# Chemical Background for Spring 2010 BIO 311C – Brand
# Part I

## Discussion Period 1: Jan. 22 & 25

**Atoms and Ions**

Ninety two naturally occurring kinds of fundamental substance, called **elements,** occur on earth**.**
**Hydrogen** is the **smallest** element; uranium the largest.
All material substances on earth are composed of combinations of these 92 elements.

An **atom** is a single unit of an element.
Each atom is composed of **protons**, **electrons**, and neutrons.
The 92 different kinds of naturally-occurring atoms are distinguished from each other by their differing number of protons.

For example, hydrogen atoms each have one proton, uranium atoms have 92.
An atom is defined by the number of protons that it contains. That number never changes under ordinary conditions on earth, only under the very extreme conditions of a nuclear reaction.

Each proton has an electrical charge of +1 and each electron has an electrical charge of -1.
A **neutral atom** has no net electrical charge; its number of electrons is equal to its number of protons.

The electrons of an atom are much less tightly associated with the atom than are its protons.

Electrons occur in somewhat diffuse regions of space around an atom; in contrast, the protons of an atom are confined within a tight nuclear center. Yet, the region of space available to each electron of an atom, called an **orbital**, is defined and limited. The orbitals of an atom with their confined electrons can be thought of loosely as analogous to highways that confine vehicles to specific regions of travel.

Under appropriate circumstances one or more electrons in an atom may vacate its orbital and leave the atom altogether. The atom then contains more protons than electrons, which gives it a net positive charge.

Under other circumstances an atom may accept one or more additional electrons. These additional electrons are also confined to specific orbitals of the atom. An atom with one or more additional electrons has a net negative charge.

Atom X, which has lost one electron, then carries a net single positive charge and is written as $X^+$.
Atom Y, which has gained two electrons, then carries two net negative charges and is written as $Y^{2-}$.

Sometimes we write a circle around the electrical charges when showing the charges on an atom.
i.e. $X^{\oplus}$

An atom with a net positive charge or a net negative charge is called an **ion**.

Some kinds of atoms easily lose one or more electrons; they may be described as "**potential electron donors**".

Other kinds of atoms easily accept one or more electrons; they may be described as "**potential electron acceptors**".

When a potential electron acceptor atom comes near to a potential electron donor atom, then an electron may pass from the potential donor to the potential acceptor, simultaneously creating a positively charged ion and a negatively charged ion.

The two oppositely charged ions may then lie in close proximity to each other because opposite electrical charges attract each other. Salts, such as sodium chloride (table salt), consist of positively charged ions ($Na^+$ in the case of sodium chloride) held in a regular packed pattern with negatively charged ions ($Cl^-$ in the case of sodium chloride).

## Covalent Bonds and Molecules

Some kinds of atoms do not willingly serve as an electron donor or an electron acceptor, but instead prefer to share one or more of their electrons with a suitable neighboring atom. If the shared electron can be accommodated in a new well-defined orbital that is associated with both atoms, then the new orbital is called a **hybrid orbital** and pair of atoms may be held together by the shared electron in the hybrid orbital. Hybrid orbitals are available for many different combinations of paired atoms.

When two suitable atoms come in close proximity such that a stable hybrid orbital becomes available, then a very stable arrangement of the two atoms in close proximity may form when each atom of the pair contributes one electron to the hybrid orbital.

The adhesive attraction between two or more atoms, due to some rearrangement of electrons within and between the atoms is called a **chemical bond**.

The adhesive attraction between a pair of atoms, resulting form the sharing of a pair of electrons within a hybrid orbital common to the two atoms, is called a **covalent bond**.

There are several different kinds of chemical bonds; a covalent bond is one kind.

A **chemical reaction** may be defined broadly as the re-distribution of one or more electrons among two or more atoms.

A **molecule** may be defined as a unit of substance that consists of two or more atoms held together by chemical bonding.

A **compound** is a molecule that is composed of two or more different kinds of atoms.

Molecules, like individual atoms, may carry a positive or a negative electrical charge. A molecule that carries an electrical charge may also be called an ion.

A molecule or individual atom that carries one or more positive electrical charge is called a **cation**.
A molecule or individual atom that carries one or more negative electrical charge is called an **anion**.

In BIO 311C we will frequently use the words “atom”, “molecule”, “compound” and “ion” to describe units of a chemical substances. We prefer to not use the non-descriptive word “chemical”. Thus, we prefer to call a sodium ion ($Na^+$) an ion (or better still a “cation”) rather than a “chemical”.

## Molecules of Living Cells

Living cells contain thousands of different kinds of compounds, almost all of which are held together by covalent bonds. Most of these molecules carry electrical charges so they could also be described as ions.

Generally an electrically-charged individual atom or an electrically-charged molecule consisting of only a few atoms is described by its ionic name. Many of the molecules in living cells are very large compounds, some containing many thousands of atoms held together by covalent bonds. Many of them carry electrical charges. These large and electrically-charged molecules are usually described by their name as a compound, not as an ion.

Most of the largest molecules in living cells carry many positive electrical charges and many negative electrical charges simultaneously.

Although thousands of different kinds of compounds are required to sustain a single cell in the living state, only 16 different kinds of atoms are used to construct all of these different compounds.

The vast majority of the compounds within living cells are made of combinations of only 6 different kinds of atoms - **Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorous and Sulfur** - held together in most kinds of molecules by covalent bonds. However, other kinds of bonds also occur in many compounds within living cells.

Molecules that are characteristically found in association with living organisms, such as those which occur within living cells, are called **biological molecules**. Thus, most kinds of biological molecules are composed of combinations of only 6 different kinds of atom, and most are held together by covalent bonds.

## Chemical and Structural Formulas of Molecules

By international convention each kind of atom (element) is abbreviated with a universally recognized **chemical symbol**. All chemical symbols are written with either a single capital letter, or else a two-letter designation with the first letter capitalized.

A single covalent bond holding two atoms together is usually shown as a straight line between the chemical symbols for the two atoms. For example, the covalent bond that holds two atoms of hydrogen together in a molecule of hydrogen (molecular hydrogen) can be shown as:

$$H-H$$

where the two capital letters “H" represent hydrogen atoms and the line between them represents a covalent bond.

A covelent bond between two atoms can also be shown as a pair of dots, representing electrons, between the two atoms that are held together by the covalent bond.

$$H : H$$

Molecular hydrogen is sometimes shown in more abbreviated form by a chemical formula, $H_2$.

A **chemical formula** of a molecule shows the number of each kind of atom in the molecule, but generally doesn’t show any information about how the atoms of the molecule are bonded together. For example, the chemical formula for a molecule of water is written as:

$$H_2O$$

where the subscript “2” indicates that water contains two atoms of hydrogen, and the letter “O” is the chemical symbol for an atom of oxygen. Thus, the chemical formula of water shows that a molecule of water contains two atoms of hydrogen and one atom of oxygen.

A **structural formula** of a molecule illustrates how each individual atom is bonded to other atoms in the molecule. The structural formula of molecular hydrogen was shown previously as

$H-H$ and as $H : H$

Although a chemical formula is often the easiest way to illustrate a molecule, for most kinds of molecules a structural formula is more informative. The structural formula of water can be illustrated as:

$H-O-H$ or $H : O : H$

Each kind of atom forms a characteristic number of covalent bonds. The characteristic number of simultaneous covalent bonds that an atom forms to other atoms is called the **covalency** of the atom.

The chemical symbol and the covalency for each of the 6 kinds of atoms most central to life are shown in the table below:

| Atom | Chemical symbol | Covalency in biomolecules |
|---|---|---|
| Hydrogen | H | 1 |
| Oxygen | O | 2 |
| Carbon | C | 4 |
| Nitrogen | N | 3 |
| Phosphorous | P | 5 |
| Sulfur | S | 2 |

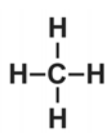
Consistent with its covalency of 2, the oxygen atom in a molecule of water simultaneously forms two covalent bonds. Each hydrogen atom, with a covalency of 1, forms only one covalent bond.

Structural formulas of molecules that contain only a few atoms can sometimes be written clearly without showing all of the covalent bonds. For example, the structural formula of water could be shown meaningfully as:

**HOH**

The chemical formula of methane is **$CH_4$**.

Its structural formula can be shown as:



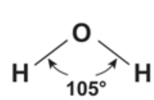
Of the various kinds of chemical bonds capable of holding molecules together, covalent bonds are among the strongest. Thus, even though the vast majority of biological molecules contain many covalent bonds, most are quite stable due to the chemical strength of individual covalent bonds.

## Stereo Formulas and Shapes of Molecules

The shapes of a molecule can be illustrated with a structural formula that shows the geometric (3-dimensional) arrangements of its atoms with respect to each other. A structural formula illustrated in three dimensions is called a **stereo formula**.

Some stereo formulas, such as the stereo formula of water, can be illustrated accurately in two dimension, such as on a flat piece of paper.

Stereo formula of water, a planar molecule:



Most larger molecules are not planar. Their stereo formulas are best illustrated with a 3-dimensional models. Three-dimensional models that illustrate stereo formulas of proteins, a class of biological molecules that contain many thousands of atoms covalently bonded together, can be generated and observed with modern computers.

## Inorganic and Organic Molecules

Most kinds of molecules found in living organisms contain carbon atoms. Carbon-containing molecules are sometimes referred to as molecules of life and most of them are classified as **organic molecules**. Molecules that do not contain any carbon atoms are classified as **inorganic molecules**.

A few small and oxidized carbon-containing molecules and ions that occur commonly outside of living systems are generally categorized with inorganic molecules. They include:

**Carbon dioxide ($CO_2$),**

**Carbonic acid ($H_2CO_3$**, which can be thought of as $CO_2$ chemically bonded to $H_2O$),

**Bicarbonate ($HCO_3^-$**, a monovalent anion; a carbonic acid devoid of a proton), and

**Carbonate ($CO_3^{2-}$**, a divalent anion; a carbonic acid devoid of two protons).

Each of the inorganic molecules or ions whose chemical formula is shown above contains only a few atoms, and each carries a higher number of oxygen atoms than hydrogen atoms. These carbon-containing inorganic compounds are highly important to living organisms.

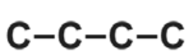
We will consider mostly organic compounds in BIO 311C, water being a notable exception.

A single living cell contains thousands of different organic molecules.

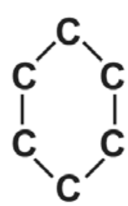
## Structures of Organic Molecules

Almost all organic molecules of biological importance contain more than one carbon atom. The carbon atoms occur as chains or rings of atoms held together covalently.

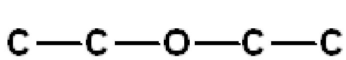
Examples:




and

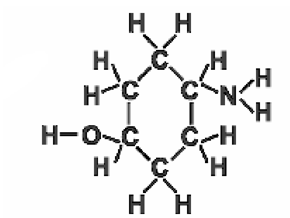



Although the chains or rings of atoms found in biological molecules contain mostly carbon atoms, occasionally another atom may be included in the ring, as shown below.



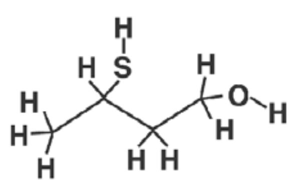
The three structures shown above are not complete molecules, since the numbers of covalent bonds drawn from the carbon atoms does not match the covalency of carbon. There must be 4 covalent bonds (illustrated, for example, by four straight lines) shown for each carbon atom, so additional atoms must be present. The structures shown above may be described as **skeletons** of organic molecules.
Some organic molecules are huge. For example, a single molecule of DNA may contain hundreds of millions of atoms, including many millions of carbon atoms.

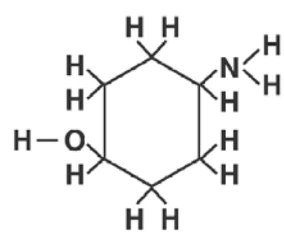
The structure of an organic molecule that contains only a few carbon atoms may look rather complicated when all atoms and bonds in the molecule are shown. The molecule shown below has the same carbon skeleton as does one of the structures shown previously. Note that each atom in the molecule shown below has the correct number of lines drawn from it (covalent bonds) to satisfy its covalency.



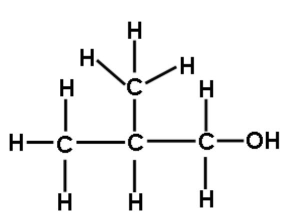
In some cases the atom at one or both ends of a covalent bond may not be shown, in order to simplify the appearance of a rather complex molecule. But in order to understand the chemical properties of the molecule it is necessary to show enough atoms and bonds that the structural formula can be visualized.

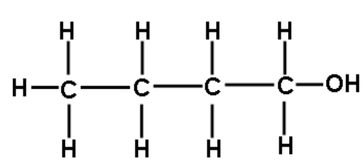
For example, the two illustrations below represent structural formulas shown in an abbreviated form, whereby each carbon atom is represented only as vertex where four lines (representing covalent bonds) converge.





A chain of carbon atoms may be branched (three or four carbon atoms covalently bonded to the same carbon atom). A **branched-chain organic molecule** is illustrated in the structural formula shown at left below. Note that the structures of these molecules are slightly abbreviated since the covalent bond between the oxygen atom and a hydrogen atom is not shown.

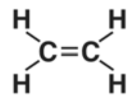




Branched-chain organic molecules are typically more compact in shape than are straight-chain organic molecules of the same size. The two molecules shown above have the same chemical formula ($C_4H_{10}O$) although their chemical properties are somewhat different.

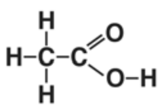
In some organic molecules, the same two carbon atoms are held together by two different covalent bonds, as illustrated in the structural formula shown below. The bonding between the two carbon atoms is then called a **carbon-carbon double bond**.

**ethylene**

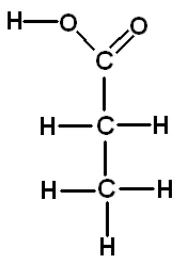


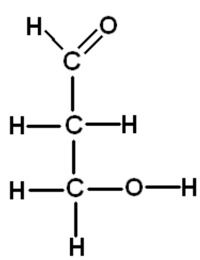
Ethylene is one of the smallest biologically important organic molecules; it is a plant hormone.

The structural formula of **acetic acid** is illustrated below. It also contains a double bond, in this case a carbon-oxygen double bond. Acetic acid is synthesized and excreted by various kinds of bacteria, where it may sour food. It is produced commercially as vinegar.



All of the formulas shown above are structural formulas (even if abbreviated). Generally it is necessary to show a structural formula rather than a chemical formula to demonstrate the properties of an organic molecule, because many different organic compounds, with very different chemical properties, may be represented by the same chemical formula.





Both molecules shown above have the chemical formula $\mathbf{C_3H_6O_2}$, but their chemical properties are very different.

Sometimes a structural formula can be shown in a somewhat condensed form without losing structural information. For example, the two structures shown above can be represented in the more abbreviated form shown below without losing structural information.