

Chemical Foundations of Life

The origin of life and organic compounds of organisms

Atomic Structure

- Atoms are the smallest units that retain the properties of elements.
- Atoms are composed of protons, neutrons, and electrons.
- Protons are positively charged and neutrons carry no charge. Together, these two subatomic particles make up the atomic nucleus.
- Electrons carry a negative charge and orbit rapidly around the atomic core region.

- Each element has its own atomic number which refers to the number of protons that it contains.
- Each element also has an atomic mass, which refers to the number of protons and neutrons in the nucleus.
- These numbers are important because we can predict how some of these substances will behave in cells under various conditions.

Atoms

- Electrons are associated with energy
 - electrons have energy of position, called **potential energy**
 - the field of energy around an atom is arranged as levels called **electron shells**
 - within this volume of space, **orbitals** are where electrons are most likely to be found

Ions and Isotopes

- **Ions** – atoms that have gained or lost one or more electrons

- **Isotopes** – atoms that have the same number of protons but different numbers of neutrons
 - most elements in nature exist as mixtures of different isotopes

Molecules

- A group of atoms held together by some energy of force comprises a molecule.
- The force that holds them together is called a chemical bond.
- There are different kinds of chemical bonds: covalent bonds, ionic bonds, hydrogen bonds, and Van der Waals interactions.

Covalent bonds

- These bonds are strong ones and are those in which one or more pairs of electrons are shared by two atoms.
- The two key features of covalent bonds are that they are strong bonds that involve the sharing of energy and that they are directional (which means that they form complex structures).

Ionic bonds

- An ionic bond is one in which one or more electrons from one atom are removed and attached to another atom, resulting in positive and negative ions which attract each other.
- They are called ionic bonds because an atom with an electrical charge is called an ion.
- An example of ionic bonding can be seen in ordinary table salt.

- Ionic bonds are about 30 times weaker than covalent bonds.
- They are non-directional and, as a consequence, form crystals
- Because of this, they do not form complex shapes.

Hydrogen Bonds

- Hydrogen bonding differs from other uses of the word "bond" since it is a force of attraction between a hydrogen atom in one molecule and a small atom of high electronegativity in another molecule.
- That is, it is an intermolecular force, not an intramolecular force as in the common use of the word bond.
- Hydrogen bonding has a very important effect on the properties of water and ice.

- Hydrogen bonding is responsible for the various physical properties of water including heat storage, ice formation, vaporization, and its high polarity.

- Heat Storage
 - water temperature changes slowly and holds temperature well
- Ice Formation
 - few hydrogen bonds break at low temperatures
 - water becomes less dense as it freezes because hydrogen bonds stabilize and hold water molecules farther apart

- High Heat of Vaporization
 - at high temperatures, hydrogen bonds can be broken
 - water requires tremendous energy to vaporize because of all the hydrogen bonds that must be broken

- Water molecules are sticky
 - **cohesion** – when one water molecule is attracted to another water molecule
 - **adhesion** – when polar molecules other than water stick to a water molecule

- Water is highly polar
 - in solution, water molecules tend to form the maximum number of hydrogen bonds
 - **hydrophilic** molecules are attracted to water and dissolve easily in it
 - these molecules are also polar and can form hydrogen bonds
 - **hydrophobic** molecules are repelled by water and do not dissolve
 - these molecules are non-polar and do not form hydrogen bonds

- Hydrogen bonding is also very important in proteins and nucleic acids and therefore in life

processes. The "unzipping" of DNA is a breaking of hydrogen bonds which help hold the two strands of the double helix together.

Van der Waals Interactions

- This is the WEAKEST bond found.
- The surface area of a molecule will determine the strength of the van der Waals interactions between molecules.
- So, these forces are distance-dependent (the distance between each atoms van der Waals radii)
- Although these are weak, many of these forces may lead to a strong interaction

The ionization of water

- When a water molecule dissociates, it forms a positively charged hydrogen ion and a negatively charged hydroxide ion.
- This is a very important fact because the pH is based on the concept of the concentration of hydrogen ions present.

pH

- A convenient way to express the hydrogen ion concentration of a solution.
- $\text{pH} = -\log [\text{H}^+]$
- The pH scale is logarithmic
 - A difference of one unit represents a ten-fold change in H^+ concentration
- Acid
 - Dissociates in water to increase H^+ concentration
- Base
 - Combines with H^+ when dissolved in water
- pH is a measure of the activity of hydrogen ions (H^+) in a solution and, therefore, its acidity or alkalinity.
- The pH value is a number without units, usually between 0 and 14, that indicates whether a solution is acidic ($\text{pH} < 7$), neutral ($\text{pH} = 7$), or basic/alkaline ($\text{pH} > 7$).

Macromolecules

- Organic molecules are those that have a carbon-based core and are formed by living organisms.
- These molecules also have functional groups attached to them which may have special chemical properties or may be part of special chemical reactions.
- Although the body may produce many different organic molecules, most of the body is made up of four in particular and they are: lipids, carbohydrates, proteins, and nucleic acids.

Putting them together and taking them apart

- These macromolecules are built by attaching bits and pieces together.
- These chains of small subunits are called polymers.
- There are ways to build and break macromolecules.
- These include dehydration synthesis, enzymes, and hydrolysis.

- Dehydration synthesis involves the removal of water from a macromolecule.
- Enzymes are proteins that can break down molecules at certain places in their chemical structure.
- Hydrolysis is the exact opposite of dehydration synthesis. It involves the addition of water.

Proteins

- They are complex, high molecular weight organic compounds that consist of amino acids joined by peptide bonds.
- Amino acids are small molecules that contain a carboxyl group, an amino group, a central carbon, and a functional group.
- There are 20 amino acids and they are all differentiated by the functional groups they have.
- A peptide bond is a covalent bond that joins two amino acid groups together.
- Proteins are essential to the structure and function of all living cells and viruses.
- Many proteins are enzymes or subunits of enzymes.
- Other proteins play structural or mechanical roles, such as those that form the struts and joints of the cytoskeleton.
- In nutrition, proteins serve as the source of amino acids for organisms that do not synthesize those amino acids natively.

Protein Structure

- Proteins can fold into unique 3-dimensional structures.
- The shape into which a protein naturally folds is known as its native state, which is determined by its sequence of amino acids.
- Biochemists refer to four distinct aspects of a protein's structure.
- Primary structure: the amino acid sequence.
- Secondary structure: highly patterned sub-structures - alpha helix and beta sheet - or segments of chain that assume no stable shape. Secondary structures are locally defined, meaning that there can be many different secondary motifs present in one single protein molecule.
- Tertiary structure: the overall shape of a single protein molecule.
- Quaternary structure: the shape or structure that results from the union of more than one protein molecule, usually called subunit proteins.
- In addition to these levels of structure, proteins may shift between several similar structures in performing their biological function.

Lipids

- The one property that lipids have in common is that they are all hydrophobic.
- This group of molecules includes fats and oils, waxes, phospholipids, steroids (like cholesterol), and some other related compounds.
- Fats and oils are made from two kinds of molecules: glycerol (a type of alcohol with a

hydroxyl group on each of its three carbons) and three fatty acids. Since there are three fatty acids attached, these are known as triglycerides.

Fatty acid structure

- The tail of a fatty acid is a long hydrocarbon chain, making it hydrophobic.
- The head of the molecule is a carboxyl group which is hydrophilic.
- Fatty acids are the main component of soap, where their tails are soluble in oily dirt and their heads are soluble in water to emulsify and wash away the oily dirt.
- However, when the head end is attached to glycerol to form a fat, that whole molecule is hydrophobic.

- The terms saturated, mono-unsaturated, and poly-unsaturated refer to the number of hydrogens attached to the hydrocarbon tails of the fatty acids as compared to the number of double bonds between carbon atoms in the tail.
- Fats, which are mostly from animal sources, have all single bonds between the carbons in their fatty acid tails, thus all the carbons are also bonded to the maximum number of hydrogens possible.

- Since the fatty acids in these triglycerides contain the maximum possible amount of hydrogens, these would be called saturated fats.
- The hydrocarbon chains in these fatty acids are, thus, fairly straight and can pack closely together, making these fats solid at room temperature.
- Oils, mostly from plant sources, have some double bonds between some of the carbons in the hydrocarbon tail, causing bends or kinks in the shape of the molecules.

- Because some of the carbons share double bonds, they're not bonded to as many hydrogens as they could, if they weren't double bonded to each other.
- Therefore, these oils are called unsaturated fats. Because of the kinks in the hydrocarbon tails, unsaturated fats can't pack as closely together, making them liquid at room temperature.

Steroids

- The general structure of cholesterol consists of two six-membered rings side-by-side and sharing one side in common, a third six-membered ring off the top corner of the right ring, and a five-membered ring attached to the right side of that.
- The central core of this molecule, consisting of four fused rings, is shared by all steroids, including estrogen (estradiol), progesterone, corticosteroids such as cortisol (cortisone), aldosterone, testosterone, and Vitamin D.

- In the various types of steroids, various other groups/molecules are attached around the edges.
- Our bodies make about 2 g of cholesterol per day, and that makes up about 85% of blood cholesterol, while only about 15% comes from dietary sources.
- Cholesterol is the precursor to our sex hormones and Vitamin D.

- Vitamin D is formed by the action of UV light in sunlight on cholesterol molecules that have risen to near the surface of the skin.
- Our cell membranes contain a lot of cholesterol (in between the phospholipids) to help keep them fluid even when our cells are exposed to cooler temperatures.

Carbohydrates

- Starch and cellulose are two common carbohydrates.
- Both are macromolecules with molecular weights in the hundreds of thousands.
- Both are polymers (hence "polysaccharides"); that is, each is built from repeating units, monomers, much as a chain is built from its links.

- The monomers of both starch and cellulose are the same: units of the sugar glucose.
- Three common sugars share the same molecular formula: $C_6H_{12}O_6$. Because of their six carbon atoms, each is a hexose.

- They are: glucose, galactose, and fructose.
- Glucose is the immediate source of energy for cellular respiration.
- Galactose is a sugar found in milk (and yogurt).
- Fructose is a sugar found in honey and fruits.
- Although all three share the same molecular formula ($C_6H_{12}O_6$), the arrangement of atoms differs in each case.

- Substances such as these three, which have identical molecular formulas but different structural formulas, are known as structural isomers.
- Glucose, galactose, and fructose are "single" sugars or monosaccharides.
- Two monosaccharides can be linked together to form a "double" sugar or disaccharide.

- There are three common disaccharides: sucrose, lactose, and maltose.
- Sucrose is common table sugar and is made up of glucose and fructose.
- Lactose is the major sugar in milk and is made up of glucose and galactose.
- Maltose is a product of starch digestion and is made up of two glucoses.

- Although the process of linking the two monomers is rather complex, the end result in each case is the loss of a hydrogen atom (H) from one of the monosaccharides and a hydroxyl group (OH) from the other.
- The resulting linkage between the sugars is called a glycosidic bond.
- The molecular formula of each of these disaccharides is $C_{12}H_{22}O_{11}$.
- Sugars are very soluble in water because of their many hydroxyl groups.

- Although not as concentrated a fuel as fats, sugars are the most important source of energy for many cells.
- Carbohydrates provide the bulk of the calories in most diets, and starches provide the bulk of that.
- Starches are polysaccharides.

Starch

- Starches are polymers of glucose.
- Two types are found: amylose and amylopectin.
- Amylose consists of linear, unbranched chains of several hundred glucose residues (units).

- Amylopectin differs from amylose in being highly branched.
- The total number of glucose residues in a molecule of amylopectin is several thousand.

- Starches are insoluble in water and thus can serve as storage depots of glucose.
- Plants convert excess glucose into starch for storage.
- Rice, wheat, and corn are also major sources of starch in the human diet.
- Before starches can enter (or leave) cells, they must be digested.

- The hydrolysis of starch is done by amylases.
- With the aid of an amylase (such as pancreatic amylase), water molecules enter certain linkages, breaking the chain and eventually producing a mixture of glucose and maltose.
- A different amylase is needed to break the certain bonds of amylopectin.

Glycogen

- Animals store excess glucose by polymerizing it to form glycogen.
- The structure of glycogen is similar to that of amylopectin, although the branches in glycogen tend to be shorter and more frequent.
- Glycogen is broken back down into glucose when energy is needed (a process called glycogenolysis).

- In glycogenolysis, phosphate groups, not water, break certain linkages and the phosphate group must then be removed so that glucose can leave the cell.
- The liver and skeletal muscle are major depots of glycogen.

- There is some evidence that intense exercise and a high-carbohydrate diet ("carb-loading") can increase the reserves of glycogen in the muscles and thus may help marathoners work their muscles somewhat longer and harder than otherwise.
- But for most of us, carb-loading leads to increased deposits of fat.

Cellulose

- Cellulose is probably the single most abundant organic molecule in the biosphere.
- It is the major structural material of which plants are made.
- Wood is largely cellulose while cotton and paper are almost pure cellulose.
- Like starch, cellulose is a polysaccharide with glucose as its monomer. However, cellulose differs profoundly from starch in its properties.

Nucleic Acids

- The nucleic acids are very large molecules that have two main parts. The backbone of a nucleic acid is made of alternating sugar and phosphate molecules bonded together by phosphodiester linkages in a long chain.

- Each of the sugar groups in the backbone is attached to a third type of molecule called a nucleotide base.
- The order in which these nucleotide bases appear in the nucleic acid, codes for the information carried in the molecule.
- In other words, the nucleotide bases serve as a sort of genetic alphabet on which the structure of each protein in our bodies is encoded.

DNA

- In most living organisms, genetic information is stored in the molecule deoxyribonucleic acid, or DNA.
- DNA is made and resides in the nucleus of living cells.
- DNA gets its name from the sugar molecule contained in its backbone (deoxyribose), however it gets its significance from its unique structure.
- There are four different nucleotide bases that occur in DNA: adenine (A), cytosine (C), guanine (G) and thymine (T).
- The versatility of DNA comes from the fact that the molecule is actually double-stranded.
- The nucleotide bases of the DNA molecule form complementary pairs: the nucleotides hydrogen bond to another nucleotide base in a strand of DNA opposite to the original.
- This bonding is specific, and adenine always bonds to thymine (and vice versa) and guanine always bonds to cytosine (and vice versa).

RNA

- Ribonucleic acid, or RNA, gets its name from the sugar group in the molecule's backbone - ribose.
- Several important similarities and differences exist between RNA and DNA.
- Like DNA, RNA has a sugar-phosphate backbone with nucleotide bases attached to it.
- Like DNA, RNA contains the bases adenine (A), cytosine (C) and guanine (G).
- However, RNA does not contain thymine, instead, RNA's 4th nucleotide is the base uracil (U).
- Unlike the double-stranded DNA molecule, RNA is a single-stranded molecule.
- RNA is also important in the production of proteins in other living organisms.
- RNA can move around the cells of living organisms and thus serves as a sort of genetic messenger, relaying the information stored in the cell's DNA out from the nucleus to other parts of the cell where it is used to help make proteins.