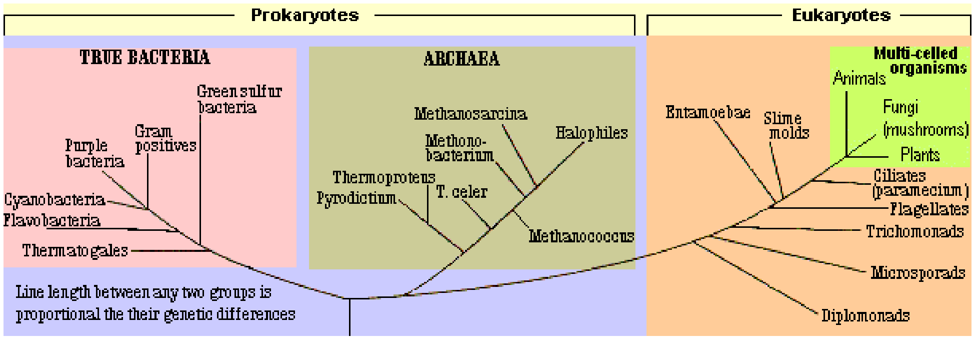
# 4.1: Chemistry and Energetics of the Life Process

The biosphere comprises the various regions near the earth's surface that contain and are dynamically affected by the metabolic activity of the approximately 1.5 million animal species and 0.5 million plant species that are presently known and are still being discovered at a rate of about 10,000 per year. The biosphere is the youngest of the dynamical systems of the earth, having had its genesis about 2 billion years ago. It is also the one that has most profoundly affected the other major environmental systems, particularly the atmosphere and the hydrosphere.




***"The tree of life"***

About a third of the chemical elements cycle through living organisms, which are responsible for massive deposits of silicon, iron, manganese, sulfur, and carbon. Large quantities of methane and nitrous oxide are introduced into the atmosphere by bacterial action, and plants alone inject about 400,000 tons of volatile substances (including some metals) into the atmosphere annually.

> It has been suggested that biological activity might be responsible for the deficiency of hydrogen on Earth, compared to its very high relative abundance in the solar system as a whole. Bacteria capable of reducing hydrogen compounds into $H_2$ transform this element into a form in which it can escape from the earth; such bacteria may have been especially active in the reducing atmosphere of the early planet.
>
> A second mechamism might be the microbial production of methane, which presently injects about $10^9$ T of $CH_4$ into the atmosphere each year. Some of this reaches the stratosphere, where it is oxidized to $CO_2$ and $H_2O$. The water vapor is photolyzed to $H_2$, which escapes into space. This may be the major mechanism by which water vapor (and thus hydrogen) is transported to the upper atmosphere; the low temperature of the upper atmosphere causes most of the water originating at lower levels to condense before it can migrate to the top of the atmosphere.

The increase in the abundance of atmospheric oxygen from its initial value of essentially zero has without question been the most important single effect of life on earth, and the time scale of this increase parallels the development of life forms from their most primitive stages up to the appearance of the first land animals about 0.5 billion years ago.

## Bioenergetics

All life processes involve the uptake and storage of energy, and its subsequent orderly release in small steps during the metabolic process. This energy is taken up in the combination of ADP with inorganic phosphate to form ATP, in which form the energy is stored and eventually delivered to sites where it can provide the free energy needed for driving non-spontaneous reactions such as protein and carbohydrate synthesis.

$ADP + PO_4^{3-} \rightarrow ATP \quad \Delta G° = +30 \text{ kJ}$

The three main metabolic processes are glycolysis, respiration, and photosynthesis. The first two of these extract free energy from glucose by breaking it up into smaller, more thermodynamically stable fragments. Photosynthesis reverses this process by capturing the energy of sunlight into ATP which then drives the buildup of glucose from $CO_2$.

### Glycolysis and fermentation.

As its name implies, this most primitive (and least efficient) of all metabolic processes is based on the breakdown of a sugar into fragments having a smaller total free energy. Thus the 6-carbon sugar glucose can be broken down into two 3-carbon lactic acid units, or into three 2-carbon ethanol units.

$C_6H_{12}O_6 \rightarrow 2\ CH_3CHOHCOOH$ $\Delta G° = –197$ kJ

In this process, two molecules of ATP are produced, thus capturing 61 kJ of free energy. Since the standard free energy of glucose (with respect to its elements) is –2870 kJ, this represents an overall efficiency of about 2 percent.

The net reaction of glycolysis is essentially a rearrangement of the atoms initially present in the energy source. This is a form of fermentation, which is defined as the enzymatic breakdown of organic molecules in which other organic compounds serve as electron acceptors. Since there is no need for an external oxidizing or reducing agent, there is no change in the oxidation state of the environment.

### Respiration

When the enzymatic degradation of organic molecules is accompanied by transfer of electrons to an external (and usually better) electron acceptor, the process is known as respiration. The overall reaction of respiration is the oxidation of glucose to carbon dioxide:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ $\Delta G° = –2380$ kJ

In this process, 36 molecules of ADP are converted into ATP, thus capturing 1100 kJ of free energy: an efficiency of 38 percent.

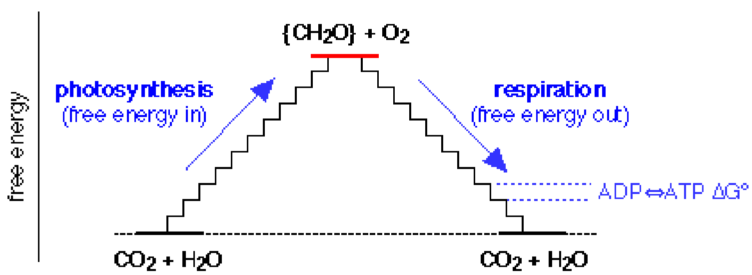
The oxidizing agent (electron sink) need not be oxygen; some bacteria reduce nitrates to NO or to $N_2$, and sulfates or sulfur to $H_2S$. These metabolic products can have far-reaching localized environmental effects, particularly if hydrogen ions are involved. Falling down the respiratory ladder presents a succinct picture of oxidation-reduction and the role of non-$O_2$ electron sinks in biological energy capture.

## Photosynthesis

The energy of sunlight is trapped in the form of an intermediate which is able to deliver electrons to successively lower free-energy levels through the mediation of various molecules (mainly cytochromes) comprising an electron-transport chain. The free energy thus gained is utilized in part to reduce $CO_2$ to glucose, which is then available to supply metabolic energy by glycolysis or respiration. In green plants and eukaryotic algae, the source of hydrogen is water, the net reaction being

$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$ $\Delta G° = +2830$ kJ

For every $CO_2$ molecule fixed in this way, 469 kJ of free energy must be supplied. Red light of 680 nm wavelength has an energy of 168 kJ/mol; this implies that about three photons must be absorbed for every carbon atom taken up, but experiment indicates that about ten seem to be required.




**The photosynthetic - respiration cycle.**

**Photosynthesis** utilizes the energy of red light to add hydrogen (from $H_2O$) and electrons (from the O in $H_2O$) to $CO_2$, reducing it to **carbohydrate**. **Respiration** is the reverse of this process; electrons are removed from the carbohydrate (food is "burned") in small steps, each one releasing a small amount of energy. Some of this energy is liberated as heat, but part of it is used to add a phosphate group to ADP, converting it into ATP. **ATP** (adenosine triphosphate) is to an organism's energy needs as money is to our material needs; it circulates to wherever it is required in order to bring about energy-requiring reactions or to make muscle cells contract. Each increment of energy given up by ATP converts it back to ADP and phosphate, ready to repeat the cycle.

**Green plants** are able to operate in both modes during the daylight hours, reverting to respiration-only at night. **Animals** carry out only the right side of the cycle and thus require as source of carbohydrate ("**food**") either directly (by eating plants), or indirectly by eating other animals that eat plants.

There are many kinds of photosynthetic bacteria, but with one exception (cyanobacteria) they are incapable of using water as a source of hydrogen for reducing carbon dioxide. Instead, they consume hydrogen sulfide or other reduced sulfur compounds, organic molecules, or elemental hydrogen itself, excreting the reducing agent in an oxidized state. Green plants, cyanobacteria, green filamentous bacteria and the purple nonsulfur bacteria utilize glucose by respiration during periods of darkness, while the green sulfur bacteria and the purple sulfur bacteria are strictly anaerobic.