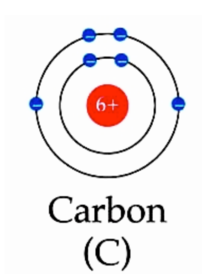
Although water is the most abundant compound of living organisms, and the "medium" for the existence of life, the molecules that are comprise most of living organisms fall into four categories: **carbohydrates, lipids, proteins** and **nucleic acids.** These molecules are all based on the element, **carbon**, which has the ability to form large, complex and diverse molecules.

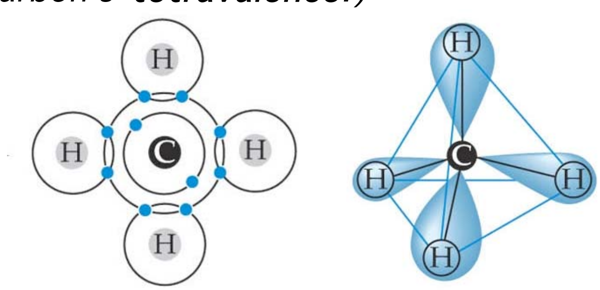
Carbon's versatility provides for the uniformity of chemicals and atomic proportions of the elements found in living organisms. A living organism can manufacture a multitude of different substances needed to sustain life from simple carbon backbones that combine in precise ways with atoms of hydrogen, oxygen, nitrogen, sulfur and phosphorus. The variation among this multitude of organic molecules from species to species and individual to individual distinguishes one from another.

Before we examine the molecules of living organisms by reviewing the properties of carbon. The chemistry of carbon, or carbon–hydrogen molecules, which are called **hydrocarbons**, is the field of organic chemistry, and the organic molecules of living organisms, biochemistry. The specific properties of carbon-containing molecules are derived from the **functional groups**, small molecular fragments with specific chemical properties that bond to the hydrocarbon backbone, affecting the chemical nature of the resulting compound.

Properties of Carbon

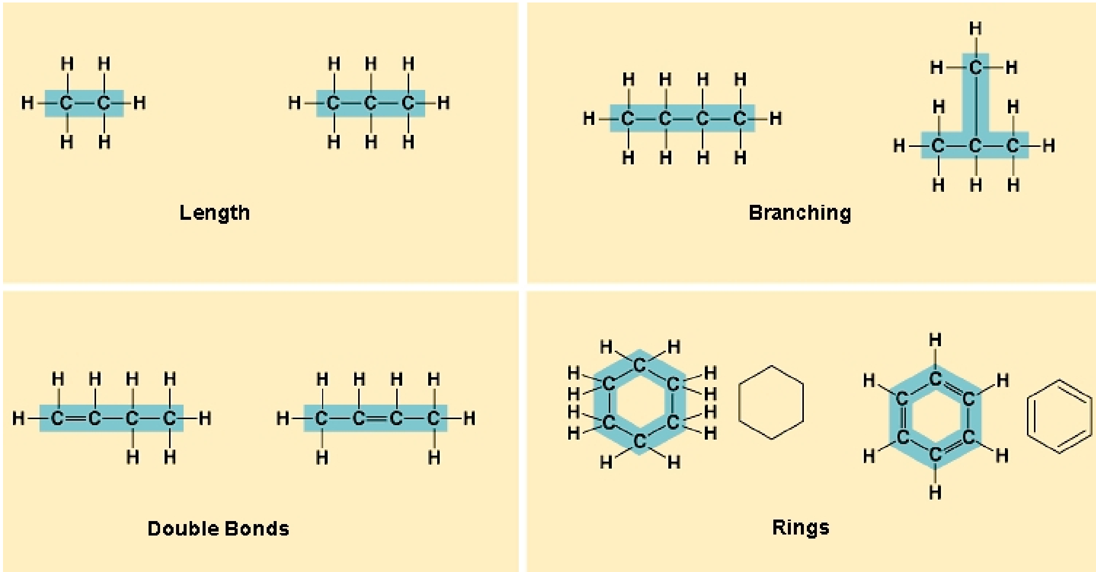
An atom's electrons determine the chemical characteristics and bonds an atom will make. Carbon always forms covalent bonds to become stable. You will recall that a covalent bond is one in which one or more electrons is/are shared between atoms. The carbon atom has 6 electrons, 2 in its inner shell (energy level) and 4 in its outer energy level. Carbon has a valence of 4 so each carbon atom makes **4 bonds** to obtain 8 electrons in its outer shell. (*And generally in 4 different directions. This is known as carbon's* ***tetravalence.****)*



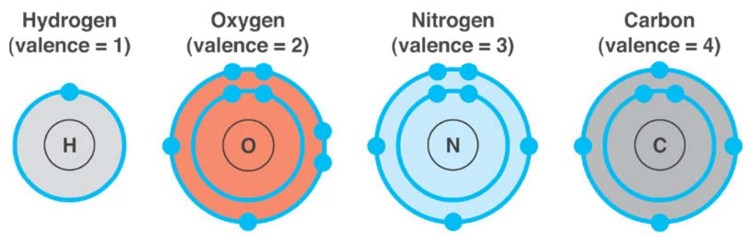


Methane

Carbon may make bonds with other carbon atoms forming chains, branching chains or rings of linked carbon atoms. Ring compounds are common in living organisms. The bonding of carbons to carbons is called the carbon skeleton. Carbon makes single covalent (bonding angle 109°, forming a tetrahedron shaped molecule), double covalent and triple covalent bonds. Double and triple bonds alter the bonding angles and shape of the resulting molecule. Double-bonded carbon bonds, for example, are flat. As we will see many times the shape of molecules is critical to molecular function.



When carbon is not bonding to other carbon atoms, it covalently bonds to a number of other atoms, notably hydrogen, oxygen and nitrogen. Recall the basic organic carbon compound is the **hydrocarbon**, formed from carbon and hydrogen.

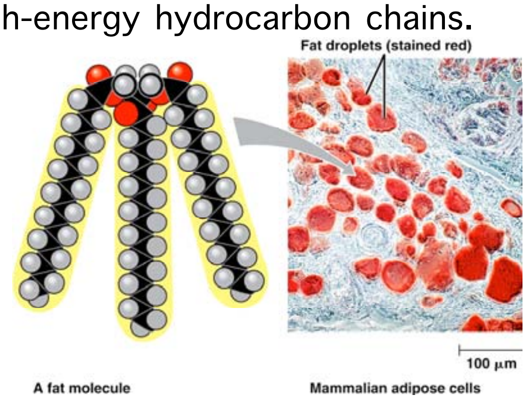


Properties of Hydrocarbons

Hydrocarbons, like carbon, typically vary in:

- The number of carbons on the chain
- The arrangement of the atoms
  - Whether the chain is straight, branching or forms a ring
  - Type of carbon-carbon bonds (single, double, triple)
  - Where hydrogen atoms are attached

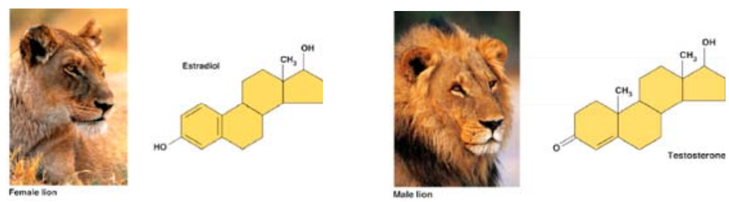
Most hydrocarbons have similar properties. The C—H bond is a **high-energy bond**; hydrocarbons are good fuels (methane, propane, butane, heptane). Fats are excellent examples of high-energy hydrocarbon chains.



Functional Groups and Compounds of Living Organisms

The unique chemical properties of molecules determine function. The major compounds of living organisms are modifications of hydrocarbons modified by **functional groups,** molecular fragments that confer particular chemical properties to the hydrocarbon.

For example, the steroid hormones, estradiol and testosterone, share a common interlocking carbon-ring backbone. They differ in the functional groups attached to that backbone.



Functional groups are often involved in the chemical reactions that occur between molecules, determining the "behavior" of the molecules and are consistent in different organic molecules. We shall review common functional groups

The Hydrocarbon and the Methyl Functional Group

The hydrocarbon backbone of most molecules is formed from an alkane, a molecule with all single bonded carbons and hydrogens attached at the other carbon bonds. The smallest alkane is methane, CH_4, a single carbon atom bonded to 4 hydrogen atoms. The hydrocarbon backbone is lengthened by adding the **methyl** functional group, CH_3, a carbon with 3 hydrogen atoms attached.

The naming convention for alkanes is important because this naming convention is used for most carbon compounds. The number of carbon atoms determines the prefix. For example:

- 1 carbon = methane
- 2 carbons = ethane
- 3 carbons = propane
- 4 carbons = butane

Hydroxyl Functional Group

The hydroxyl function group is formed from an oxygen atom bonded to a hydrogen atom, with the second bond of the oxygen free to attach to the carbon chain (–OH). (The bond between the oxygen and hydrogen atoms of the hydroxyl functional group is rarely illustrated – it is assumed. The actual bonding arrangement is: –O-H.)

- Hydroxyl functional groups confer properties of an alcohol to hydrocarbons.
- Hydroxyl functional groups are polar (from the oxygen's electronegativity), and attract water. This helps macromolecules, such as sugars, which have hydroxyl functional groups in their structure, dissolve in water.
- The naming convention for alcohols is to end in "ol". The number of carbon atoms determines the prefix (based on the hydrocarbon naming convention). For example, the two-carbon alcohol is ethanol.
- An alcohol can have more than one hydroxyl functional group. Such molecules are called poly-hydroxy alcohols.

The Aldehyde and Keto Functional Groups

Both aldehydes and ketones have a double-bonded oxygen atom (=O).

- Because double bonds restrict flexibility and rotation on the carbon skeleton, the location of the carbonyl functional group affects structure, and function.
  - The **aldehyde** functional group attaches to an "end" carbon forming an aldehyde.
  - The **keto** functional group attaches to any non-end carbon forming a ketone.
- The naming convention for ketones uses the suffix "one" and aldehydes the suffix "al". Except for a few conventional names, the prefix is determined by the number of carbons. For example, the 3-carbon ketone is called acetone.

Carboxyl Functional Group

The carboxyl function group has both hydroxyl and aldehyde functional groups attached to a common carbon atom. The carboxyl functional group will always be at the end of a carbon chain.

- Carboxyl functional groups form organic (or carboxylic) acids. The -OH portion of the functional group dissociates in solution, donating a H^{+}. This dissociation is aided by the electronegativity of the =O of the aldehyde portion of the functional group.

Amino Functional Group

The amino function group is - NH_2.

- Compounds with the amino functional group are amines. Most amines are in molecules that also have carboxyl function groups and form **amino acids**.
- The amino functional group is a base. The nitrogen region of the amino functional group can attract a proton (generally attached to a hydrogen, thereby removing hydrogen ions from solution) resulting in a positive charge.

Phosphate Functional Group

The phosphate functional group is the negatively changed ion composed of a phosphorus atom bonded to 4 oxygen atoms (PO_4^{-2}).

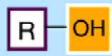
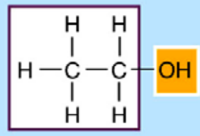
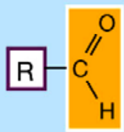
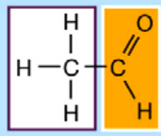
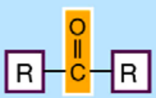
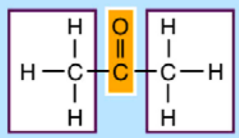
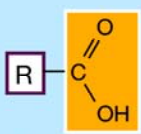
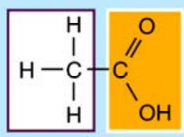
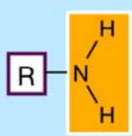
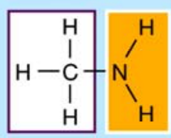
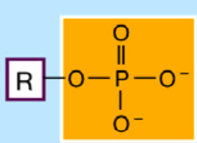
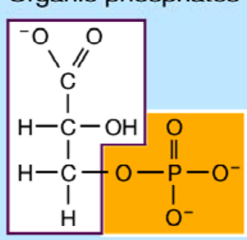
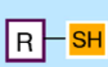
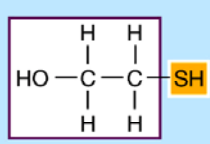
- Phosphate functional groups are important in energy transfer. We will study the energy transfer molecule, ATP, later.

Sulfhydryl Functional Group

Sulfur, like oxygen, forms two covalent bonds. The sulfhydryl functional group (-SH) is similar to the hydroxyl functional group.

- Sulfhydryl functional groups are important in the structure of proteins. When two amino acids have sulfhydryl functional groups, disulfide bonds can form between the two, stabilizing the protein's functional structure.
- Compounds containing sulfhydryl groups are called **-thiols.**

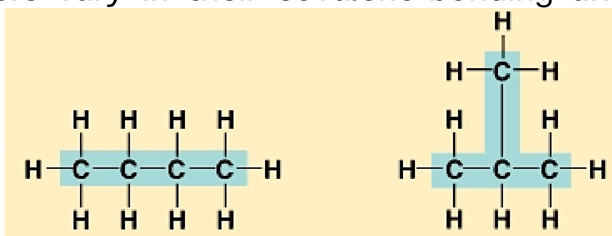
Functional Groups Important in Living Organisms

Functional group	Class of compounds and an example	Properties
 Hydroxyl	Alcohols  Ethanol	Polar. Hydrogen bonds with water to help dissolve molecules. Enables linkage to other molecules by dehydration.
 Aldehyde	Aldehydes  Acetaldehyde	C═O group is very reactive. Important in building molecules and in energy-releasing reactions.
 Keto	Ketones  Acetone	C═O group is important in carbohydrates and in energy reactions.
 Carboxyl	Carboxylic acids  Acetic acid	Acidic. Ionizes in living tissues to form $-COO^-$ and H^+. Enters into dehydration synthesis by giving up —OH. Some carboxylic acids important in energy-releasing reactions.
 Amino	Amines  Methylamine	Basic. Accepts H^+ in living tissues to form $-NH_3^+$. Enters into dehydration synthesis by giving up H^+.
 Phosphate	Organic phosphates  3-Phosphoglycerate	Negatively charged. Enters into dehydration synthesis by giving up —OH. When bonded to another phosphate, hydrolysis releases much energy.
 Sulfhydryl	Thiols  Mercaptoethanol	By giving up H, two —SH groups can react to form a disulfide bridge, thus stabilizing protein structure.

Carbon and Isomers

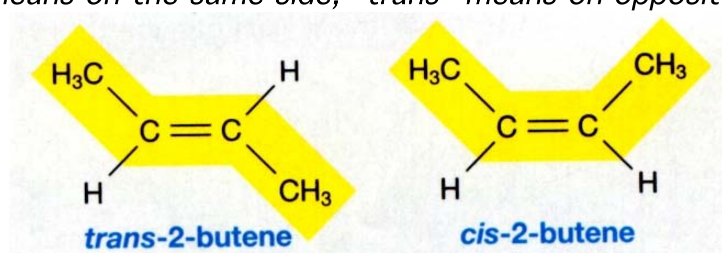
Molecules that differ only in the arrangement of atoms are called **isomers.** Isomers are very important in biology, and we shall see many examples. Isomers are common in carbon compounds. There are three types of isomers: **structural, geometric and optical** (enantiomers or mirror image isomers).

- **Structural** isomers vary in their covalent bonding arrangement.

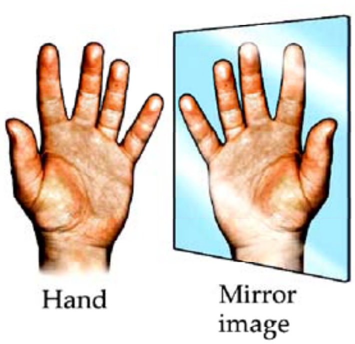


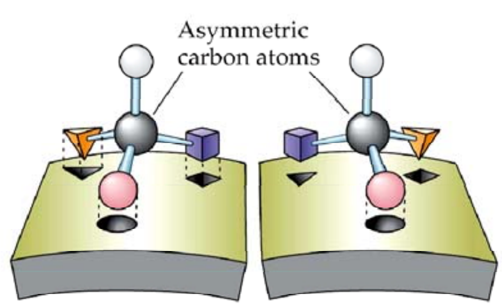
Butane Isobutane

- **Geometric** isomers share common covalent bonding, but **different spatial arrangements.** Because the carbon-carbon double bonds found in geometric isomers are inflexible (prevent rotation), the differing shape of geometric isomers can dramatically affect their biological function. (This is sometimes called the cis-trans difference.) Geometric isomers are important in vision. Light hitting the pigment, rhodopsin, in the rods of the eye causes a change in its structure, which triggers the nerve transmission. Cis-trans changes also occur when one partially hydrogenates fats, forming trans-fatty acids. *(Note: "cis" means on the same side; "trans" means on opposite sides.)*



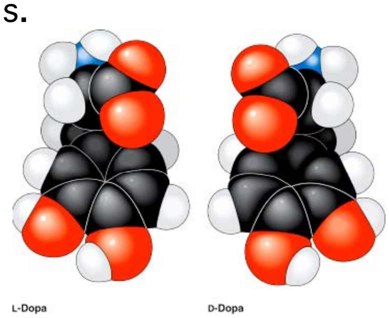
- **Enantiomers** or **optical isomers** (or stereoisomers) are molecules that have the same molecular formula but are mirror images of each other. Optical isomers are formed when a carbon atom (called an asymmetric carbon) has four different molecular groups attached to it so that they can be arranged in just two different ways. The two shapes of optical isomers are called the D- and L- (for dextro and levo – right and left).





- As with other types of isomers, the different shapes of optical isomers can dramatically alter function. The L-forms of optical isomers are generally biologically active; D forms can be inactive or even harmful to living organisms. All amino acids are optical isomers, because the α carbon of each amino acid is an asymmetric carbon.

  Vitamin E has four isomer forms; only one (α-tocopherol) is biologically active. L-dopa, a drug that helps treat Parkinson's disease, is another. D-dopa is biologically inactive. An isomer of Thalidomide, a drug used to treat depression in Europe caused severe birth defects when the drug was first introduced in the 1950's.



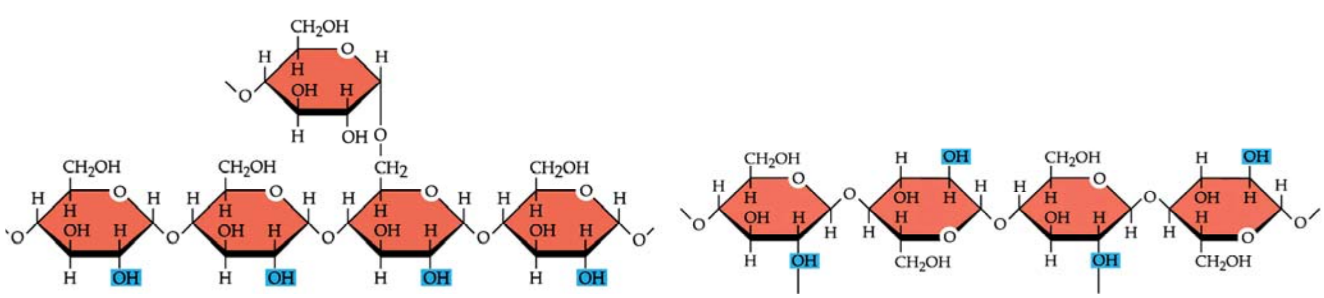
Other Molecular Differences in Carbon Compounds

Hydrocarbons can, in general, have other variations in bonding which result in compounds that are different in shape and often function. The number of and kind of atoms as well as the types of bonds formed are important. For example, the covalent bond angles in a ring compound determine the molecule's shape.

Formation of Macromolecules – Polymers from Monomers

Many of our biological molecules, such as proteins and complex carbohydrates and our nucleic acids, are **polymers**, large molecules formed by joining many smaller subunits, called **monomers**, together.

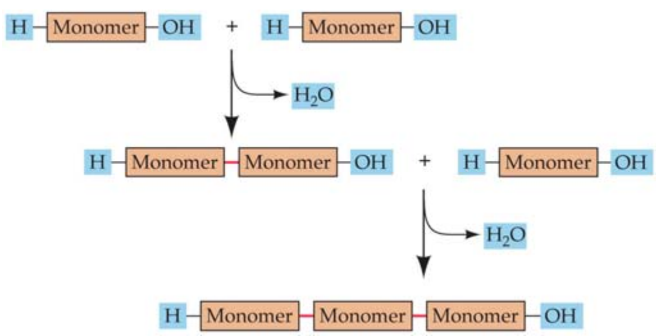
For example, the primary difference between cellulose and starch, two carbohydrate macromolecules, is that starch is formed by α 1-4 linkages of glucose, forming a helical, branching molecule, and cellulose is formed from β 1-4 linkages, forming a straight molecule. Starch and cellulose are not isomers, although they are composed of the polymers of the monosaccharide, glucose.



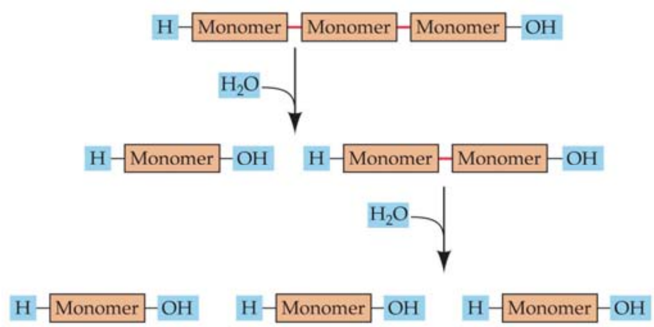
Starch Cellulose

Most of our biological molecules are assembled or broken down using the same type of chemical reaction, one that involves adding or removing water molecules. Macromolecules (polymers) are formed from their subunits or monomers by removing molecules of water (a hydrogen (-H) from one subunit and a hydroxyl (-OH) from the second) to join the subunits together. This is called a **condensation or dehydration synthesis.**

When larger molecules are broken down, such as in digestion, water molecules are added in to break the polymers into their subunits, a process called **hydrolysis.** The enzymes that facilitate digestion are called hydrolytic enzymes.



Condensation (Dehydration Synthesis)



Hydrolysis

Let's now look with some detail at the major compounds of living organisms. We shall look at proteins, carbohydrates, lipids, and briefly the fourth: nucleic acids. We will deal with the nucleic acids in depth during our unit on molecular genetics.