UNIT 1: METABOLIC PROCESSES

C. Photosynthesis: The Details

Photosynthesis is divided into two major processes: **light reactions** and **carbon fixation**

I. LIGHT REACTIONS

- light reactions are further divided into three parts:

1. **Photoexcitation:** absorption of a photon by an electron of chlorophyll – what starts it all!

   - the electron in a chlorophyll a molecule moves from ground state to an excited state, gaining potential energy, as it is struck by photonic energy – this is called **excitation**
   - as the electron falls back down to ground state, the amount of energy that it gained in the excitation is released as both heat and light
   - the light given off in the fall back down to ground state is called **fluorescence**
   - in vivo conditions chlorophyll a does not fluoresce when it is struck by photonic energy – it appears green simply because it (by nature) absorbs all bands of light except green
   - in vitro conditions chlorophyll a fluoresces red
   - this is because when chlorophyll is in vivo, it is embedded in the thylakoid membrane, and is tightly associated with a special molecule called a **primary electron acceptor** – a strong oxidizing agent that captures the excited electron and prevents it from falling back down to its ground state, which in turn inhibits the fluorescence to occur
   - in a flask (in solution – see Figure 2, p. 256) the chlorophyll is separated from its primary electron acceptor and the electron that becomes excited is allowed to fall back to ground state and give off the amount of energy it gained in excitation as heat and light of a fixed energy quantity which represents a particular wavelength that appears red to the naked eye
   - the pigments of photosynthesis are all arranged in an organized system called a **photosystem** – a cluster of accessory pigments called an **antenna complex**, a **reaction center** chlorophyll a molecule, and a **primary electron acceptor**
   - Figure 3, p. 157 is a model of the three components of a photosystem
   - the harnessing of light occurs in the following manner:

     1. light strikes a photosystem
     2. an antenna pigment absorbs a photon and transfers the energy from pigment to pigment until it reaches a chlorophyll a molecule in an area called the reaction centre
     3. 1 electron of this chlorophyll a molecule absorbs the transferred energy and is raised to a high energy level
     4. a redox reaction transfers the excited electron from this chlorophyll molecule to a primary electron acceptor, leaving the chlorophyll in an oxidized state – deficient in one electron

   - chloroplast thylakoid membranes contain two types of light harvesting photosystems:

     a. Photosystem I – doesn't happen first, it was discovered first, thus the name

        - the chlorophyll a molecule in the reaction centre of photosystem I is called P700 because its absorption spectrum peaks at a wavelength of 700 nm (red light)

     b. Photosystem II – doesn't happen second, it was discovered after Photosystem I, thus the name

        - the chlorophyll a molecule in the reaction centre of photosystem II is called P680 because it is best at absorbing photons with a wavelength of 680 nm (red light)

   - what makes the photosystems peak at different wavelengths is the fact that each photosystem is associated with its own unique protein complexes within the thylakoid membrane – the chlorophyll a in both photosystems is identical

2. **Electron Transport:** takes place in two stages….

   a. the transfer of the excited electron through a series of membrane-bound electron carriers, down a gradient, through a series a redox reactions in one of two paths:

      (i) Non-Cyclic Electron Flow

- a photon strikes photosystem II and an electron of P680 reaction centre chlorophyll a gets excited
- the excited electron is captured by P680's primary electron acceptor called **pheophytin**
- through a series of redox rxs, the electron is transferred to an electron carrier called **plastoquinone (PQ)**, and then to an electron transport chain similar to than in cellular respiration
- this process occurs twice, causing two electrons to pass through the electron transport chain
- a **Z protein**, inside the thylakoid lumen, splits a water molecule into 2Hs and one O atom
- the two electrons of the hydrogen atoms refill P680 chlorophyll a's electron void, and the $2H^+$s remain in the lumen to eventually contribute in the chemiosmotic gradient for ATP synthesis
- as the electrons pass down the chain of proteins, they lose potential, and the free energy in the loss goes to pumping H^+ ions into the lumen, from the stroma of the chloroplast
- every pair of electrons that pass through the chain results in 4 H^+ ions (protons) pumped from the stroma to the lumen
- the electrons pass from **plastocyanin (Pc)** and eventually to the electron-deficient chlorophyll a of the P700 photosystem, as they replace the two electrons that were lost by photosystem I when it was struck by photons
- the electrons from photosystem I pass through another electron transport chain containing an iron-containing protein called **ferredoxin (Fd)**
- they then move to the enzyme **NADP reductase** that uses the two electrons and H^+ ions from the stroma to reduce $NADP^+$ to NADPH
- this process is called **non-cyclic photophosphorylation**
- Figure 4, p. 158 illustrates non-cyclic electron flow

(ii) Cyclic Electron Flow

- occurs under certain conditions
- uses photosystem I, not II
- a "short circuit" – the electrons cycle back to the P700 chlorophyll via the same electron transport chain used in non-cyclic flow, passing into the cytochrome b_6-f complex of the ETC
- no production of NADPH and no release of O_2
- generates ATP, thus the name **cyclic photophosphorylation**
- this happens because Calvin cycle uses up more ATP than NADPH – therefore cyclic flow makes up this difference
- high [NADPH] relative to [ATP] in the Calvin cycle may cause cyclic flow to occur until ATP production is substantial to drive the Calvin
- the extra ATP is needed to regenerate the RuBp in the Calvin cycle
- Figure 6, p. 160 illustrates the process of cyclic electron flow

b. the pumping of a proton through the photosynthetic membrane, which creates an H^+ reservoir and eventually reduces an electron acceptor

- protons that accumulate in the thylakoid lumen contribute to an electrochemical gradient that drives the posphorylation of ADP to ATP – as protons move through the ATPase complex from the thylakoid lumen into the stroma, ATP is formed
- every four H^+ ions leaving the lumen produces 1 ATP

3. **Chemiosmosis:** the movement of protons through ATPase complexes to drive phosphorylation of ADP to ATP

- Figure 3, p. 158 shows how the movement of the H^+ ions out of the lumen, through the ATPase, and into the stroma, causes the phosphorylation of ADP to ATP

II. CARBON FIXATION AND THE CALVIN CYCLE

- named after Melvin Calvin – a biochemist at the University of Berkeley, California, who discovered the process in 1960
- this process uses up the ATP and NADPH from the light reactions to convert gaseous CO_2 into sugar
- in the Calvin cycle, the NADPH is the reducing power and the ATP is the fuel – both produce the driving force of the Calvin cycle
- 6 NADPH molecules supply three carbons of the three separate CO_2 molecules the electrons and protons (in the form of hydrogen atoms), thereby reducing it to a less random, more chemically stable, high potential energy molecule called PGAL (G3P) – a versatile building block of carbohydrates
- 9 ATP molecules supply the necessary fuel to appropriately modify various Calvin cycle acids so as to help the cycle proceed in a cyclical manner
- in order for one PGAL molecule to be made, the cycle must happen 3 times
- the Calvin Cycle can be divided into three parts:

1. Carbon Fixation

- each CO_2 molecule is attached to a 5-carbon sugar called **ribulose bisphosphate (RuBp)**, with the help of an enzyme called RuBp carboxylase or **rubisco**
- rubisco is the most abundant protein on Earth
- the result is a very unstable, 6-carbon intermediate that immediately splits into two 3-carbon molecules called **phosphoglycerate (PGA)**
- thus three 1-carbon CO_2s with three 5-carbon RuBps makes three 6-carbon intermediates which immediately change to six 3-carbon molecules of PGA

2. Reduction of diphosphoglycerate (DPGA)

- each PGA receives an additional phosphate from an ATP of the light reactions, forming diphosphoglycerate (DPGA)
- therefore 6 ATPs are needed for 6 DPGA molecules to be made
- a pair of electrons donated from each NADPH, from the light reactions, reduce the carboxyl group of each DPGA to make phosphoglyceraldehyde, or PGAL (G3P)
- therefore, as 3 CO_2s enter the cycle, 6 PGALs are made, 3 waters are released
- one of theses PGALs spins off the cycle and the remaining five 3-carbon PGALs recycle back towards the regeneration of more RuBp

3. Regeneration of CO_2 Acceptor RuBp

- five molecules of the 3-carbon PGALs are rearranged by the last series of steps of the Calvin cycle into three 5-carbon molecules of RuBp
- this requires the energy of 3 ATP molecules

- therefore, for the production of 2 PGAL spin-off molecules, that would ultimately make ONE glucose molecule, you need 18 ATPs, and 12 NADPHs
- 6 H_2Os are released in the Calvin cycle, and 12 H_2Os are needed in the light rxs

- the PGAL molecules that spin off the cycle can…..

1. turn into a-glucose molecules that combine in 1-4 glycosidic linkages to form the polysaccharide starch
2. exit the chloroplast and become a-glucose there
3. some a-glucoses can be restructured into b-fructoses and link with other a-glucoses to make the disaccharide sucrose, which is transported throughout the plant for cellular respiration purposes
4. the a-glucoses can be restructured into b-glucoses, which are then strung together to form cellulose fibrils for plant cell structure
5. the a-glucose can be oxidized directly by mitocondria in the cytoplasm for the synthesis of ATP

- Figure 14, p. 165 illustrates what can happen to the spin off PGAL molecules from the Calvin cycle

- for detailed animations of LIGHT REACTIONS, click on http://instruct1.cit.cornell.edu/courses/biomi290/MOVIES/OXYGENIC.HTML, or http://www.bio.davidson.edu/courses/Bio111/Photosynth/PS.html, or http://www.cst.cmich.edu/users/baile1re/bio101fall/enzphoto/photoanima.htm
- for LIGHT REACTION TUTORIALS, PRACTICE QUIZZES, AND ILLUSTRATIONS, click on http://www.biology.arizona.edu/biochemistry/problem_sets/photosynthesis_1/photosynthesis_1.html
- for a complete PHOTOSYNTHESIS TUTORIAL, click on http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookPS.html#Chlorophyll

Homework: 1-13, p. 166