasing a hydrogen ion (H\(^+\)) is the same as releasing a proton and therefore increases the concentration of protons in the solution.
    • Increases the concentration of H\(^+\) ions in solution.
A compound that removes a proton or breaks into hydroxide (OH⁻) ions and another compound when dissolved in water is a **Base**

- **Remember!** A hydroxide ion (OH⁻) can bond to a hydrogen ion (H⁺) to form H₂O
  - This is the same as removing a proton and therefore decreases the concentration of protons in the solution.
  - Decreases the concentration of H⁺ ions in solution.
Acids, Bases and pH

- The pH scale is a system designed by scientists to measure the amount of hydrogen ions (H\(^+\)) in solution.
  - The scale ranges from 0 to 14.
    - 0 is many hydrogen ions!!!
    - 14 is few hydrogen ions!!!
The pH of a solution depends on the concentration of H⁺ ions.

- Stomach acid pH between 1 and 3
- Pure water pH 7
- Blood pH 7.4
- Bile pH between 8 and 9

The concentration of H⁺ ions varies depending on how acidic or basic a solution is.

- High H⁺ concentration
- Low H⁺ concentration
**ACIDS**: More hydrogen ions ($H^+$) than hydroxide ions ($OH^-$).

Most biological fluids have pH values in the range of 6 to 8.

**BASES**: More hydroxide ions ($OH^-$) than hydrogen ions ($H^+$).
• The scale ranges from 0-14.
  • A pH below 7 is acidic
    - This means the solution has a greater concentration of $\text{H}^+$ (and a lower concentration of $\text{OH}^-$)
  • A pH above 7 is basic (alkaline)
    - This means the solution has a lower concentration of $\text{H}^+$ (and a greater concentration of $\text{OH}^-$)
  • A pH of 7 is neutral
    - This means the solution has an equal concentration of $\text{H}^+$ and $\text{OH}^-$. 
Acids, Bases, and pH

- **Acids**
  - **High H⁺ ion concentration**
  - **Low pH below 7**
  - **Sour taste**
  - **Examples:**
    - Stomach acid  pH 1-3
    - Lemon juice  pH 2-4
    - Coffee
    - Tabasco
    - Soft drinks
Acids, Bases, and pH

- **Bases**
  - Low $\text{H}^+$ ion concentration
  - High pH above 7
  - Bitter taste
  - Tend to feel slippery
- **Examples**
  - Cleaning products: bleach, lye, ammonium  pH 11-14
  - Seawater  pH 7.8 – 8.3
  - Baking soda  pH 9.0
Acids, Bases and pH

• In any aqueous solution at 25°C the product of H⁺ and OH⁻ is constant and can be written as

$$[\text{H}^+][\text{OH}^-] = 10^{-14}$$

  • Pure water (distilled) is neutral allowing it to be a component of even really strong acids and bases.

• The value of the pH is the negative log of the H⁺ concentration in moles per liter, written as  
  $$\text{pH} = -\log [\text{H}^+]$$

• For a neutral aqueous solution  
  $$[\text{H}^+] \text{ is } 10^{-7} = -(−7) = 7$$
Acids, Bases and pH

- A substance with a pH of 3 has $1.0 \times 10^{-3}$ (0.001) moles per liter of hydrogen ions in solution.
- A value of pH 4 means that the substance in question has a pH of $1.0 \times 10^{-4}$ (0.0001) moles per liter of hydrogen ions in solution.
- Therefore, a solution of pH 3 is 10 times more acidic than a solution with a pH of 4.
- A solution with a pH of 6 is 1,000 times more acidic than a solution with a pH of 9.
Acids, Bases and pH

- Each change in value on the pH scale reflects a tenfold change.
  - A pH of 4 is 10 times more acidic than a pH of 5.
  - A pH of 4 is 100 times more acidic than a pH of 6.
Buffers and pH

• The internal pH of most living cells must remain close to pH 7
  • Human body cells have a pH of 6.5-7.5
  • Our body uses substances known as buffers to maintain homeostasis in regards to pH

• Buffers - substances that resist changes in pH
  • A buffer works by absorbing excess hydrogen ions or donating hydrogen ions when there are too few.
  • Most important in humans is bicarbonate ion.

  \[
  \begin{align*}
  H_2CO_3 & \rightleftharpoons HCO_3^- + H^+ \\
  \text{H}^+ \text{ donor (acid)} & \quad \text{H}^+ \text{ acceptor (base)} \\
  \text{Hydrogen ion} &
  \end{align*}
  \]
Most buffers consist of an acid-base pair that reversibly combines with $H^+$

$$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

Carbonic acid \hspace{2cm} bicarbonate ion

Example: Human blood contains carbonic acid which acts as a buffer and maintains homeostatic pH ranges in our blood.

- The pH range of blood is between pH of 7.35-7.45
  - Slightly basic
  - If blood pH is greater than 7.8 or below 6.8 chemical reactions will not longer occur and death will result!
Measuring pH

➢ There are several INDICATORS used to measure pH:
  - pH paper
  - litmus paper
  - pH meter
The pH of a solution depends on the concentration of $H^+$ ions.

- Stomach acid pH between 1 and 3
- Pure water pH 7
- Blood pH 7.4
- Bile pH between 8 and 9

The concentration of $H^+$ ions varies depending on how acidic or basic a solution is.

- High $H^+$ concentration
- Low $H^+$ concentration
The pH scale measures the concentration of hydrogen ions ($H^+$) in a solution. A pH of 7 is neutral, with $[H^+] = [OH^-]$. A pH below 7 indicates an acidic solution, with increasingly acidic from 1 to 0. A pH above 7 indicates a basic solution, with increasingly basic from 8 to 14.

- **Acidic solutions** (pH < 7): Battery acid, Gastric juice, lemon juice, Vinegar, beer, wine, cola, Tomato juice, Black coffee.
- **Neutral solutions** (pH = 7): Rainwater, Urine, Saliva, Pure water, Human blood, tears, Seawater.
- **Basic solutions** (pH > 7): Milk of magnesia, Household ammonia, Household bleach, Oven cleaner, Sodium hydroxide.