Photosynthesis

1. Photosynthesis converts light energy to the chemical energy of food.
    a. Organisms obtain organic compounds by one of two major modes: autotrophic nutrition or heterotrophic nutrition. Autotrophs produce their organic molecules from CO_2 and other inorganic raw materials obtained from the environment. Heterotrophs live on organic compounds produced by other organisms. Photosynthesis produces about 160 B tons of carbohydrate per year.
    b. All green parts of a plant have chloroplasts (500,000/mm^2 of leaf and 30-40/mesophyll cell) but the leaves are the major site of photosynthesis for most plants. There are about half a million chloroplasts per square millimeter of leaf surface. The chloroplasts of plants use a process called photosynthesis to capture light energy from the sun and convert it to chemical energy stored in sugars and other organic molecules.
    c. Different pigments absorb photons of different wavelengths, and the wavelengths that are absorbed disappear. A leaf looks green because **chlorophyll**, the dominant pigment, absorbs red and blue light, while transmitting and reflecting green light. Other pigments with different structures absorb light of different wavelengths.
    d. The general equation is $6CO_2 + 6H_2O$ + light energy $\rightarrow C_6H_{12}O_6 + 6O_2$. Note that the reaction is the reverse of cellular respiration.
    e. Light energy is captured by low energy CO_2 and converted into high energy $C_6H_{12}O_6$
    f. Photosynthesis is a redox reaction. It reverses the direction of electron flow in respiration. In other words, water is split and electrons transferred with H^+ from water to CO_2, reducing it to sugar. In cellular respiration electrons move from high energy glucose to O_2 making low energy water; in photosynthesis, low energy water is split and electrons move to CO_2 making high energy glucose. The energy required for the reduction is provided by the sun.

2. Leaf structure
    a. Each chloroplast has two membranes around a central aqueous space, the stroma.
    b. In the stroma is an elaborate system of interconnected membrane-bound sacs, the thylakoids. Chlorophyll is located in the thylakoids.
    c. Thylakoids are arranged into stacks called grana.
    d. O_2 exits and CO_2 enters the leaf through microscopic pores called **stomata** in the leaf.
    e. Chloroplasts are found mainly in **mesophyll** cells forming the tissues in the interior of the leaf. A typical mesophyll cell has 30–40 chloroplasts.
    f. Veins deliver water from the roots and carry off sugar from mesophyll cells to nonphotosynthetic areas of the plant.
    g. Each chloroplast has two membranes around a central aqueous space, the **stroma.** In the stroma are many disks called **thylakoids.** Chlorophyll is located in the membranes of the thylakoids.

3. Photosynthesis occurs in two phases: the light reactions occur on the thylakoid membranes, while the Calvin cycle occurs in the stroma.
    a. The **light reactions** (the photo part) convert solar energy to chemical energy.
        i. In the light reactions, light energy absorbed by chlorophyll in the thylakoids drives the transfer of electrons and hydrogen from water to **$NADP^+$**, forming NADPH (an electron carrier like NADH) carries those electrons to the Calvin cycle.

ii. When a molecule absorbs a photon, one of that molecule's electrons is excited to a higher energy level. Excited electrons are unstable and usually release the energy as heat in a billionth of a second.

iii. In the thylakoid membrane, chlorophyll is organized along with special proteins into **photosystems**. A photosystem is composed of a reaction center surrounded by a light-harvesting complex of a few hundred pigment molecules.

iv. When any pigment molecule absorbs a photon, the energy is transmitted from molecule to molecule until it reaches a particular chlorophyll molecule called the **reaction center.**

v. At the reaction center is a **primary electron acceptor,** which accepts an excited electron from the reaction center chlorophyll.

vi. There are two types of photosystems in the thylakoid membrane: **Photosystem I** (PS I) and **Photosystem II (PS II)**. These two photosystems work together to use light energy to generate ATP and NADPH.

vii. During the light reactions, there are two possible routes for electron flow:

(1) **Noncyclic electron flow,** the predominant route, produces both ATP and NADPH.

(a) Photosystem II absorbs a photon of light and an electron is excited to a higher energy state.

(b) This electron is captured by the primary electron acceptor, leaving the reaction center oxidized.

(c) Electrons from water are used replace those lost by the reaction center. This reaction creates O_2 as a by-product.

(d) Excited electrons pass along an electron transport chain before ending up at the reaction center of photosystem I. As they move along the chain, their energy is used to produce ATP. This ATP is used by the Calvin cycle.

(e) Meanwhile, light energy has excited an electron of the reaction center of PS I. The electron was captured by PS I's primary electron acceptor, but is replaced by an electron that reaches the bottom of the electron transport chain from PS II.

(f) Photoexcited electrons are passed from PS I's primary electron acceptor down a second electron transport chain.

(g) Electrons from this chain are transferred to NADP+, forming NADPH, which will carry these high-energy electrons to the Calvin cycle.

(2) Noncyclic electron flow produces ATP and NADPH in roughly equal quantities but the Calvin cycle consumes more ATP than NADPH. To compensate, excited electrons from photosystem I, but not photosystem II, can take an alternative pathway, **cyclic electron flow.**

(a) Excited electrons cycle from their reaction center to a primary acceptor, along an electron transport chain, and return to the oxidized reaction center.

(b) As electrons flow along the electron transport chain, they generate ATP by but there is no production of NADPH and no release of oxygen.

(c) Cyclic electron flow allows the chloroplast to generate enough surplus ATP to satisfy the higher demand for ATP in the Calvin cycle.

viii. Chloroplasts and mitochondria generate ATP by the same mechanism: chemiosmosis. In both organelles, an electron transport chain pumps protons across a membrane as electrons are passed along a series of increasingly electronegative carriers.

b. The **Calvin cycle** (the synthesis part) uses ATP and NADPH from the light reactions to convert CO_2 from the atmosphere to a three-carbon sugar. The purpose is to reduce low energy CO_2 into a high energy sugar. The energy needed comes from ATP while the electrons needed come from NADPH - both produced by the light reactions.

i. The Calvin cycle has three phases.

(1) Phase 1: Carbon fixation

(a) In the **carbon fixation** phase, each CO_2 molecule is attached to a 5C (RuBP) sugar to form a 6C sugar. This is catalyzed by the enzyme **rubisco**, the most abundant protein in chloroplasts and probably the most abundant protein on Earth.

(b) The 6C intermediate is unstable and splits in half to form two 3 carbon molecules.

(2) Phase 2: Reduction

(a) During **reduction,** each 3C intermediate is reduced by a pair of electrons from NADPH.

(b) The product is G3P (PGAL), some of which can exit the cycle and be used by the plant cell to make glucose (for energy), starch, cellulose, and other molecules.

(3) Phase 3: Regeneration

(a) The remaining G3P are used to regenerate RuBP. In a complex series of reactions, the carbon skeletons of five molecules of G3P are rearranged to regenerate three molecules of RuBP.

ii. About 50% of the product from photosynthesis is consumed as fuel for cellular respiration in plant mitochondria. Most of the rest is used to make cellulose.