INTRODUCTION

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Even the simplest of organisms is an incredibly organized bit of matter. Cells are complex three-dimensional structures made up of different kinds of macromolecules (polysaccharides, lipids, nucleic acids and proteins). The ability to create and maintain this organized structure is one of the most important characteristics of life.

As you may have noticed in your everyday life, maintaining order is not easy. One of the fundamental natural principles is that the degree of disorder (entropy) in the universe always increases. Every chemical reaction or physical event that occurs increases the overall "randomness" of the universe. How then, can living things exist and grow? How could life have ever evolved in the first place?

The answer is that decreased entropy in some parts of the universe is offset by increased entropy in other parts so that the overall entropy of the universe increases. Organisms are pockets of order which maintain and increase themselves while causing increased entropy outside of themselves. In every energy transaction of biological systems, entropy is increased with some energy converted to heat energy which is not useful to the cells. Local decreases in entropy require energy inputs. This means that organisms must have external energy sources so that they can maintain their organized structures and grow.

The initial capture of external energy is the topic of this unit. The main external energy source for life on this planet is the sun. Plants, algae and some bacteria use special pigments to trap light energy and convert it to chemical energy. Organisms that use light as their energy source are called [1]**phototrophs**. Most phototrophs use trapped energy to make organic matter (carbohydrate) from CO_2, a process called CO_2 fixation. Organisms that can fix CO_2 are called [2]**carbon autotrophs or C-autotrophs**; phototrophs that fix CO_2 are thus **photoautotrophs**. The combined process of trapping light energy and using it to produce organic matter from CO_2 is called **photosynthesis**. Some phototrophic bacteria cannot fix CO_2 and therefore require preformed organic carbon to synthesize new cell material. These bacteria are [3]**photoheterotrophs**.

The mechanism phototrophs use to capture light energy is described in Chapter 8 of Purves, Orians and Heller. This description is based on material in Chapter 7, specifically, pages 135-140 on ATP and NADH and pages 148-153 on the respiratory chain. The mechanism of photosynthesis is summarized below.

Energy is absorbed by light-harvesting pigments which gather characteristic spectra and extend the photosynthetically useful range of light wavelengths (POH Fig. 8.9). The light-harvesting pigments reemit the light, which is then absorbed by chlorophyll a (POH Fig. 8.12). When chlorophyll a absorbs light energy, it becomes activated and easily loses an electron. The electron goes to an electron transport chain (series of circles in POH Fig. 8.14). The electron transport chain allows the energy gained from the photon of light to drive the formation of ATP.

In addition to forming ATP, photoautotrophs use light energy to drive the reduction[4] of $NADP^+$ to NADPH (POH Fig. 8.3). Photoautotrophs require a great deal of NADPH, because it is used to reduce CO_2 to carbohydrate (POH Fig. 8.4). They therefore must have an external supply of hydrogen atoms for the reduction of $NADP^+$ to NADPH:

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[1] "photo" = "light", "troph" = "feeding"; thus, "feeding on light"

[2] "auto" = "self"; "self-feeding"

[3] "hetero-" = "other", referring to the requirement for preformed organic carbon

[4] Remember that oxidation is the loss of electrons and reduction is the gain of electrons. In biological systems, protons often travel with the electrons, so that entire hydrogen atoms are transferred during biological oxidation/reduction reactions.

$$\text{Equation 1:}\quad H_2X + NADP^+ \longrightarrow NADPH + H^+ + X$$

Common examples of hydrogen donors (H_2X) include H_2O and H_2S. If H_2O is the hydrogen donor, then the reaction is:

$$\text{Equation 2:}\quad H_2O + NADP^+ \longrightarrow NADPH + H^+ + 1/2\ O_2$$

This reaction, carried out by plants, algae and cyanobacteria, is the source of the oxygen we breathe. However, the oxygen in water does not give up electrons readily. A special "double" photosynthetic apparatus using the energy of two photons is required by oxygen-producing phototrophs to move hydrogen atoms from water to $NADP^+$ (POH Fig. 8.16).

As briefly described above, light energy powers the formation of ATP and NADPH. In autotrophs, these molecules are then used to fix CO_2 (Equation 3). ATP provides the energy to drive the reactions, while NADPH provides the hydrogen atoms for CO_2 reduction. The product of CO_2 fixation is carbohydrate (often indicated as $C_6H_{12}O_6$; see POH Fig. 3.9-3.12 for representative carbohydrates):

Equation 3:

$$6CO_2+18ATP+12(NADPH+H^+) \rightarrow C_6H_{12}O_6+18(ADP+P_i)+12NADP^++6H_2O$$

The CO_2 fixation pathway most common in green plants is the Calvin cycle (POH Figures 8.24 and 8.25). The energy to drive the Calvin cycle is provided by the ATP in Equation 3. In the Calvin cycle, a five-carbon sugar (ribulose biphosphate) serves as the CO_2 acceptor, forming a six-carbon intermediate which immediately falls apart into two three-carbon acids. The NADPH used in Equation 3 reduces the three-carbon acids to sugars. Each turn around the pathway fixes one molecule of CO_2, so six turns around the pathway are required to produce one new glucose molecule.

The carbohydrate from the Calvin cycle provides the energy for plant growth and reproduction and is also the carbon and energy source for animal life on earth. Much carbohydrate is used to build plant structural material. Planet-wide, plants produce 10^{11} tons of cellulose (POH Figure 3.12), per year!

Much of the carbohydrate formed in photosynthesis is stored for future use. Only small amounts of simple sugars can be maintained in the cell; high sugar concentrations would upset the cell's osmotic balance. For this reason, and because large molecules are less likely to escape through the cell membrane, plant cells store carbohydrate as polymeric glucose, or starch (POH Figure 3.12).

Phototrophs are not the only C-autotrophs. Certain bacteria are able to trap energy released during the oxidation of inorganic substrates such as H_2, NH_3, H_2S, S and Fe^{2+}. Most of these [5]**lithotrophs** are C-autotrophs, capable of fixing CO_2. Some of the inorganic compounds oxidized by lithotrophs are geothermal in origin. Thus, a small fraction of the energy for life on this planet is geothermal, rather than solar. A startling example of a geothermal ecosystem is the deep sea vent system (POH Figure 17.5), which is powered by H_2S.

The most obvious phototrophs, and the ones with the most apparent significance to us, are terrestrial plants. Many of the activities in this unit concern the photosynthetic activities and structures of terrestrial plants. Others deal with ecological aspects of phototrophs or photosynthesis. Two activities concern autotrophic microbes; the phototrophic cyanobacteria and the lithotrophic *Thiobacillus*.

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[5] "litho" = "rock"; thus, "rock-eaters"