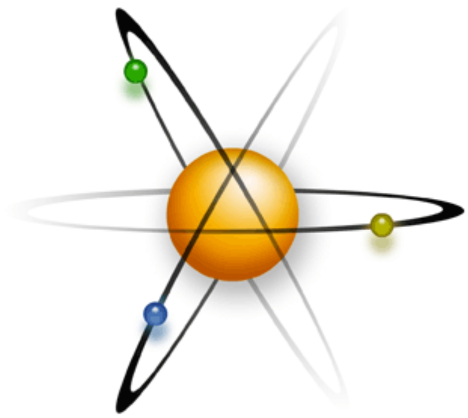
Lesson 1

The Chemistry of Life (Part one)



MATTER AND ENERGY

All living and non-living things consist of **matter**, which is anything that occupies space and has mass, such as wood, water, air, metal, plastic and food. Matter exists in one or more states: solid, liquid or gas. It is important to distinguish between mass and weight: your **mass** is always the same, but your **weight** varies with the force of gravity at your location - on a mountain peak, swimming in the ocean, or walking on the moon. Mass is the amount of matter that a substance contains, and weight is the force of gravity acting on the mass.

Energy is the capacity to do work, or to put a mass into motion. Energy and mass cannot be created or destroyed, but they can be converted from one into the other. **Potential energy** is stored energy, such as in a battery, a tank of gas, or the water in a reservoir above a hydro generating plant. **Kinetic energy** is the energy of any object in motion, from a molecule to a bouncing ball to a river. Kinetic and potential energy can exist in several different forms, and can be transformed from one form into another.

Chemical energy is the energy released or absorbed when chemical bonds are broken or formed. When our body builds new tissues or replaces injured cells, it requires energy. When we break down the foods we eat we release chemical energy that can be used for the building processes.

Radiant energy is energy that travels in waves, such as heat and light. When the waves are spaced closely together, this is called a short wavelength. From longest to shortest wavelength, some forms of radiant energy include: radio waves, microwaves, infrared waves, visible light waves, ultraviolet waves, x-rays and gamma rays (used for ultrasound imaging).

Electrical energy results from the flow of electrons or ions. Our nerve and muscle cells act on electrical impulses called action potentials.

ELEMENTS AND ATOMS

All forms of matter are made up of a number of chemical **elements**, substances that cannot be split into simpler substances by ordinary chemical reactions. It is thought that there are 92 elements that occur in nature, and an additional 17 that have been briefly synthesized. We have 26 elements in the human body, with 96% comprised of the four elements oxygen (O), carbon (C), hydrogen (H) and nitrogen (N). An additional nine elements comprise 3.9% of our mass, and the remaining 1% is made up of 13 trace elements (Figure 1-1). The elements are organized on the periodic table of the elements, using their chemical symbols.

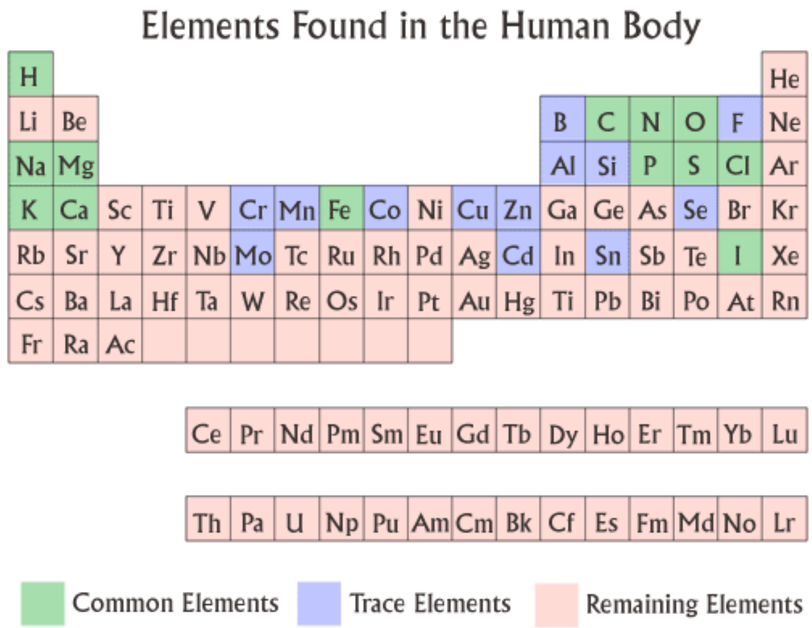


Figure 1-1: Periodic Table of the Elements highlighting elements found in the human body

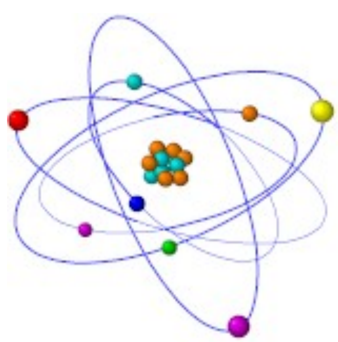


Figure 1-2:

The structure of an Atom

Atoms are the smallest unit of matter that react in chemical reactions. A chunk of coal or a diamond is made up of carbon atoms, and a tank of oxygen is made up entirely of oxygen atoms. Hydrogen is the smallest atom, and the elements lower on the periodic table are larger. If 50 million of the largest atoms were placed end to end, they would span about 2.5 cm.

Atoms (Figure 1-0-2) consist of three major subatomic particles: electrons, protons and neutrons. Positively charged protons, and uncharged neutrons form the very dense nucleus. Negatively charged electrons move rapidly around the nucleus and form an electron cloud, which is most of the volume of the atom. Astronomer Carl Sagan once remarked that if you could enlarge a single atom to the size of Mt Everest, the nucleus would be about the size of a football! Atoms are neutral particles since the positive and negative particles are equal in number.

The **atomic number** is the number of protons in the element, and therefore the number of electrons. Each atom has a different atomic number, and the periodic table is organized according to the atomic number of each element. Hydrogen is the first element with an atomic number of one, helium is the second with two, carbon is sixth with an atomic number of six, and so on.

The **mass number** of each element is the sum of protons and neutrons for each isotope. For carbon it can be 12 or 13, depending on the number neutrons. This number may also be displayed on some periodic tables.

The **atomic mass** of an atom is the sum of the mass of protons, neutrons and electrons of an element, measured in atomic mass units (amu's). For carbon, the atomic mass is 12.011 amu.

ISOTOPES

Most elements are composed of mixtures of two or more **isotopes**, or atoms that differ in the number of neutrons they contain. For example, oxygen is composed mostly of atoms with eight neutrons, but it also contains some isotopes with 9 or 10 neutrons. Isotopes are named by their mass numbers, eg. O-17 and O-18. The nature of chemical reactions of each element depends on the number of electrons, so isotopes of one element have the same chemical reactions, and act the same in the human body.

Some isotopes are not stable, and are continually emitting radiation in an effort to achieve a more stable state. Types of radiation include alpha and beta particles and X and gamma rays. Radiation has many controversial applications including in medicine, food irradiation, estimating the age of rocks and fossils, energy production, and weapons of destruction! In medicine, isotopes are used to tag substances that can be followed through various biochemical pathways. They are also used for diagnostic imaging of many tissues including the thyroid gland, brain, heart, lungs, kidneys, and bones.

Food irradiation: A controversial issue

Ionizing radiation food processing involves the use of large doses of cobalt-60 or cesium-137 to preserve foods. It inhibits sprouting of root vegetables, kills insects, parasites, and microorganisms, and sterilizes packaging and prepared foods.

However, the process causes chemical changes in foods that

- May harm malnourished, young, or old people, reduces vitamins and overall nutritional value,
- Prevents the development of safer alternatives, and
- Contaminates our environment with radioactive materials from food irradiation plants.

REACTIONS BETWEEN ATOMS

When atoms bond with other atoms, or break apart from them, a **chemical reaction** occurs. New products with different chemical properties are formed. In the body, breaking chemical bonds usually releases energy, and forming bonds usually requires energy. Chemical reactions are the foundation of all life processes, and electron interactions are the basis of all chemical reactions. When two or more atoms combine in a chemical reaction, the resulting combination is called a **molecule**. It may be two different atoms or two that are the same, such as the hydrogen molecule, H_2.

Atoms bond together to form more stable configurations. It is useful to visualize how electrons surround the nucleus of atoms to grasp the concept of stability. Electrons whiz around the nucleus of atoms within certain regions called shells, and are most stable when each shell is full. The first shell can hold up to two electrons. Hydrogen's single electron is found in this first shell, and helium's two electrons fill the first shell (Figure 1-3).

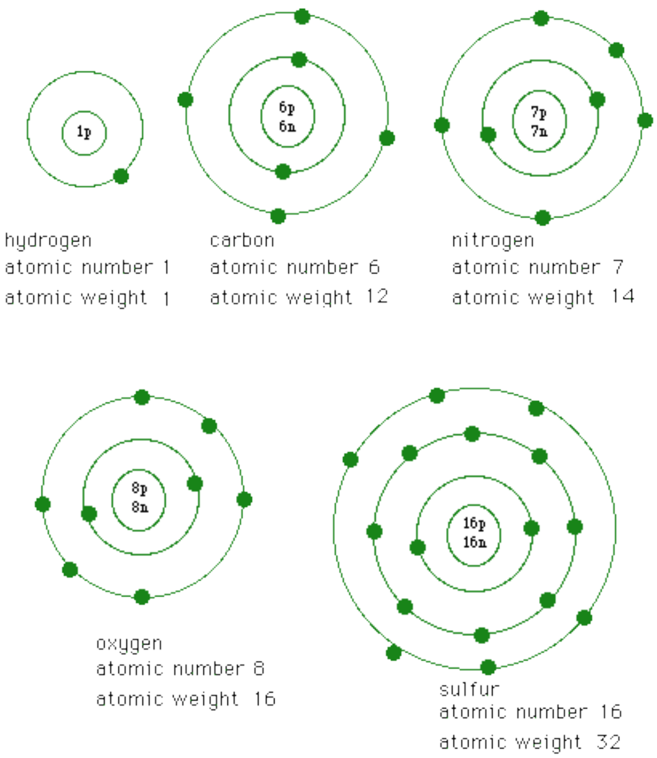


Figure 1-3: Atomic structures of several different atoms

The second shell can hold up to eight electrons. It is actually divided into sub-shells, called **orbitals**, which specify the shape of the region within the shells where the electrons can be found. The carbon atom can half fill the second shell with its six electrons, and the neon atom completely fills it with 10 electrons. Helium and neon are both stable configurations, called **inert gasses**. Iodine, the largest element in the human body, holds 18 electrons in the fourth shell and seven in the fifth.

Ionic Reactions

When the outermost shell is full, it becomes stable and is said to satisfy the octet rule (this term refers to the third shell that is filled with eight electrons). To achieve this stability, atoms sometimes "donate" electrons from one to another. The **valence** is the number of extra or deficient electrons in the **valence shell**, the outermost shell. An atom that requires one electron to fill its outer shell, such as chlorine, gains an electron from an atom that has one too many, such as sodium. Both atoms then become charged **ions**. Sodium acquires a positive charge, called a **cation**, since it has given up an electron, and is written Na^+. Chlorine gains an electron and becomes a negatively charged **anion** called the chloride ion, written Cl^-. The two charged ions become attracted by a weak electrostatic force called an *ionic bond*. In this case, the sodium and chloride ions form the sodium chloride molecule that is common table salt (Figure 1-4).

In nature we do not find single atoms bonded together, but crystals formed of numerous sodium and chloride ions, called an ionic compound. A compound is a substance that can be broken down into two or more different elements. Ions in solution are called **electrolytes**, since they are charged and capable of conducting electricity.

Ionic bonds tend to form between atoms found on opposite sides of the periodic table. Elements on the left side tend to be electron donors, and elements on the right side tend to be electron acceptors. Take a moment to note where sodium and chlorine are located.

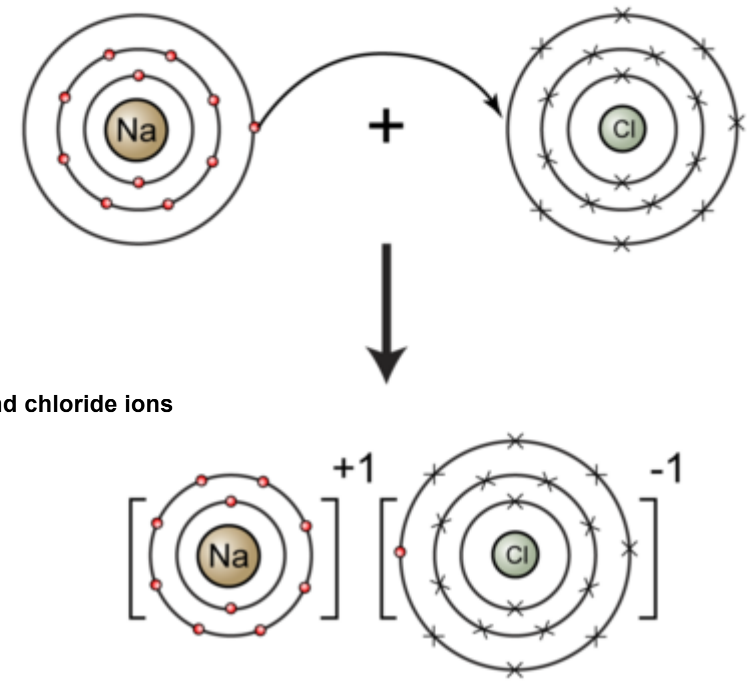


Figure 1-4: Ionic bond of sodium and chloride ions

Covalent Reactions

Ionic bonds form when one atom "gives" an electron to another atom. Sometimes compared to a good marriage or friendship, covalent bonds occur when two atoms share outer-shell electrons so that both atoms fill their outer shells. This sharing also satisfies the octet rule, and produces a much stronger bond.

Covalent bonds form between two atoms of similar or identical electron affinity. They are far more common than ionic bonds.

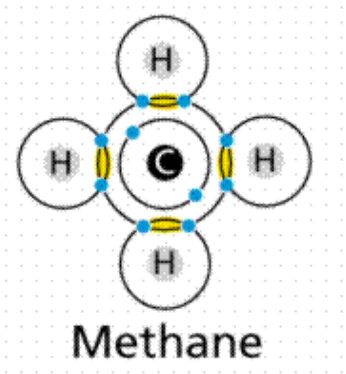


Figure 1-5: The methane molecule

Two hydrogen atoms share their single electrons to form one shared pair of electrons, creating a molecule of hydrogen gas, H_2. The outer shell of each atom is filled with two electrons, satisfying the octet rule, and creating a more stable configuration.

Methane is a flammable gas given off by rotting vegetation (or livestock). It consists of a carbon atom bonded to four hydrogen atoms. Carbon has six electrons, with four in the outer shell. It needs four more to fill the outer shell. Each hydrogen atom shares its single electron with one of the four electrons from the carbon atom, creating four shared pairs of electrons and filling the outer shells of all five of the atoms (Figure 1-5).

Covalent bonds are often represented graphically by a structural formula. A dash between two atoms represents a sharing of one pair of electrons, forming a single covalent bond. For example, hydrogen gas is written H-H.

The water molecule (H_2O) is formed of an oxygen atom covalently bonded to two hydrogen atoms. The oxygen atom has eight electrons, two in the inner shell and six in the outer shell. It requires two more, so it shares two electrons with two hydrogen atoms, filling the outer shell of all three atoms. It is represented as H-O-H. One can imagine the electrons that formerly revolved only around the hydrogen or the oxygen molecules, now circulating around a hydrogen atom and the oxygen atom.

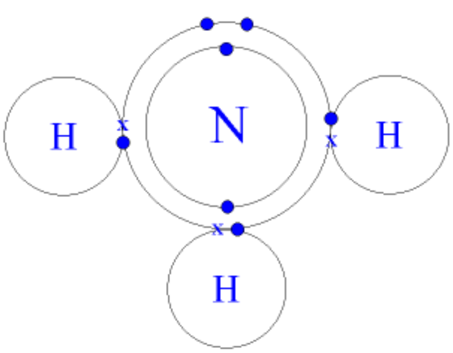


Figure 1-6: Ammonia molecule

Ammonia gas (NH_3) is formed with nitrogen, which has seven electrons. It has five electrons in the outer shell, and needs three more. It shares the three electrons with three hydrogen atoms to create a more stable molecule with three covalent bonds (Figure 1-6).

Some atoms share two electrons with each other, represented by a double dash, such as C=O. Carbon often forms a double bond with oxygen, sharing two pairs of electrons to fill the outer shell of oxygen. Two shared pairs of electrons circulate around the carbon and oxygen atoms. The carbon molecule requires four electrons to fill its outer shell, so it often bonds with two oxygen atoms, forming CO_2, represented by the structural formula O=C=O.

Carbon can form triple bonds with other carbon atoms, sharing three electrons between the two atoms.

Polar covalent bonds

Atoms with low **electron affinity** share electrons to form covalent bonds, but sometimes the electron affinity differs between atoms, resulting in polar covalent bonds. In the case of the water molecule, oxygen has a slightly higher affinity for electrons than hydrogen, and the shared electron spends more time around the oxygen than the hydrogen molecule. This gives a slight negative charge to the oxygen atom and a slight positive charge to the hydrogen atom. The greater the difference in electron affinity, the more polar the bond becomes.

A polar covalent bond in a large molecule will make the entire molecule polar.

Hydrogen bonds

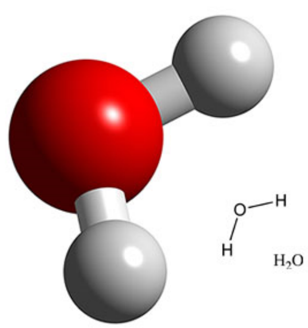


Figure 1-7: Water molecule

Water has two polar covalent bonds and three slightly charged atoms (Figure 1-7). In solution, the positive charge of the hydrogen atoms forms a **weak electrostatic attraction** with the negative charge of the oxygen atoms, called a hydrogen bond. This weak bond is responsible for many of the properties of water that make it essential for life on Earth.

Hydrogen bonds form between hydrogen and other elements with a negative charge resulting from a polar covalent bond. Oxygen, nitrogen and fluorine are the elements that are most commonly involved in hydrogen bonds, since they all have a slightly higher affinity for electrons and acquire a slight negative charge.

Hydrogen bonds form between small molecules with polar covalent bonds, and between atoms within large molecules with polar covalent bonds, such as DNA. The three dimensional shape of large molecules is due to hydrogen bonding.

Synthesis and decomposition reactions

The term metabolism refers to all the chemical reactions that occur in the body. Chemical reactions are nothing more than the making or breaking of bonds between atoms. They occur in the body because atoms, ions and molecules are continually colliding with each other, due to their kinetic energy.

Chemical reactions are most likely to occur in a favourable environment, including: a high concentration of the necessary atoms, a high temperature to ensure particles are travelling at high speed, enough energy to start a chemical reaction, and a proper orientation of the appropriate sides of the particles together.

A **synthesis reaction** is the process of forming new and larger molecules from atoms, ions and molecules. Two reactants, such as N_2 and $3H_2$ combine to form a product, in this case, two molecules of ammonia, NH_3. This reaction can be written:

$$N_2 + 3H_2 \rightarrow 2NH_3.$$

All synthesis reactions that occur in the body are called **anabolic** reactions, and they all require energy. Building new proteins from amino acids is an example of anabolism.

The reverse of a synthesis reaction is a **decomposition reaction**. Molecules are broken down into smaller components, involving a breaking of bonds. All the decomposition reactions that occur in the body are collectively called **catabolism**. When we digest our food, we break apart molecules and release the energy stored within them for use by our cells.

All chemical reactions are based on synthesis and decomposition processes. In **exchange reactions**, bonds are both broken and formed, for example:

$$AB + CD \rightarrow AC + BD.$$

Our body uses a reaction of this type, called a buffer reaction, to maintain a normal acid-base balance.

When a chemical reaction is reversible, the product can revert to the original reactants. A reversible reaction is indicated by a double arrow:

$$A + B \leftrightarrow AB$$

The double arrow indicates that the reaction can occur in either direction. If a reaction is reversible only in special conditions such as in the presence of heat or water, this can be indicated with that arrow. For example, the breakdown and reformation of ATP is a reversible reaction. Our body continuously uses the energy stored in ATP, breaking it down to ADP. It also rebuilds ATP from ADP within the mitochondria of our cells with an adequate supply of glucose.