Water: Life's Solvent

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Every time we feel thirsty, we are reminded about how much our bodies depend on water for survival. In fact, all living organisms depend on water. Up to 60 % of human body weight comes from water. About 70 % of the brain, 90 % of the lungs, and 22 % of bone tissue is water. Virtually all cellular processes occur in water, since cellular components are dissolved, suspended, and surrounded by water. Without water, we would not exist.

Water is a ubiquitous substance—all living organisms contain water, and many kinds of organisms live directly in water (**Figure 1**). It is both simple in its structure and complex in its functions. More substances dissolve in water than in any other liquid solvent. The reason for the excellent dissolving ability of water is related to its polarity. In this section, you will explore the properties of water. You will learn how it acts as the universal solvent and how it plays a role in so many chemical reactions.

Figure 1 Jellyfish are about 95 % water. They have one of the highest ratios of water content to body mass in the animal kingdom.

Properties of Water

Water is the most abundant liquid on Earth and is known as the "universal solvent." Water molecules are special because of their size, shape, polar structure, and ability to associate with each other through hydrogen bonding. Hydrogen bonds form readily between water molecules in both liquid water and ice. In liquid water, each water molecule forms an average of 3.4 hydrogen bonds with its neighbouring water molecules. This bonding forms an arrangement known as the water lattice (**Figure 2(a)**). The water lattice is a unique feature of water. Most molecules that are the size of water, such as H_2, O_2, CO_2, HCl, and H_2S, are gases at room temperature. In liquid water, the hydrogen bonds that hold the lattice together constantly break and reform, allowing water molecules to slip past one another and reform the lattice in new positions. This gives liquid water its fluid properties.

In ice, the water lattice is a rigid crystalline structure. Each water molecule in ice forms four hydrogen bonds with its neighbouring water molecules. The rigid ice water lattice spaces the water molecules farther apart than they are in the liquid water lattice (**Figure 2(b)**). Because of the greater spacing, water has the unusual property of being about 10 % less dense in its solid state than in its liquid state. Imagine what Earth would be like if ice sank to the bottom of oceans, lakes, and streams.

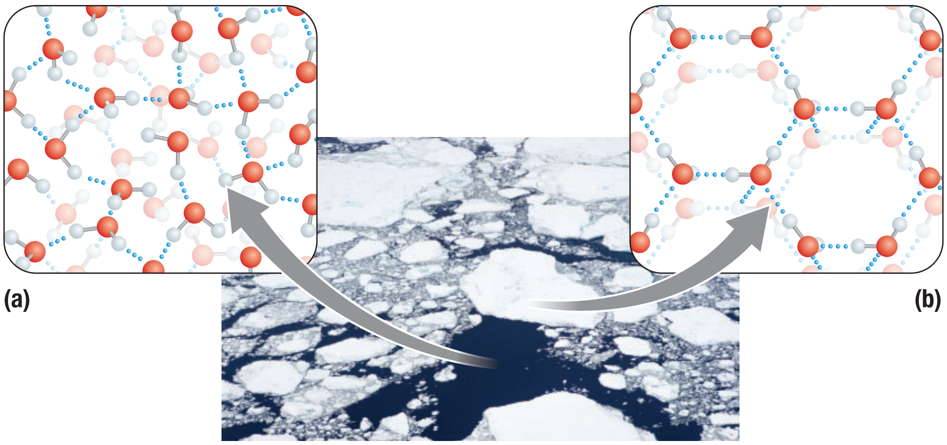

Figure 2 (a) Hydrogen bonding forms the liquid water lattice. Each water molecule makes an average of 3.4 bonds with its neighbours. (b) Hydrogen bonding forms the ice water lattice. Each water molecule bonds to four of its neighbours, creating a greater distance between the water molecules in ice.

As a result of its stabilizing hydrogen bond lattice, water has a high specific heat capacity. **Specific heat** is the amount of thermal energy that is required to increase the temperature of a given quantity of water by one degree Celsius. As thermal energy flows into a sample of water, much of it is absorbed by the process of breaking

specific heat the amount of thermal energy required to raise the temperature of a given quantity of a substance by 1 °C

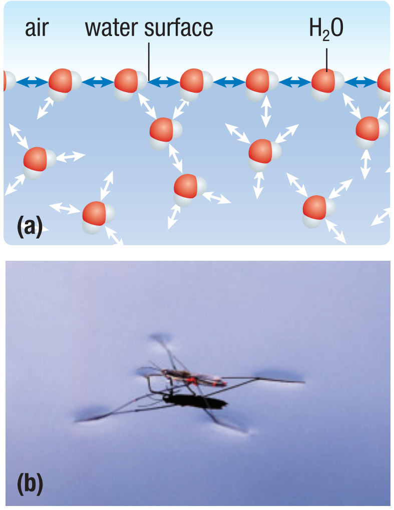

Figure 3 (a) The hydrogen bonding between water molecules creates surface tension. (b) The surface tension allows this water strider to walk on water.

hydrogen bonds. Therefore, the temperature of water increases relatively slowly as thermal energy is added. As a result, a lot of thermal energy and a relatively high temperature are needed to break enough bonds in water for it to boil. The high boiling point of water ensures that it is in a liquid state from 0 °C to 100 °C. Without its hydrogen bond lattice, water would boil at −81 °C. If the boiling point of water were −81 °C, most of the water on Earth would be in the gaseous state. We would not be able to drink it, swim in it, or have it inside our cells.

The hydrogen bond lattice of water results in water molecules staying close together—a property called cohesion. Surface tension is related to the concept of cohesion. Surface tension is the measure of how difficult it is to stretch or break the surface of a liquid (**Figure 3(a)**). Water molecules on the surface of a body of water can form hydrogen bonds on all sides, except the side that faces the air. This creates an imbalance in bonding, which produces a force that places the surface water molecules under tension and makes them more resistant to separation than the molecules below the surface. Surface tension is strong enough to allow small insects, such as water striders, to walk on water (**Figure 3(b)**).

Water molecules can also form hydrogen bonds with other polar molecules—a property called adhesion. For example, in a plant growing in soil, water moves in an unbroken column within microscopic conducting tubes of xylem tissue that extend from the roots of the plant to the highest leaves. Cohesion helps the water molecules stick together as they are transported up the xylem tubes, while adhesion helps the water molecules stick to the cell walls as they are transported. As water evaporates from leaves, water molecules move through the xylem tubes to replace the evaporated water. The unique properties of water are summarized in **Table 1**.

Table 1 The Unique Properties of Water

Characteristic	Property	Explanation	Effect	Example
Water clings.	cohesion	Water molecules form hydrogen bonds with each other.	high surface tension	• A water strider walks on the surface of a pond.
	adhesion	Water molecules form hydrogen bonds with other polar molecules.	capillary action and solubility of polar compounds	• Capillary action causes water to move up the xylem tubes in plants. • Polar substances, such as sugars, are highly soluble in water.
Water absorbs thermal energy.	high specific heat capacity	Hydrogen bonding causes water to absorb large amounts of thermal energy as its temperature increases, or lose large amounts of thermal energy as its temperature decreases.	temperature moderation	• High heat capacity helps organisms maintain a constant body temperature.
	high specific heat of vaporization	Hydrogen bonding causes liquid water to absorb large amounts of thermal energy and become a vapour (gas).	evaporation and cooling	• Many organisms, including humans, dissipate body heat by the evaporation of water from the surface of the body, often by sweating.
Solid water is less dense than liquid water.	highest density at 4 °C	As water molecules cool below 0 °C, they form an ice water lattice. The hydrogen bonds keep the water molecules spread apart, reducing the density so that it is below the density of liquid water.	ice floats on water	• Fish and other aquatic organisms survive in winter because water freezes from the top down. • Snow is a very good insulator. It provides protection from extreme cold for many organisms.

Aqueous Solutions

Water molecules are small and strongly polar—two qualities that allow them to readily surround polar and charged molecules and ions of other substances. The surface coat of water, called a hydration shell, reduces the attraction between the molecules or ions of another substance and promotes their separation. This separation allows the substance to go into solution. As the molecules and ions dissociate, water molecules surround them, forming the hydration shell. The hydration shell tends to prevent the ions from re-associating. The result is an aqueous (water-based) solution in which water is the solvent and the molecules or ions of the other substance are the solute.

A typical ionic substance is sodium chloride, commonly known as table salt. Sodium chloride dissociates in water because water molecules quickly form hydration shells around the Na^+ and Cl^- ions of the salt crystals (**Figure 4**). The surrounding water molecules reduce the attraction between ions so much that they separate from their normal crystal lattice structure and enter the surrounding water lattice as hydrated ions. This is why ionic substances or salts dissolve so easily in water. In much the same way, hydration shells surround macromolecules, such as sugars, nucleic acids, and proteins, that have ionic or polar regions on their surface. The surrounding water molecules act to reduce the electrostatic interaction between these macromolecules and other molecules. Polar molecules or charged ions that are strongly attracted to water are called **hydrophilic** (Greek for "water-loving") **molecules**. Non-polar molecules that are not strongly attracted to water are called **hydrophobic** (Greek for "water-fearing") **molecules**. Small and modest sized hydrophilic substances are highly soluble in water, while hydrophobic substances have very low solubility in water. As the solvent inside all our cells and in our blood, water dissolves thousands of solutes that are necessary for life. Because these substances are dissolved, they can float around and collide with each other, allowing chemical reactions to occur.

hydrophilic molecules polar or charged molecules that are strongly attracted to water

hydrophobic molecules non-polar molecules that are not strongly attracted to water

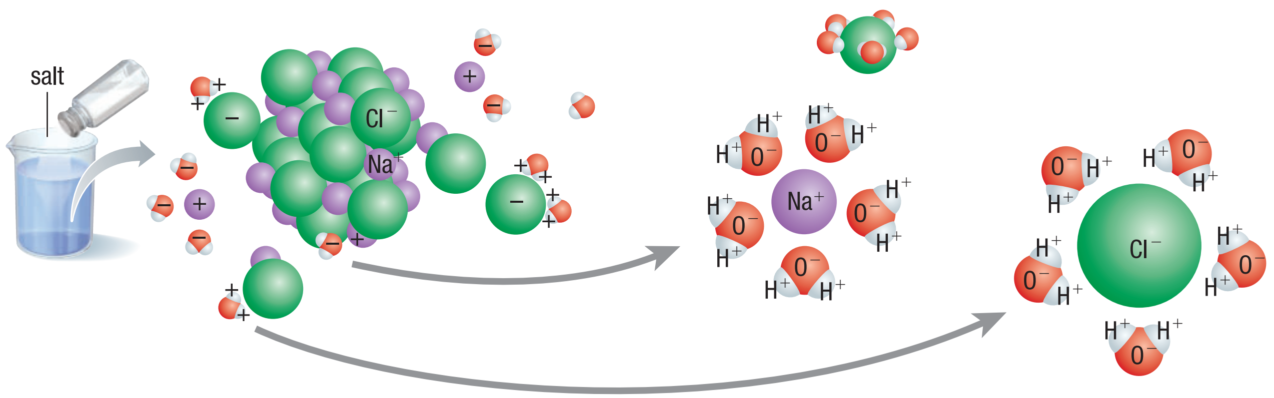

Figure 4 Salt dissolves in water. As water molecules surround Na^+ and Cl^- ions, they dissociate from one another and dissolve completely in the water.

Ionization and pH

Perhaps the most critical property of water, aside from its hydrogen bonding properties, is its ability to separate or dissociate into ions. Pure water is more than just H_2O molecules. Any given sample of water at 25 °C is a mixture of H_2O molecules, OH^- ions, and H_3O^+ ions. At this temperature, about two in every 550 million H_2O molecules react with each other. When two water molecules react, one water molecule transfers an H^+ ion to the other molecule, forming a hydronium ion, H_3O^+, and a hydroxide ion, OH^-. This process is called the **autoionization** of water (**Figure 5**). Autoionization always produces equal numbers of hydronium and hydroxide ions. Other dissolved substances, however, can alter this equal balance of ions.

autoionization the process in which a molecule spontaneously dissociates into ions

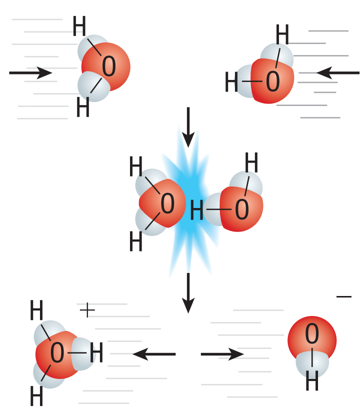

Figure 5 The autoionization of water

Acids and Bases

When the concentration of hydronium ions, H_3O^+, in a solution is greater than the concentration of hydroxide ions, OH^-, the solution has the properties of an acid. Acidic solutions are characterized by a sour taste, the ability to conduct electricity, and the ability to turn blue litmus paper red. Acids increase the hydronium ion concentration when dissolved in water and, in high enough concentrations, will cause a chemical burn. Acids contain at least one ionizable hydrogen ion in their chemical structure. The following equation shows the reaction of hydrogen chloride with water to produce hydrochloric acid:

$$HCl\ (g) + H_2O\ (l) \rightarrow H_3O^+\ (aq) + Cl^-\ (aq)$$

When the concentration of OH^- ions in a solution is greater than the concentration of H_3O^+ ions, the solution has the properties of a base: a bitter taste and slippery feel, the ability to conduct electricity, and the ability to change red litmus paper blue. Bases increase the OH^- concentration of an aqueous (water-based) solution. In high enough concentrations, bases are caustic and will cause a painful chemical burn if brought in contact with the skin. The increase in OH^- ions is accomplished in one of two ways. Strong ionic bases, such as sodium hydroxide, may contain an OH group and thus dissociate when added to water, releasing OH^- ions:

$$NaOH(s) + H_2O(l) \rightarrow Na^+(aq) + OH^-(aq)$$

Other bases combine directly with H^+ ions. For example, ammonia, NH_3, which is a weak base and a product of decomposed plant matter, combines directly with an H_2O molecule. An H^+ ion from the water binds to ammonia, forming an ammonium ion, NH_4^+, and an OH^- ion:

$$NH_3(g) + H_2O(l) \rightarrow NH_4^+(aq) + OH^-(aq)$$

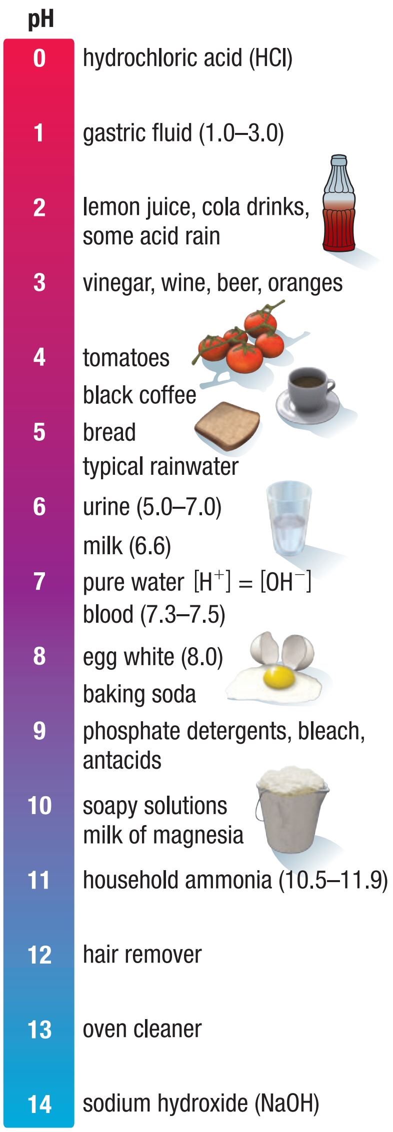

Figure 6 The pH values of common substances

The concentration of H_3O^+ ions, compared to the concentration of OH^- ions, in an aqueous solution determines the acidity of the solution. Scientists measure the acidity of a solution using a numerical scale from 0 to 14, called the pH scale. The scale is based on logarithms to make the values more manageable:

$$pH = -\log_{10}[H^+]$$

where $[H^+]$ represents the concentration of H^+ or H_3O^+ ions in an aqueous solution.

Each whole number on the pH scale represents a 10-fold difference in pH. Therefore, a change of one pH number is actually a significant difference in acidity. In pure water, there is a balance of the concentrations of H_3O^+ and OH^- ions, so pure water is a neutral solution (neither acidic nor basic). The pH value assigned to a neutral solution is 7, since the concentration of H_3O^+ ions in pure water at 25 °C is 1.0×10^{-7} mol/L. Solutions with a pH that is less than 7 are considered to be acidic. Examples of acidic solutions are coffee, milk, and fruits such as oranges and tomatoes. Solutions with a pH that is greater than 7 are considered to be basic. Examples of basic solutions are hand soap, ammonia-containing solutions used for household cleaning, and egg whites (**Figure 6**).

Both the pH within cells and the pH of the external environment are important for the optimal functioning of life. A change of 0.1 or even 0.01 in the pH level of a cell can drastically affect biological reactions. A small change in the pH surrounding some proteins causes structural changes that can alter or destroy the functions of the proteins. Correct blood pH levels are essential for maintaining good health. The pH levels in the stomach are also critical for proper digestion and for defence against micro-organisms.

The pH of water in the environment is also critical for the survival of most organisms on Earth. The changing pH of freshwater bodies and oceans has a serious impact on ecosystems that depend on these water supplies for food or habitat. The pH of the oceans is about 8. The burning of fossil fuels is increasing atmospheric concentrations of carbon dioxide, which in turn is resulting in an increase in carbon dioxide entering oceans and fresh water. As more carbon dioxide is absorbed by ocean water, the water and the carbon dioxide form carbonic acid, and the water becomes more acidic. Scientists are becoming alarmed by the potential impacts of these processes. Increasingly acidic ocean water is harming many marine organisms and ecosystems, including coral reefs, and ultimately threatens the health of Earth's oceans.

Strong and Weak Acids and Bases

Acids and bases can be classified as strong or weak. The strength of an acid or base depends on the degree to which it ionizes when dissolved in water. A strong acid, such as HCl, and a strong base, such as NaOH, are completely dissociated in an aqueous solution. This means that all the molecules of HCl release H^+ ions that interact with water to form H_3O^+, and all the OH^- ions are released from NaOH and increase the hydroxide ion concentration of the water in which they are dissolved. Conversely, a weak acid and a weak base only partially ionize in water. For example, only 10 % of ammonia, a weak base, forms ammonium ions in water. Similarly, only 1.3 % of acetic acid, CH_3COOH, a weak acid, dissociates in water:

$$CH_3COOH + H_2O \leftrightarrow CH_3COO^- + H_3O^+$$

Thus, 98.7 % of the CH_3COOH stays together.

The reaction of a weak acid or a weak base in water is a reversible reaction. This means that the molecules can dissociate in water to form a weak acid or base, and the ions can re-associate once in solution. For example, when first placed in water, acetic acid molecules begin to form hydronium and acetate ions. At this point, the forward reaction is favoured. As the concentration of these ions in solution increases, the reverse reaction occurs more frequently. When about 1.3 % of the acetic acid molecules have ionized, equilibrium is reached. The forward and backward reaction rates are the same, so the concentrations of all the entities of the solution remain constant. Most acids and bases that are involved in biochemical reactions are weak.

Neutralization Reactions and Buffers

Water has a neutral pH value of 7. It is neither an acid nor a base. However, when an acid and a base react with one another, the products of the reaction include water and salt. This type of reaction is called a neutralization reaction, since its products, water and salt, are neutral. For example, when the acid HCl and the base NaOH react with one another in solution, the products that are formed are water and a salt, sodium chloride:

$$HCl\ (aq) + NaOH\ (aq) \rightarrow H_2O\ (l) + NaCl\ (aq)$$

Living organisms have some control over the internal pH of their cells by using buffers. A **buffer** is a chemical that compensates for relatively small pH changes by absorbing or releasing hydrogen ions. When a biological reaction releases excess H^+ ions, buffers combine with the H^+ ions so they are no longer free in the solution. Conversely, if the concentration of H^+ ions in a solution decreases, buffers can release H^+ ions into the solution to increase their concentration. Since weak acids and bases dissociate in a reversible reaction in water, most buffers are weak acids, weak bases, or a combination of the two. These buffers release or absorb H^+ and OH^- as necessary.

buffer a chemical that compensates for pH changes in a solution by accepting or donating H^+ ions

The buffering mechanism that helps to maintain a healthy blood pH in the narrow range of 7.35 to 7.45 is a good example of how buffers work in your body. In humans and many other animals, a buffering system that is based on carbonic acid, H_2CO_3, which is a weak acid, helps to maintain proper blood pH levels. In water solutions, carbonic acid dissociates readily into bicarbonate ions, HCO_3^-, and H^+. Like dissociation reactions in weak acids, this dissociation reaction is reversible:

$$H_2CO_3 \rightarrow HCO_3^- + H^+ \quad \text{or} \quad H^+ + HCO_3^- \rightarrow H_2CO_3$$

Therefore, if there is a very large number of hydrogen atoms in a solution, these atoms will collide frequently with the bicarbonate ions. As a result, the second reaction (the reverse reaction) will occur more frequently, and the H^+ ions will be absorbed as carbonic acid molecules form. Conversely, if there are very few H^+ ions in solution, they will not collide as frequently with the bicarbonate ions, and the reverse reaction will occur at a slower rate than the forward reaction (the first equation above). The forward reaction is favoured, and this causes the release of more H^+ ions. These back and forth adjustments of the buffer system help to keep human blood within its normal pH range.

1.2 Review

Summary

- Water forms a lattice structure through hydrogen bonding in liquid water and ice.
- The hydrogen bonding of water molecules to one another gives water a high surface tension.
- As polar molecules or charged ions dissolve in solution, they are completely surrounded by water molecules, which reduce the electrostatic interactions between them.
- The proper pH of cells inside living organisms and their environment is critical for the survival of the organisms.
- Strong acids and bases dissociate completely in water. Weak acids and bases dissociate only partially in water. Acids and bases react to form water and a salt in neutralization reactions.
- A buffer is a weak acid or base that can compensate for changes in a solution to maintain the proper pH level.

Questions

1. Water is a polar molecule. Explain how the polarity of water accounts for its lattice structure. K/U
2. How does the structure of water account for its properties, such as its boiling point, surface tension, and adhesion? K/U
3. Potassium bromide, KBr, is an ionic compound. Describe what happens to its ions when it is dissolved in water. K/U
4. Will water form a surface coat around a molecule such as octane, $CH_3(CH_2)_6CH_3$ (**Figure 7**)? Explain. K/U

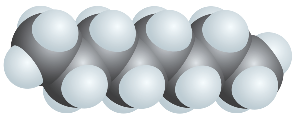

Figure 7

5. How does polarity influence water's role as a solvent? K/U
6. How do acids and bases differ in terms of how they behave when added to pure water? K/U T/I
7. What determines whether an acid or a base is classified as strong or weak? Explain your answer. K/U
8. Why is it important that we help to maintain the proper pH of our environment? Make a connection between the proper pH of our environment and your life and surroundings. K/U A
9. How do buffers in your cells help to keep your body functioning properly? K/U
10. Why would it be inaccurate to say that a buffer is a solution that maintains a constant pH? K/U
11. Vitamin C is also known by its chemical name, ascorbic acid. T/I
    (a) What does this name suggest about its chemical and physical properties?
    (b) Which of these properties might you notice if you ate some pure vitamin C?
12. Ants belong to the family Formicidae, named after their ability to release formic acid (**Figure 8**). Do online research to find out why ants produce formic acid. What other well-known insects produce formic acid? T/I

Figure 8

WEB LINK