WATER - Structure, Properties and Importance

- The first biologically important molecule we need to look at is water. Besides being the most abundant substance on the surface of the planet, it is **absolutely essential to all life** and it is also a very unique molecule.
- **Life began** in water, and all living organisms are "water-based."
- All living organisms have **adaptations for maintaining water levels** (e.g. human skin, plant stomata, bacterial cysts)
- Humans life requires water. But why?
  a) We are mostly made of it! A human body is approximately 60 - 70% water.
  b) Only **substances dissolved in water** can enter cell membrane of our cells (e.g. glucose, amino acids).
  c) **Water carries away dissolved wastes** from our cells, and wastes excreted in liquid (sweat, urine)
  d) **Ions** necessary for many body processes (e.g. Ca++ for movement, Na+, K+ for generation of nerve impulses). Ions are formed when an ionic substance is dissolved in water.
  e) Water and water-based solutions **ACT AS LUBRICANTS.** For example, your joints are lubricated by a watery fluid called synovial fluid.
  f) Water **REGULATES TEMPERATURE** in living systems. Compared to most other substances, water doesn’t heat up easily or cool down easily (e.g. compare water to metal or sand). Therefore it helps living organisms – since they contain so much water in their tissues and blood, for example, to maintain a relatively constant internal temperature.
  g) Our **brains** partially protected against shock by a watery layer
  h) Sense organs require water: eyes are filled with thick fluid; hearing depends upon a fluid-filled structure (called the cochlea) that detects and transmits vibrations.
  i) **Hydroltyic enzymes:** the chemical reactions that take place in your body rely on chemicals called enzymes. Hydroltyic enzymes are enzymes involved in breaking bonds between molecules. To do this, they require water.

The Chemistry of Water

- Water is **covalently bonded** (i.e. bonds formed when atoms share electrons). Covalent bonds are strong bonds, compared with the other two types of bonds we’ll be talking about: ionic bonds and hydrogen bonds.
- For example, let’s compare this to an ionic bond (a bond in which electron(s) are transferred between atoms).
- Ionic bonds are weaker than covalent bonds.
- So, water is covalently bonded, but it is **POLAR** - the shared electrons spend more "time" circulating the larger oxygen than the smaller hydrogens. Thus, the oxygen has a slight net negative charge, while the hydrogens have a small net positive charge.
  - **Hydrogen Bonds** occurs whenever a partially positive H is attracted to a partially negative atom (like oxygen and nitrogen. It is represented by a dashed line because it is **WEAK** and fairly easily broken. Covalent and ionic bonds are both much stronger.
  - However, when you consider the astronomical numbers of water molecules found in living systems, the net effect of all those weak H-bonds, can add up to have a large effect. Indeed, it is the polar nature of water, which leads to hydrogen bonding, that gives water its unique properties.
WATER HAS SEVERAL UNIQUE CHARACTERISTICS

- It is **abundant** throughout biosphere.
- H-bonding makes it have a **LOW FREEZING POINT** and a **HIGH BOILING POINT**, so that it is **liquid** at body temperature.
- Water **absorbs** much heat before it warms up or boils, and **gives off** much heat before it **freezes** (this is why oceans maintain a **basically constant temperature**, and accounts for **cooling effect** of sweating). This is also due to H-bonding.
- Water has high **COHESIVENESS** – Water molecules tend to cling together and draw dissolved substances along with it. This makes it **good for transporting materials** through tubes.
- **Liquid water is more dense than ice** because of H-bonding (so ice will form on top). Ice layers helps protect organisms below.

- Water **DISSOLVES** other polar molecules -- is one of the best **solvents** known (--> promotes chem. reactions). Called the “**UNIVERSAL SOLVENT**.”
- Now let’s look at a couple of important water-based solutions: acids, bases, and buffers.

**ACIDS, BASES, & BUFFERS**
- **ACIDS** are compounds that **dissociate in water** and release **H+ ions**. e.g. HCl, H₂CO₃, H₂O, CH₃COOH, H₂SO₄
- **BASES** are compounds that **dissociate in water** and release **OH− ions**. e.g. NaOH, KOH, H₂O
• **pH** is a measure of the **concentration of hydrogen ions** (how much acid is in a solution) and ranges from 0 to 14. The **lower the number**, the more **acidic** the solution. A pH **less than 7.0** is **acidic**.

• The **higher** the number, the more **basic** (or “**alkaline**”) the solution. A pH **more than 7.0** is a **basic** solution.

• A pH of 7 is said to be **neutral**. Pure water has a pH of 7.0.

• pH can be calculated using the following formula:

\[
pH = -\log[H^+]\]

For example, if pH = 3, \([H^+] = 10^{-3}\)

• The numbers in the pH scale can seem misleading, because the pH scale is a **logarithmic scale**. That means each number on the pH scale represents a difference in magnitude of **10**.

  • For example, a pH of 2 is ten times more acidic than a pH of 3.

  • A pH of 2 is 100 times more acidic than a pH of 4.

  • A pH of 13 is 1000 times more basic than a pH of 10, and so on.

• An easy way to figure out these sorts of calculations is to do the following:

  1. Take the two pH's and subtract them. e.g. pH 10 and pH 4
      \[10 - 4 = 6\]

  2. Take that number and put that many zeros in front of the number one.

      \[1000000\]

      This means that a pH of 10 is **1,000,000 times** more **basic** than a pH of 4. (you could also say it the other way -- a pH of 4 is 1,000,000 times **acidic** than a pH of 10)

• All living things need to maintain a **constant pH** (e.g. human blood pH = 7.4). **Why is pH so important?** If pH changes, it can cause **enzymes** – the chemical helpers that run the chemical reactions essential to life - to “denature” (i.e. change shape - more on this later!).

• To keep the pH from changing, living cells contain **BUFFERS** to keep the pH constant. A BUFFER is a chemical or combination of chemicals that can take up excess hydrogen ions or excess hydroxide ions. Buffers **resist** changes in pH when acid or base is added.

  ![pH Scale](image)

<table>
<thead>
<tr>
<th>pH of Common Substances</th>
<th>[H^+]</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrochloric acid (HCl)</td>
<td>0</td>
</tr>
<tr>
<td>stomach acid</td>
<td>1</td>
</tr>
<tr>
<td>lemon juice</td>
<td>2</td>
</tr>
<tr>
<td>Coca-Cola, beer, vinegar</td>
<td>3</td>
</tr>
<tr>
<td>tomatoes</td>
<td>4</td>
</tr>
<tr>
<td>black coffee</td>
<td>5</td>
</tr>
<tr>
<td>urine</td>
<td>6</td>
</tr>
<tr>
<td>pure water, tears</td>
<td>7</td>
</tr>
<tr>
<td>seawater</td>
<td>8</td>
</tr>
<tr>
<td>baking soda, stomach antacids</td>
<td>9</td>
</tr>
<tr>
<td>Great Salt Lake</td>
<td>10</td>
</tr>
<tr>
<td>household ammonia</td>
<td>11</td>
</tr>
<tr>
<td>bicarbonate of soda</td>
<td>12</td>
</tr>
<tr>
<td>oven cleaner</td>
<td>13</td>
</tr>
<tr>
<td>sodium hydroxide (NaOH)</td>
<td>14</td>
</tr>
</tbody>
</table>

**CH₃COOH**

When added to water, some will break down to form

**CH₃COO⁻**

This part can react with acid to form

**H⁺**

This part can react with base to form

**CH₃COOH**

When added to water, some will break down to form

**CH₃COO⁻**

This part can react with acid to form

**H⁺**

This part can react with base to form
added. However, buffers can be overwhelmed if acid or base continues to be added.

- Two common buffers in living systems are carbonic acid-bicarbonate ion (H₂CO₃, HCO₃⁻) and acetic acid-acetate ion (CH₃COOH, CH₃COO⁻). Let's look at how the acetic acid-acetate ion buffer works.

<table>
<thead>
<tr>
<th>BIOCHEMISTRY &amp; CELL COMPounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>- For the rest of the chapter, we will look at biologically important molecules that are based around carbon atoms. It is said that life on Earth is &quot;Carbon Based...&quot;</td>
</tr>
<tr>
<td>- Biochemistry is the chemicals of life and their study. Organic chemistry is the study of carbon compounds. As will see, a lot of biochemistry revolves around organic chemistry.</td>
</tr>
<tr>
<td>- Why Carbon?</td>
</tr>
</tbody>
</table>
  - has four available covalent bonds -- allows for other atoms to bind. |
  - capable of forming strong bonds with itself |
  - therefore can form long chains -- can be straight or branched --> great VARIETY of possible combinations. |
  - carbon atoms in chains can rotate, forming single, double, and multiple ring structures (e.g. glucose, nucleotides, lipids, proteins)

<table>
<thead>
<tr>
<th>POLYMER FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Making Big Molecules from Small Molecules!</td>
</tr>
<tr>
<td>- a POLYMER is a large molecule formed from repeating subunits of smaller molecules (e.g. proteins, starch, DNA are all polymers).</td>
</tr>
</tbody>
</table>

| DEHYDRATION SYNTHESIS: forms large molecules (polymers) from small molecules. (Dehydration = to remove water) In the process water is produced. Here is how two amino acids (small molecules) form a dipeptide. |
| - In synthesis, one molecule loses an H⁺, one molecule loses an OH⁻. In the above example, amino acids can continue to be added to either end of the dipeptide to form polypeptides. Large polypeptides are called proteins. |
| - HYDROLYSIS (hydro = water, lysis = to split): is the opposite reaction. Water breaks up another molecule. The addition of water leads to the disruption of the bonds linking the unit molecules together. One molecule takes on H⁺ and the other takes an OH⁻. This also requires the action of helping molecules called enzymes. Enzymes that do this are called hydrolytic enzymes. |
The FOUR MAIN CLASSES of Biologically Significant Molecules: Proteins, Carbohydrates, Lipids, Nucleic Acids

I. PROTEINS

- large, complex organic macromolecules that have three main functions
  1) provide **STRUCTURAL SUPPORT** (e.g. elastin, collagen in cartilage and bone, muscle cells)
  2) **MOVEMENT** (actin and myosin etc. in muscle cells)
  3) **METABOLIC FUNCTIONS**:
     - **ENZYMES** (biochemical catalysts that speed up biochemical reactions). Crucial to life.
     - **ANTIBODIES**: proteins of your immune system that fight disease.
     - **Transport** HEMOGLOBIN is a protein that transports oxygen in your blood. Proteins in cell membranes act as **channels** for molecules entering or leaving the cell.
     - **Hormones**: many hormones, like insulin, are proteins. Hormones control many aspects of homeostasis.
- All proteins are composed of **AMINO ACIDS** (like a train is made up of individual railway cars)

  - Note the "amine" group on right (ammonia = NH₃), "acid" group on the left (COOH = organic acid) of the central carbon. All amino acids have this formula.
  - Difference is in "R" (= Remainder) group -- different for each amino acid.
  - There are 20 different amino acids in living things. Our bodies can make 12 of these. The other 8, which we must get from food, are called "Essential Amino Acids."

i. Amino acids join together through dehydration synthesis. The bonds formed are called **PEPTIDE BONDS**. **Circle the peptide bond** on the dipeptide below.

ii. Peptide bonds are **polar bonds** (this leads to H-Bonding, as we will see).

iii. **Dipeptide**: two amino acids joined together

iv. **Polypeptide** (abbreviation = ppt): >2 amino acids joined together. Usually short: less than 20 amino acids or so.

v. **Protein**: a polypeptide chain is called a protein when it gets large (usually ~75 or more amino acids in length – though there is no absolute rule here)
Proteins have 4 levels of organization:

i. **PRIMARY STRUCTURE**: the sequence of a.a.’s joined together in a line. Here are two polypeptide chains that are 12 amino acids long. Note however, that they have different primary structures (different sequences of the 20 amino acids).
   - On the right is the entire primary structure for the hormone insulin.

ii. **SECONDARY STRUCTURE**: since peptide bonds are polar, H-Bonding routinely occurs between amino acids in the primary line. Often, this will cause the chain to coil up into a shape called an alpha helix. Layers called “β-pleated sheets” can also form.

iii. **TERTIARY STRUCTURE**: different types of bonding (covalent, ionic, hydrogen) between -R groups makes the alpha helix bend and turn, forming "globs" of protein of all shapes. This three-dimensional arrangement of the amino acid chain is called the tertiary structure. Although it may look randomly formed, the final 3-D shape is very exact and precise. The shape is due to the original sequence of amino acids (the primary structure), as this is what will determine which amino acids in the chain will bind with each other, and in what way.

iv. **QUARTERNARY STRUCTURE**: for proteins with more than one polypeptide chain, the quarternary structure is the specific arrangement of polypeptide chains in that protein. (e.g. hemoglobin: this is the O₂ carrying protein in blood -- made of four polypeptide chains interlocked in a specific way).

**DENATURING PROTEIN**

- protein shape is critical to its function
- changes in temperature or pH, or the presence of certain chemicals or heavy metals, can disrupt the bonds that hold a protein together in its particular shape.

If a protein is DENATURED, it has lost normal structure/shape because normal bonding between -R groups has been disturbed.
- Examples of denaturing include
  - heating an egg white (raising the temperature above 50°C will reliably denature most animal enzymes)
  - adding vinegar to milk (this is the same thing as changing the pH, since vinegar is an acid)
  - adding heavy metals such as lead and mercury also denature proteins.

**II. CARBOHYDRATES**

- Carbohydrates are molecules made of Carbon, Hydrogen, and Oxygen
- all carbohydrates have the general formula: Cₙ(H₂O)ₙ - hence the name "Hydrated Carbon" or "Carbo-Hydrate"
- Different forms used for **ENERGY, FOOD STORAGE, & STRUCTURAL SUPPORT** in plants and animals.
  Carbohydrates are very important in living systems for the following functions:
1. **Short-term energy supply** (e.g. glucose is used by all cells to produce ATP energy)
2. **Energy storage** (e.g. glycogen is stored in liver and muscles and can be rapidly converted to glucose: starch has a similar role in plants)
3. As **cell membrane markers** (receptors & "identification tags")
4. As **structural material** (e.g. plant cell walls are made of cellulose, insect exoskeletons are made of the carbohydrate chitin)
   - Carbohydrates can be small molecules like glucose, or very large polymers like starch and glycogen.
   i. **MONOSACCHARIDES** (e.g. Glucose, ribose, galactose, fructose)
      - simple sugars with only one unit molecule
      - groups of monosaccharides may be designated by the number of carbons they contain (i.e. "hexose" = 6-C sugar, 5-C sugars = "pentose" sugars). *Note the "-ose" suffix! Most carbohydrates end in "ose."
      - Probably the most common monosaccharide in living systems is glucose. All cells “burn” glucose to make ATP energy to meet their immediate energy demands.

   ![Detailed structure of glucose showing all atoms](image)
   ![Simplified glucose diagram](image)

   ii. **DISACCHARIDES** (e.g. maltose, sucrose). At right is maltose
      - are formed from dehydration synthesis reaction between two monosaccharides.

   ![Condensation synthesis](image)
   ![Hydrolysis](image)

      • maltose = 2 glucose. Table sugar (sucrose) = 1 glucose + 1 fructose
      • Monosaccharides and disaccharides are all water soluble. That means they can be dissolved in water.

   iii. **POLYSACCHARIDES**
      - a carbohydrate that contains a large number of monosaccharide molecules
      - Three main important types in living systems. All are made of repeating glucose subunits:
        1. **STARCH** - the storage form of glucose in **plants**. Made of fairly straight chains of glucose, with few side branches off the main chain. Starch forms from dehydration synthesis between many glucose molecules.
           
           \[
           n \text{ glucose} \rightarrow \text{starch} + (n - 1)\text{H}_2\text{O}
           \]

           ![Starch Structure](image)

        2. **GLYCOGEN** - the storage form of glucose in **animals**. The chains of glucose have many side chains

   ![Glycogen structure – more branching!](image)
compared to starch. In animals, the liver converts glucose to glycogen for storage. In between meals, liver releases glucose into blood concentrations remains at 0.1%.

3. **CELLULOSE** - primary structural component of plant cell walls. Linkage of glucose subunits different than in starch or glycogen. See the structure below.

- Human digestive system can't digest cellulose, so it passes through the intestines undigested. Other names for the cellulose in plant foods are "fiber" or "roughage."
- Dietary fiber is important to health and for the prevention of such things as colon cancer.

### III. LIPIDS

- Lipids are a wide variety of compounds, more frequently known by their common names, including fats, oils, waxes.
- are all insoluble in water.
- Functions of Lipids include the following:
  1. **Long-Term Energy storage**: (fat is excellent for storing energy in the least amount of space, and packs 9.1 calories of energy per gram, versus 4.4 for carbohydrates and proteins).
  2. Insulation ("blubber")
  3. Padding of vital organs
  4. Structural (e.g. cell membranes are mostly composed of phospholipids, white matter of brain contains a high proportion of lipid material)
  5. Chemical messengers (e.g. steroid hormones like testosterone, estrogen, prostaglandins).

#### THE MAIN TYPES OF LIPIDS

**i. FATTY ACIDS**: a long chain of carbons with hydrogens attached, ending in an acid group (-COOH).

There are two main types:

- **Saturated fatty acids** - no double bonds between carbons. All carbons are "saturated" with hydrogens. Saturated fats tend to be solid at room temp. These are the "bad" dietary fats (e.g. butter, lard, meat fat), which are known to contribute to heart disease, strokes, and cancer.

- **Unsaturated fatty acids** - have one (monounsaturated) or more (polyunsaturated) double bonds between carbons in chain. That means that the carbons are not "saturated" with hydrogens.

- Unsaturated fats tend to be liquid at room temperature. e.g. vegetable oils, Omega-3 unsaturated fatty acids. Are thought to be better for your heart than saturated fats.

**ii. NEUTRAL FATS**: (also called **TRIGLYCERIDES**)

- formed by dehydration synthesis reaction between **glycerol** (a molecule of 3 hydrated carbons and 3 fatty acids.

- The fatty acids in a neutral fat can be saturated or unsaturated.
- They are often drawn in a shorthand form that looks like this:
Saturated triglyceride | Monounsaturated triglyceride | Polyunsaturated neutral fat

- All triglycerides are **non-charged, non-polar molecules**.
- Neutral fats are also sometimes drawn like this:
- They do not mix with water. This property of not mixing with water is called "hydrophobic" which literally means "water-fearing." This is the opposite of polar molecules, which mix readily with water and are called "hydrophilic" which means "water-loving."
- **Soap** is made by combining a base and a fatty acid.
- Soaps are polar, will mix with water. Soap molecules surround oil droplets to their polar ends project outwards, causing the oil to **dispers** in water (this process called **EMULSIFICATION**).

iii. **PHOSPHOLIPIDS**: important components of cell membranes
- Phospholipids have the same basic structure as neutral fats except that one fatty acid is replaced by a phosphate group with a charged nitrogen attached.
- phospholipids have a Phosphate-containing "head" and two long fatty acid tails. Head is hydrophilic ("water-loving"), tail is hydrophobic ("water-fearing")

iv. **STEROIDS**: a different type of lipid
- They are multi-ringed structures, all derived from **CHOLESTEROL**
- You've heard many bad things about cholesterol, but it is actually an essential molecule found in every cell in your body (it forms parts of cell membranes, for example).
- The problem is that dietary cholesterol helps to form arterial plaques, which lead to **strokes** and **heart attacks**. Dietary cholesterol only found in **animal products** (meat, fish, poultry, dairy products). There is no cholesterol in **plant foods**. Your blood cholesterol should be no more than 150 mg/dl.
Steroids can function as chemical messengers, and form many important hormones (e.g. testosterone, estrogen, aldosterone, cortisol) that have a wide variety of affects on cells, tissues, and organs (especially sex characteristics, ion balance, and gluconeogenesis).

IV. NUCLEIC ACIDS: DNA & RNA

- huge, macromolecular compounds that are polymers of nucleotides. There are two types:
  1. **DNA: DEOXYRIBONUCLEIC ACID** - makes up chromosomes and genes. **Controls all cell activities including cell division and protein synthesis.** DNA also undergoes mutations which are important to the process of evolution.
  2. **RNA: RIBONUCLEIC ACID** - works with DNA to direct protein synthesis.
- DNA and RNA are polymers of nucleotides that form from the dehydration synthesis between nucleotides.

<table>
<thead>
<tr>
<th>Nucleotide (Purine (A,G))</th>
<th>Nucleotide (Pyrimidine (T,C))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P</strong></td>
<td><strong>N</strong></td>
</tr>
<tr>
<td><strong>N</strong></td>
<td><strong>P</strong></td>
</tr>
<tr>
<td>Sugar</td>
<td>Phosphate</td>
</tr>
<tr>
<td>Base</td>
<td>Base</td>
</tr>
</tbody>
</table>

- Nucleotides consist of a five-carbon sugar (ribose or deoxyribose), a phosphate, and a nitrogen-containing base (which may have one or two rings). There are 4 different nucleotides in DNA. The sequence of these nucleotides is the "Genetic Code."
- DNA consists of two antiparallel strands of nucleic acids. Each strand has a backbone of the sugars and phosphates of joined nucleotides. The bases stick out the side and hydrogen-bond with the complementary bases of the other strand. The two strands wind around each other to form a double helix.

- Sections of DNA form functional units called GENES. A gene is one instruction for making one polypeptide, and is about 1000 nucleotides long, on average.
- DNA is packaged into chromosomes, and is located in the nucleus. You have about 4 billion nucleotide pairs in each of your cells. Each of your 46 chromosomes contains one very long polymer of DNA around 85,000,000 nucleotides long!
• RNA is a single strand of nucleic acid, which is formed off a DNA template in the nucleus. It migrates to the cytoplasm during protein synthesis.

V. ATP - Adenosine Triphosphate - the Molecule of ENERGY
• ATP is a type of nucleotide that is used as the primary CARRIER OF ENERGY in cells
• Consists of the sugar Ribose, the base Adenine, and 3 phosphate groups attached to the ribose.
• The bond between the outer two phosphates is very high in energy: when it is broken, much energy is released, which can be used by the cell (for example, for muscle contraction).
• The bond between the first and second phosphate is also high in energy, but not as high as between the two end phosphates
• ATP is produced mostly produced inside mitochondria during the process of cellular respiration.