Chapter 3 Water and the Fitness of the Environment
Lecture Outline

Overview: The Molecule That Supports All of Life

- Because water is the substance that makes life possible on Earth, astronomers hope to find evidence of water on newly discovered planets orbiting distant stars.
- Life on Earth began in water and evolved there for 3 billion years before colonizing the land.
- Even terrestrial organisms are tied to water.
  - Most cells are surrounded by water.
  - Cells are about 70–95% water.
  - Water is a reactant in many of the chemical reactions of life.
- Water is the only common substance that exists in the natural world in all three physical states of matter: solid ice, liquid water, and water vapor.

Concept 3.1 The polarity of water molecules results in hydrogen bonding

- In a water molecule, two hydrogen atoms form single polar covalent bonds with an oxygen atom.
  - Because oxygen is more electronegative than hydrogen, the region around the oxygen atom has a partial negative charge.
  - The regions near the two hydrogen atoms have a partial positive charge.
- A water molecule is a polar molecule in which opposite ends of the molecule have opposite charges.
- Water has a variety of unusual properties because of the attraction between polar water molecules.
  - The slightly negative regions of one water molecule are attracted to the slightly positive regions of nearby water molecules, forming hydrogen bonds.
  - Each water molecule can form hydrogen bonds with up to four neighbors.

Concept 3.2 Four emergent properties of water contribute to Earth's fitness for life

Organisms depend on the cohesion of water molecules.

- The hydrogen bonds joining water molecules are weak, about 1/20 as strong as covalent bonds.
- They form, break, and reform with great frequency. Each hydrogen bond lasts only a few trillionths of a second.
- At any instant, a substantial percentage of all water molecules are bonded to their neighbors, creating a high level of structure.
- Collectively, hydrogen bonds hold water together, a phenomenon called **cohesion.**
- Cohesion among water molecules plays a key role in the transport of water and dissolved nutrients against gravity in plants.
  - Water molecules move from the roots to the leaves of a plant through water-conducting vessels.

  - As water molecules evaporate from a leaf, other water molecules from vessels in the leaf replace them.
  - Hydrogen bonds cause water molecules leaving the vessels to tug on molecules farther down.
  - This upward pull is transmitted down to the roots.
  - **Adhesion,** clinging of one substance to another, contributes too, as water adheres to the wall of the vessels.
- **Surface tension,** a measure of the force necessary to stretch or break the surface of a liquid, is related to cohesion.
  - Water has a greater surface tension than most other liquids because hydrogen bonds among surface water molecules resist stretching or breaking the surface.
  - Water behaves as if covered by an invisible film.
  - Some animals can stand, walk, or run on water without breaking the surface.

Water moderates temperatures on Earth.

- Water stabilizes air temperatures by absorbing heat from warmer air and releasing heat to cooler air.
- Water can absorb or release relatively large amounts of heat with only a slight change in its own temperature.
- Atoms and molecules have **kinetic energy,** the energy of motion, because they are always moving.
  - The faster a molecule moves, the more kinetic energy it has.
- **Heat** is a measure of the *total* quantity of kinetic energy due to molecular motion in a body of matter.
- **Temperature** measures the intensity of heat in a body of matter due to the *average* kinetic energy of molecules.
  - As the average speed of molecules increases, a thermometer will record an increase in temperature.
- Heat and temperature are related, but not identical.
- When two objects of different temperatures come together, heat passes from the warmer object to the cooler object until the two are the same temperature.
  - Molecules in the cooler object speed up at the expense of kinetic energy of the warmer object.
  - Ice cubes cool a glass of pop by absorbing heat from the pop as the ice melts.
- In most biological settings, temperature is measured on the **Celsius scale** (°C).
  - At sea level, water freezes at 0°C and boils at 100°C.
  - Human body temperature is typically 37°C.
- While there are several ways to measure heat energy, one convenient unit is the **calorie (cal).**
  - One calorie is the amount of heat energy necessary to raise the temperature of one g of water by 1°C.
  - A calorie is released when 1 g of water cools by 1°C.
- In many biological processes, the **kilocalorie (kcal)** is more convenient.
  - A kilocalorie is the amount of heat energy necessary to raise the temperature of 1000 g of water by 1°C.

- Another common energy unit, the **joule (J),** is equivalent to 0.239 cal.
- Water stabilizes temperature because it has a high specific heat.
- The **specific heat** of a substance is the amount of heat that must be absorbed or lost for 1 g of that substance to change its temperature by 1°C.
    - By definition, the specific heat of water is 1 cal per gram per degree Celsius or 1 cal/g/°C.
- Water has a high specific heat compared to other substances.
    - For example, ethyl alcohol has a specific heat of 0.6 cal/g/°C.
    - The specific heat of iron is 1/10 that of water.
- Water resists changes in temperature because of its high specific heat.
    - In other words, water absorbs or releases a relatively large quantity of heat for each degree of temperature change.
- Water's high specific heat is due to hydrogen bonding.
    - Heat must be absorbed to break hydrogen bonds, and heat is released when hydrogen bonds form.
    - Investment of one calorie of heat causes relatively little change to the temperature of water because much of the energy is used to disrupt hydrogen bonds, not speed up the movement of water molecules.
- Water's high specific heat has effects that range from the level of the whole Earth to the level of individual organisms.
    - A large body of water can absorb a large amount of heat from the sun in daytime during the summer and yet warm only a few degrees.
    - At night and during the winter, the warm water will warm cooler air.
    - Therefore, ocean temperatures and coastal land areas have more stable temperatures than inland areas.
    - Living things are made primarily of water. Consequently, they resist changes in temperature better than they would if composed of a liquid with a lower specific heat.
- The transformation of a molecule from a liquid to a gas is called **vaporization** or **evaporation.**
    - This occurs when the molecule moves fast enough to overcome the attraction of other molecules in the liquid.
    - Even in a low-temperature liquid (with low average kinetic energy), some molecules are moving fast enough to evaporate.
    - Heating a liquid increases the average kinetic energy and increases the rate of evaporation.
- **Heat of vaporization** is the quantity of heat that a liquid must absorb for 1 g of it to be converted from liquid to gas.
    - Water has a relatively high heat of vaporization, requiring about 580 cal of heat to evaporate 1 g of water at room temperature.
    - This is double the heat required to vaporize the same quantity of alcohol or ammonia.
    - This is because hydrogen bonds must be broken before a water molecule can evaporate from the liquid.
    - Water's high heat of vaporization moderates climate.
    - Much of the sun's heat absorbed by tropical oceans is used for evaporation of surface water.

- As moist tropical air moves to the poles, water vapor condenses to form rain, releasing heat.

- As a liquid evaporates, the surface of the liquid that remains behind cools, a phenomenon called **evaporative cooling.**
  - This occurs because the most energetic molecules are the most likely to evaporate, leaving the lower–kinetic energy molecules behind.
- Evaporative cooling moderates temperature in lakes and ponds.
- Evaporation of sweat in mammals or evaporation of water from the leaves of plants prevents terrestrial organisms from overheating.
  - Evaporation of water from the leaves of plants or the skin of humans removes excess heat.

Oceans and lakes don't freeze solid because ice floats.

- Water is unusual because it is less dense as a solid than as a cold liquid.
  - Most materials contract as they solidify, but water expands.
  - At temperatures above 4°C, water behaves like other liquids, expanding as it warms and contracting as it cools.
  - Water begins to freeze when its molecules are no longer moving vigorously enough to break their hydrogen bonds.
- When water reaches 0°C, water becomes locked into a crystalline lattice, with each water molecule bonded to a maximum of four partners.
- As ice starts to melt, some of the hydrogen bonds break, and water molecules can slip closer together than they can while in the ice state.
- Ice is about 10% less dense than water at 4°C.
- Therefore, ice floats on the cool water below.
- This oddity has important consequences for life.
  - If ice sank, eventually all ponds, lakes, and even the ocean would freeze solid.
  - During the summer, only the upper few centimeters of the ocean would thaw.
  - Instead, the surface layer of ice insulates liquid water below, preventing it from freezing and allowing life to exist under the frozen surface.

Water is the solvent of life.

- A liquid that is a completely homogeneous mixture of two or more substances is called a **solution.**
  - A sugar cube in a glass of water will eventually dissolve to form a uniform solution of sugar and water.
  - The dissolving agent is the **solvent,** and the substance that is dissolved is the **solute.**
  - In our example, water is the solvent and sugar is the solute.
- In an **aqueous solution,** water is the solvent.
- Water is not a universal solvent, but it is very versatile because of the polarity of water molecules.
  - Water is an effective solvent because it readily forms hydrogen bonds with charged and polar covalent molecules.
  - For example, when a crystal of salt (NaCl) is placed in water, the Na^+ cations interact with the partial negative charges of the oxygen regions of water molecules.

- The Cl^- anions interact with the partial positive charges of the hydrogen regions of water molecules.

- Each dissolved ion is surrounded by a sphere of water molecules, a **hydration shell.**
- Eventually, water dissolves all the ions, resulting in a solution with two solutes: sodium and chloride ions.
- Polar molecules are also soluble in water because they form hydrogen bonds with water.
- Even large molecules, like proteins, can dissolve in water if they have ionic and polar regions.
- Any substance that has an affinity for water is **hydrophilic** *(water-loving).*
  - These substances are dominated by ionic or polar bonds.
- Some hydrophilic substances do not dissolve because their molecules are too large.
  - For example, cotton is hydrophilic because cellulose, its major constituent, has numerous polar covalent bonds. However, its giant cellulose molecules are too large to dissolve in water.
  - Water molecules form hydrogen bonds with the cellulose fibers of cotton, allowing you to dry yourself with your cotton towel as the water is pulled into the towel.
- Substances that have no affinity for water are **hydrophobic** *(water-fearing).*
  - These substances are nonionic and have nonpolar covalent bonds.
  - Because there are no consistent regions with partial or full charges, water molecules cannot form hydrogen bonds with hydrophobic molecules.
  - Oils such as vegetable oil are hydrophobic because the dominant bonds, carbon-carbon and carbon-hydrogen, share electrons equally.
  - Hydrophobic molecules are major ingredients of cell membranes.
- Biological chemistry is “wet” chemistry with most reactions involving solutes dissolved in water.
- Chemical reactions depend on collisions of molecules and therefore on the concentrations of solutes in aqueous solution.
- We measure the number of molecules in units called **moles.**
- The actual number of molecules in a mole is called Avogadro’s number, 6.02×10^{23}.
- A mole is equal to the molecular weight of a substance but scaled up from daltons to grams.
- To illustrate, how could we measure out a mole of table sugar—sucrose ($C_{12}H_{22}O_{11}$)?
  - A carbon atom weighs 12 daltons, hydrogen 1 dalton, and oxygen 16 daltons.
  - One molecule of sucrose would weigh 342 daltons, the sum of weights of all the atoms in sucrose, or the **molecular weight** of sucrose.
  - To get one mole of sucrose, we would weigh out 342 g.
- The advantage of using moles as a measurement is that a mole of one substance has the same number of molecules as a mole of any other substance.
  - If substance A has a molecular weight of 10 daltons and substance B has a molecular weight of 100 daltons, then we know that 10 g of substance A has the same number of molecules as 100 g of substance B.
  - A mole of sucrose contains 6.02×10^{23} molecules and weighs 342 g, while a mole of ethyl alcohol (C_2H_6O) also contains 6.02×10^{23} molecules but weighs only 46 g because the molecules are smaller.

- Measuring in moles allows scientists to combine substances in fixed ratios of molecules.

- In "wet" chemistry, we are typically combining solutions or measuring the quantities of materials in aqueous solutions.
  - The concentration of a material in solution is called its **molarity.**
  - A one molar solution has one mole of a substance dissolved in one liter of solvent, typically water.
  - To make a 1 molar (1M) solution of sucrose, we would slowly add water to 342 g of sucrose until the total volume was 1 liter and all the sugar was dissolved.

Concept 3.3 Dissociation of water molecules leads to acidic and basic conditions that affect living organisms

- Occasionally, a hydrogen atom participating in a hydrogen bond between two water molecules shifts from one molecule to the other.
  - The hydrogen atom leaves its electron behind and is transferred as a single proton—a **hydrogen ion** (H^+).
  - The water molecule that lost the proton is now a **hydroxide ion** (OH^-).
  - The water molecule with the extra proton is now a **hydronium ion** (H_3O^+).
- A simplified way to view this process is to say that a water molecule dissociates into a hydrogen ion and a hydroxide ion:
  - $H_2O <=> H^+ + OH^-$
- This reaction is reversible.
- At equilibrium, the concentration of water molecules greatly exceeds that of H^+ and OH^-.
- In pure water, only one water molecule in every 554 million is dissociated.
  - At equilibrium, the concentration of H^+ or OH^- is $10^{-7}M$ (at 25°C).
- Although the dissociation of water is reversible and statistically rare, it is very important in the chemistry of life.
- Because hydrogen and hydroxide ions are very reactive, changes in their concentrations can drastically affect the chemistry of a cell.
- Adding certain solutes, called acids and bases, disrupts the equilibrium and modifies the concentrations of hydrogen and hydroxide ions.
- The pH scale is used to describe how acidic or basic a solution is.

Organisms are sensitive to changes in pH.

- An **acid** is a substance that increases the hydrogen ion concentration in a solution.
  - When hydrochloric acid is added to water, hydrogen ions dissociate from chloride ions: $HCl \rightarrow H^+ + Cl^-$
  - Addition of an acid makes a solution more acidic.
- Any substance that reduces the hydrogen ion concentration in a solution is a **base.**
- Some bases reduce the H^+ concentration directly by accepting hydrogen ions.
  - Ammonia (NH_3) acts as a base when the nitrogen's unshared electron pair attracts a hydrogen ion from the solution, creating an ammonium ion (NH_4^+).
  - $NH_3 + H^+ <=> NH_4^+$

- Other bases reduce H^+ indirectly by dissociating to OH^-, which then combines with H^+ to form water.
  - $NaOH \rightarrow Na^+ + OH^-$ $\qquad OH^- + H^+ \rightarrow H_2O$
- Solutions with more OH^- than H^+ are basic solutions.
- Solutions with more H^+ than OH^- are acidic solutions.
- Solutions in which concentrations of OH^- and H^+ are equal are neutral solutions.
- Some acids and bases (HCl and NaOH) are strong acids or bases.
  - These molecules dissociate completely in water.
- Other acids and bases (NH_3) are weak acids or bases.
  - For these molecules, the binding and release of hydrogen ions are reversible.
  - At equilibrium, there will be a fixed ratio of products to reactants.
  - Carbonic acid (H_2CO_3) is a weak acid:
    - H2CO3 <=> HCO3− + H+
    - At equilibrium, 1% of the H2CO3 molecules will be dissociated.
- In any solution, the *product* of the H^+ and OH^- concentrations is constant at 10^{-14}.
- Brackets ($[H^+]$ and $[OH^-]$) indicate the molar concentration of the enclosed substance.
  - $[H^+]\,[OH^-] = 10^{-14}$
  - In a neutral solution, $[H^+] = 10^{-7}\,M$ and $[OH^-] = 10^{-7}\,M$
- Adding acid to a solution shifts the balance between H^+ and OH^- toward H^+ and leads to a decline in OH^-.
  - If $[H^+] = 10^{-5}\,M$, then $[OH^-] = 10^{-9}\,M$
  - Hydroxide concentrations decline because some of the additional acid combines with hydroxide to form water.
- Adding a base does the opposite, increasing OH^- concentration and lowering H^+ concentration.
- The H^+ and OH^- concentrations of solutions can vary by a factor of 100 trillion or more.
- To express this variation more conveniently, the H^+ and OH^- concentrations are typically expressed via the pH scale.
  - The pH scale, ranging from 1 to 14, compresses the range of concentrations by employing logarithms.
  - $pH = -\log [H^+]$ or $[H^+] = 10^{-pH}$
  - In a neutral solution, [H+] = 10−7 M, and the pH = 7.
- Values for pH *decline* as $[H^+]$ *increase*.
- While the pH scale is based on $[H^+]$, values for $[OH^-]$ can be easily calculated from the product relationship.
- The pH of a neutral solution is 7.
- Acidic solutions have pH values less than 7, and basic solutions have pH values greater than 7.
- Most biological fluids have pH values in the range of 6 to 8.
  - However, the human stomach has strongly acidic digestive juice with a pH of about 2.
- Each pH unit represents a tenfold difference in H^+ and OH^- concentrations.

- A small change in pH actually indicates a substantial change in H^+ and OH^- concentrations.

- The chemical processes in the cell can be disrupted by changes to the H^+ and OH^- concentrations away from their normal values, usually near pH 7.
- To maintain cellular pH values at a constant level, biological fluids have **buffers.**
- Buffers resist changes to the pH of a solution when H^+ or OH^- is added to the solution.
  - Buffers accept hydrogen ions from the solution when they are in excess and donate hydrogen ions when they have been depleted.
  - Buffers typically consist of a weak acid and its corresponding base.
  - One important buffer in human blood and other biological solutions is carbonic acid, which dissociates to yield a bicarbonate ion and a hydrogen ion.
  - The chemical equilibrium between carbonic acid and bicarbonate acts as a pH regulator. The equilibrium shifts left or right as other metabolic processes add or remove H^+ from the solution.

Acid precipitation threatens the fitness of the environment.

- **Acid precipitation** is a serious assault on water quality in some industrialized areas.
  - Uncontaminated rain has a slightly acidic pH of 5.6.
  - The acid is a product of the formation of carbonic acid from carbon dioxide and water.
- Acid precipitation occurs when rain, snow, or fog has a pH that is more acidic than 5.6.
- Acid precipitation is caused primarily by sulfur oxides and nitrogen oxides in the atmosphere.
  - These molecules react with water to form strong acids that fall to the surface with rain or snow.
- The major source of these oxides is the burning of fossil fuels (coal, oil, and gas) in factories and automobiles.
- The presence of tall smokestacks allows this pollution to spread from its site of origin to contaminate relatively pristine areas thousands of kilometers away.
  - In 2001, rain in the Adirondack Mountains of upstate New York had an average pH of 4.3.
- The effects of acids in lakes and streams are more pronounced in the spring during snowmelt.
  - As the surface snows melt and drain down through the snowfield, the meltwater accumulates acid and brings it into lakes and streams all at once.
  - The pH of early meltwater may be as low as 3.
- Acid precipitation has a great impact on the eggs and the early developmental stages of aquatic organisms that are abundant in the spring.
- Thus, strong acidity can alter the structure of molecules and impact ecological communities.
- Direct impacts of acid precipitation on forests and terrestrial life are more controversial.
- However, acid precipitation can impact soils by affecting the solubility of soil minerals.
  - Acid precipitation can wash away key soil buffers and plant nutrients such as calcium and magnesium ions.
  - It can also increase the concentrations of compounds such as aluminum to toxic levels.
  - This has done major damage to forests in Europe and substantial damage of forests in North America.

- Progress has been made in reducing acid precipitation.