Most of the Universe consists of matter and energy. **Energy** is the capacity to do work. **Matter** has mass and occupies space. All matter is composed of basic elements that cannot be broken down to substances with different chemical or physical properties. **Elements** are substances consisting of one type of atom, for example; carbon atoms make up diamond, and also graphite. Pure (24K) gold is composed of only one type of atom, gold atoms. **Atoms** are the smallest particle into which an element can be divided. The ancient Greek philosophers developed the concept of the atom, although they considered it the fundamental particle that could not be broken down. Since the work of Enrico Fermi and his colleagues, we now know that the atom is divisible, often releasing tremendous energies as in nuclear explosions or (in a controlled fashion in) thermonuclear power plants.

About 25 of the 92 naturally occurring elements are essential to life. Biologically important elements include carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus. These six elements make up the compounds found in over 99% of the matter in living systems.

Subatomic particles were discovered during the 1800s. The proton is located in the center (or nucleus) of an atom, each atom has at least one proton. **Protons** have a charge of +1, and a mass of approximately 1 atomic mass unit (amu). Elements differ from each other in the number of protons they have, e.g. Hydrogen has 1 proton; Helium has 2.

The **neutron** also is located in the atomic nucleus (except in Hydrogen). The neutron has no charge, and a mass of slightly over 1 amu. Some scientists propose the neutron is made up of a proton and electron-like particle.

The **electron** is a very small particle located outside the nucleus. Because they move at speeds near the speed of light the precise location of electrons is hard to pin down. Electrons occupy **orbitals** or areas where they have a 90% statistical probability of occurring. The charge on an electron is -1. Its mass is negligible (approximately 1800 electrons are needed to equal the mass of one proton).
Subatomic particles of use in biology

<table>
<thead>
<tr>
<th>Name</th>
<th>Charge</th>
<th>Location</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>+1</td>
<td>atomic nucleus</td>
<td>$1.6726 \times 10^{-27}$ kg</td>
</tr>
<tr>
<td>Neutron</td>
<td>0</td>
<td>atomic nucleus</td>
<td>$1.6750 \times 10^{-27}$ kg</td>
</tr>
<tr>
<td>Electron</td>
<td>-1</td>
<td>electron orbital</td>
<td>$9.1095 \times 10^{-31}$ kg</td>
</tr>
</tbody>
</table>

The **atomic number** is the number of protons an atom has. It is characteristic and unique for each element. The **atomic mass** (also referred to as the atomic weight) is the number of protons and neutrons in an atom. Atoms of an element that have differing numbers of neutrons (but a constant atomic number) are termed **isotopes**. If an atom has a different number of protons than electrons, it is a charged atom called an **ion**.

Some isotopes, shown in the following two diagrams that follow can be used to determine the diet of ancient peoples by determining proportions of isotopes in mummified or fossilized human tissues. Biochemical pathways can be deciphered by using isotopic tracers. The age of fossils and artifacts can be determined by using radioactive isotopes, either directly on the fossil (if it is young enough) or on the rocks that surround the fossil (for older fossils like dinosaurs). Isotopes are also the source of radiation used in medical diagnostic and treatment procedures.

![Isotopes of hydrogen](http://www.emc.maricopa.edu/faculty/farabee/BIOBK/Hyiso.gif)

![Isotopes of carbon](http://www.emc.maricopa.edu/faculty/farabee/BIOBK/cisotopes.gif)

Image sources:

http://www.emc.maricopa.edu/faculty/farabee/BIOBK/Hyiso.gif
http://www.emc.maricopa.edu/faculty/farabee/BIOBK/cisotopes.gif
A radioactive isotope is an unstable isotope in which the nucleus spontaneously decays emitting sub-atomic particles and/or energy as radioactivity. If the breakdown involves the loss of nuclear particles the may transform one element to another.

Radioisotopes have a fixed half-life. A half-life is the time required for 50% of radioactive atoms in a sample to decay.

Biological applications of radioactive isotopes include:

I. Dating geological strata and fossils.

-- Radioactive decay occurs at a fixed rate.
-- By comparing the ratio of radioactive and stable isotopes in a fossil with the ratio of isotopes in living organisms, one can estimate the age of a fossil.
-- The ratio of 14C to 12C is frequently used to date fossils less than 50,000 years old.

Image source:

II. Detection of medical disorders.

**Radioactive isotopes** are important in medicine. One example of this are the man-made isotope technetium-99 which serves as a radiation source in medicine where it is used to locate tumors in the spleen, liver, brain, and thyroid. The use of **Iodine-131** in the detection of thyroid disorders is another important example.

**Thyroid Function Testing**

Background

The radioactive form of iodine (I-131) has been used for 40 years to treat hyperthyroidism (overactive thyroid) and thyroid cancer, and in small doses, to test thyroid function. Since iodine is a natural substance your thyroid uses to make thyroid hormone, radioactive iodine (RAI) is collected by your thyroid gland in the same way as non-radioactive iodine. Since the thyroid gland is the only area of the body that uses iodine, RAI does not travel to any other areas of the body, and the RAI that is not taken up by thyroid cells is eliminated from your body, primarily in urine. It is therefore a safe and effective way to test and treat thyroid conditions. Extensive studies have shown that patients who have been treated with radioactive iodine are not an increased incidence of thyroid cancer or any other type of cancer.

When I-131 is used to test thyroid function, only a very small amount of radioactive substance is used so that the thyroid gland is not damaged and normal thyroid functioning is not affected. Pictures of the thyroid gland are then obtained at varying time periods (hours to days) after the ingestion of these substances (either in pill or liquid form). If the substance is avidly taken up by the thyroid gland, then the thyroid gland is considered to be "hot" or overactive. If these agents are not taken up well then the thyroid is called "cold" or underactive.

**Electrons and energy**

Electrons, because they move so fast (approximately at the speed of light), seem to straddle the fence separating energy from matter. Albert Einstein developed his famous $E=mc^2$ equation relating matter and energy over a century ago. Because of his (and others) work, we think of electrons both as particles of matter (having mass is a property of matter) and as units (or quanta) of energy. When subjected to energy, electrons will acquire some of that energy, as shown in the diagram below. A **photon** is a discrete defined packet of energy.
Excitation of an electron by energy, causing the electron to "jump" to a higher energy level known as the excited state. Electron excitation is critical to the ability of a chloroplast to capture light energy in photosynthesis.

![Diagram of electron excitation](http://www.emc.maricopa.edu/faculty/farabee/BIOBK/excitation.gif)

Energy levels (also referred to as electron shells) are located a certain "distance" from the nucleus. The major energy levels into which electrons fit, are (from the nucleus outward) are called K, L, M, and N. Sometimes these are numbered, with electron configurations being: $1s^22s^22p^1$, (where the first shell K is indicated with the number 1, the second shell L with the number 2, etc.). This nomenclature tells us that for the atom mentioned in this paragraph, the first energy level (shell) has two electrons in its $s$ orbital (the only orbital it can have), and second energy level has a maximum of two electrons in its $s$ orbital, plus one electron in its $p$ orbital. The further away from the nucleus an electron is, the greater its energy state.

With the exception of the K shell which requires two electrons to fill it, the other shells need 8 electrons to be filled and will attempt to interact with the electrons on other atoms to achieve that goal. This is called the **octet rule**. An inert element has a filled outer shell and is therefore very unreactive, as it does not need to gain or lose electrons.
Chemical Bonding

The type of chemical bond between atoms is determined chiefly by the electronegativity difference between the atoms. **Electronegativity** is a numerical measure of the tendency of an atom to attract electrons.

**Chemical bonds result from the** simultaneous attraction of electrons by two nuclei. **Ionic bonds** are formed between a metal and nonmetal when an electron or electrons are transferred from the metal to the nonmetal atom. We will not discuss these very often in AP Biology.
**Covalent bonds** are formed by the sharing of electrons between atoms where the electronegativity difference between the atoms is more similar. **Nonpolar covalent bonds** occur between diatomic molecules where there is no electronegativity difference, such as O$_2$ or O=O. These bonds are perfectly symmetrical as the electrons are shared perfectly between the two elements. **Polar covalent bonds** occur when there is a difference in electronegativity between the atoms, but the difference is not enough for one atom to take the electron(s) from the other atom, or form an ionic bond.

Even though the 4 individual bonds between chlorine and fluorine are polar, overall this is a nonpolar molecule because it has symmetry with the 4 nonpolar bonds perfectly cancelling each other out.
(a) Nonpolar covalent bonds

(b) Polar covalent bond

● = Atomic nucleus
△ = Center of positive charge
○ = Center of negative charge

Comparison of Bonding

Ionic

Na⁺ Cl⁻

Polar Covalent

S⁺ H⁻ Cl⁻

Non-polar Covalent

H⁻ H⁺

complete transfer of electrons - full ionic charges
unequal sharing of electrons, results in partial charges
equal sharing of electrons, results in no charges


Image source: http://www.elmhurst.edu/~chm/vchembook/images/150compare.GIF
Nonpolar molecules interact very little with polar molecules, including water. This is because they have little external charge. Nonpolar molecules are often called hydrophobic (water fearing) because they are not attracted to water.

On the other hand, polar molecules are attracted to other polar molecules, such as water. Polar molecules are often referred to as being hydrophilic (water loving or attracting).

Image source:
http://www.pc.maricopa.edu/Biology/rcotter/BIO%20181/Lesson%20Builders/Ch3PropertiesofWater/Ch3PropertiesofWater_print.html
**Hydrogen Bonds and Water**

Hydrogen bonds do not occur within molecules at all. These are weak intermolecular electrical attractions between a partially positive δ+ hydrogen atom in one molecule and a partially negative δ- atom in an adjacent molecule. Hydrogen bonds are abundant in water.

The polarity of water molecules results in hydrogen bonding. A water molecule is a polar molecule with opposite ends of the molecule having partial opposite charges. This occurs because oxygen is more electronegative than hydrogen and has a greater pull on the shared electrons between the hydrogen and oxygen atoms in the molecule.

Water’s molecular structure and its capacity to form hydrogen bonds give it unique properties that are significant for life.

Because of H-bonding, a substantial percentage of all water molecules are bonded to their neighbors. This adds to water’s structural stability. Hydrogen bonds hold water molecules together.
The **high specific heat** of water means that water gains or loses a great deal of heat when it changes state. It takes a great deal of energy for water to change state from solid to liquid, and then to gas, because to do this, the strong hydrogen bonds of the water molecule must be broken. Water's high heat of vaporization ensures **effective cooling** when water evaporates.

Water is an **excellent climate moderator** because of its high specific heat, heat of fusion (amount of heat needed to change water from a solid to a liquid) and high heat of vaporization (amount of heat needed to change water from a liquid to a gas).
The temperature of water rises and falls more slowly than that of other liquids due to hydrogen bonding. In order to change the temperature or physical state of water, hydrogen bonds must be broken. This requires a lot of heat energy. Hydrogen bonds can absorb heat without undergoing a big change in temperature. For this reason water has a low freezing point (0°C) and high boiling point (100°C). This property helps explain why humans do not "boil" on a hot day.

An important impact of the high specific heat of water is that a large body of water can absorb a large amount of heat from the sun in daytime and during the summer, while warming only a few degrees. The result of this is that ocean temperatures and coastal land areas have more stable temperatures than inland areas (climate moderator).

The cohesion of water molecules refers to their capacity to resist coming apart from one another. Hydrogen bonding holds the water molecules together. The term cohesion means the attraction of like substances. The cohesive forces between liquid molecules are responsible for the phenomenon known as surface tension. The molecules at the surface do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface. This forms a surface "film". Have you ever seen water bugs walking across the surface of water in a swimming pool or glassy pond? They are able to do that without sinking because of surface tension!

Water has a high surface tension  Surface tension is the force necessary to break the surface of a liquid. Surface tension is why raindrops are round (not tear-drop-shaped) as they fall through the air. The relatively powerful hydrogen bonds among water molecules gives water a surface tension 2-3 times higher than most common liquids!

![Surface Tension Diagram](http://science.nasa.gov/media/medialibrary/2003/02/23/25feb_nosoap_resources/surface_tension_med.gif)

Temperature again plays a role in the relative strength or weakness of water's surface tension. Increasing water's temperature will decrease its surface tension, and vice versa (inverse proportion). Another way to lower water's surface tension is to add detergent to it.

Detergents and soaps lower surface tension by rendering the hydrogen bonds much less effective among water molecules such that attraction to individual molecules is lessened. Remember that hydrogen in water molecules (as discussed earlier) attracts to the oxygen atoms of other water molecules.
Water is also attracted to unlike polar substances. This property is called **adhesion**. Adhesion produces the curved line seen in the meniscus of volume measuring implements such as graduated cylinders.

![Capillary rise of water in a small glass tube.](http://piercecollegeweather.com/img/CapillaryRise.gif)

Cohesion and adhesion work together to pull water upward in the tubes of tracheophyte plants. **Tracheophytes** have conducting tissue. These conducting tissues are called xylem and phloem. **Xylem** tubes allow water and minerals up a stem. These plants also have **phloem** tissue which transport dissolved sugars down the stem.

![Diagram showing hydrogen bonds and evaporation](http://click4biology.info/c4b/9/images/9.2/cohesion.gif)
Imbibition is the tendency for water to be absorbed by hydrophilic substances such as seeds. Seed germination could not occur if this did not happen.

Solutions are produced when solid substances (solute) dissolve in a liquid (the solvent). Water is the critically important solvent for life. Water will dissolve nearly any other polar substance.

**Acid-Base Chemistry Review**

*Water* (ionizes or dissociates) into an equal number of hydrogen (H+) and hydroxide (OH-) ions in solution. **pH** is a measure of free hydrogen ions (H+) in a solution. The term **pH** stands for power of hydrogen and is equal to the negative log of the H+ ion concentration (pH = -log [H+ ions]). Therefore, each change of one pH unit changes the amount of acidity or alkalinity (base) by 10 times. A pH of 5 is ten times more acidic than a pH of 6. A pH of 3 is 10*10*10 or 1,000 times more acidic than a pH of 6.

**Acids** are substances that release hydrogen ions (H+) and lower pH below 7. For example, HCl is a strong acid that releases H+ ions and Cl- ions. **Bases** are substances that absorb hydrogen ions or release hydroxide ions and raise pH above 7. For example, NaOH dissociates to form Na+ and OH-.
A buffer is a solution (chemical sponge) that absorbs excess hydrogen (H+) or hydroxide (OH-) ions to maintain a constant pH. An important biological buffer is carbonic acid (H$_2$CO$_3$). Carbonic acid (H$_2$CO$_3$) keeps blood pH within normal limits (pH 7.35 - 7.45).

**If blood is too acidic (low pH below 7), then bicarbonate ion (HCO$_3^-$) absorbs the H$^+$ ion to form carbonic acid (H$_2$CO$_3$).**

**If blood is too basic (high pH above 7), then carbonic acid (H$_2$CO$_3$) releases the H$^+$ ion to form bicarbonate ion (HCO$_3^-$).**

**Reaction Kinetics**

The energy involved in chemical reactions can be represented with potential energy diagrams. Chemical reactions require energy to get them started. The energy needed to start a chemical reaction is called activation energy.

**Exothermic reactions** release energy. Deltas H for these reactions are negative. These reactions result in products formed which are more stable and at a lower energy state than the reactants.
**Endothermic reactions** absorb energy. Delta H for these reactions is positive (+). These reactions form products which are less stable than the reactants. The products of these reactions are at higher energy than the reactants.

Many factors have an influence on the rate of a reaction. A **catalyst** speeds up the reaction by reducing the activation energy needed to start a reaction. A catalyst does NOT affect the heat of reaction or the potential energy of the products or the reactants.

**Enzymes** are organic catalysts which speed up the rate of reactions in living things. Enzymes are organic compounds (compounds containing carbon and hydrogen) and are classified as proteins.
Importance of Carbon to Life and Functional Groups

Carbon moves from the environment to organisms where it is used to build carbohydrates, proteins, lipids or nucleic acids. Carbon is used in storage compounds and cell formation in all organisms. Carbon’s tetravalence (four valence electrons) contributes to the diversity of organic molecules. Carbon also has an intermediate electronegativity value, which increases its tendency to share electrons.

Some of the Variations in which carbon may form different chemical compounds:

1). The length of the carbon skeleton may differ ( C-C, C-C-C, C-C-C-C-C, etc.)
2). The carbon skeleton can also form branching compounds.
3). The number of double/multiple bonds may differ ( C=C-C-C, C=C=C-C )
4). The molecular structure may be in ring form.

Many carbon molecules also have functional groups associated with them. Functional groups are groups of atoms found within molecules that are involved in the chemical reactions characteristic of those molecules. Functional groups can pertain to any molecules, but you will usually hear about them in the context of organic chemistry. The symbol R and R' refer to an attached hydrogen or hydrocarbon side chain or sometimes to any group of atoms. Some important functional groups include:

1. Hydroxyl: R- OH makes molecule polar and produces an alcohol. This is not a base, because the OH group does not split off or ionize in solution as it would in a base.
2. Carbonyl: R=O produces compounds known as ketones and aldehydes
4. Amine - NH2 charge, usually weakly basic, acts as a good buffer.
5. Thiols - R-S-H, stabilizes protein molecular structures. This is also called the sulfhydrl group.
Amino acids are the subunits of much larger compounds called proteins. These have both the amino group and the carboxyl group in their structure.