Feb 12 – Photosynthesis II: light reactions

Recall from our most recent lecture:

Photosynthesis – The process by which photoautotrophs use light energy from the sun to construct sugars (esp. glucose) from carbon dioxide and water.

We then provided an overall balanced chemical equation for photosynthesis:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

The reaction arrow in this overall reaction for photosynthesis actually represents many individual chemical reactions. These take place in chloroplasts. Today, we will figuratively peer inside a chloroplast and see how it/they function, and in our next lecture we'll explore some other reactions involved in photosynthesis.

OK, back to our overall equation for Photosynthesis:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

The many reactions represented by the equation arrow are conveniently divided into two individual series of reactions:

1) Light reactions:

Light energy of the sun is converted into chemical energy in the form of ATP and NADPH. The light reactions occur in and around the thylakoid membrane of the chloroplast. Studied in detail in today's lecture!

$$\text{Light energy} + H_2O + (ADP + P) + (NADP^+ + H) \rightarrow ATP + NADPH + O_2$$

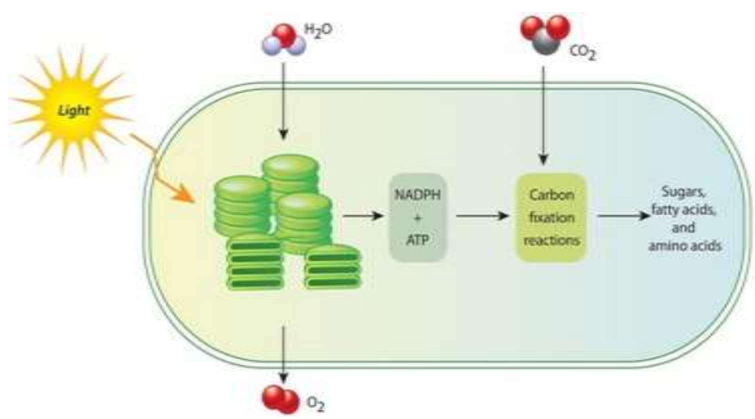
2) Light-independent reactions:

(aka "carbon fixing reactions", Calvin cycle, C_3 cycle): chemical energy produced in the light reactions (ATP and NADPH) is used to fix carbon (remove the C atom from CO_2 and use it to construct carbohydrates). The carbohydrates constructed during the Calvin cycle are later transformed into glucose and/or other biomolecules. An overview only was provided in today's lecture!!

The light-independent reactions occur in the chloroplast stroma.

$$ATP + NADPH + CO_2 \rightarrow C_6H_{12}O_6 + (ADP + P) + (NADP^+ + H)$$

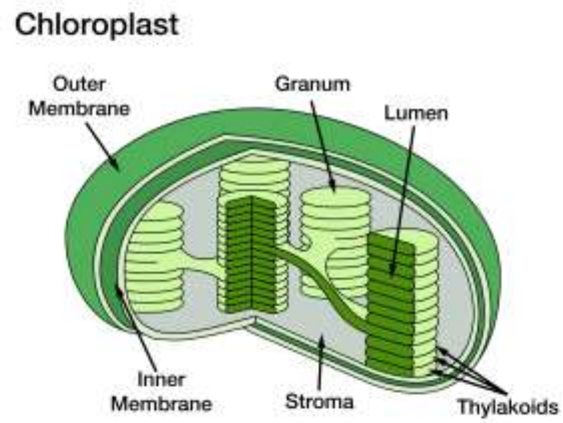
Although these two reactions seem complex, the equations provided here are simplifications (especially true for the light-independent reactions). We are after the big picture - let's paint it…



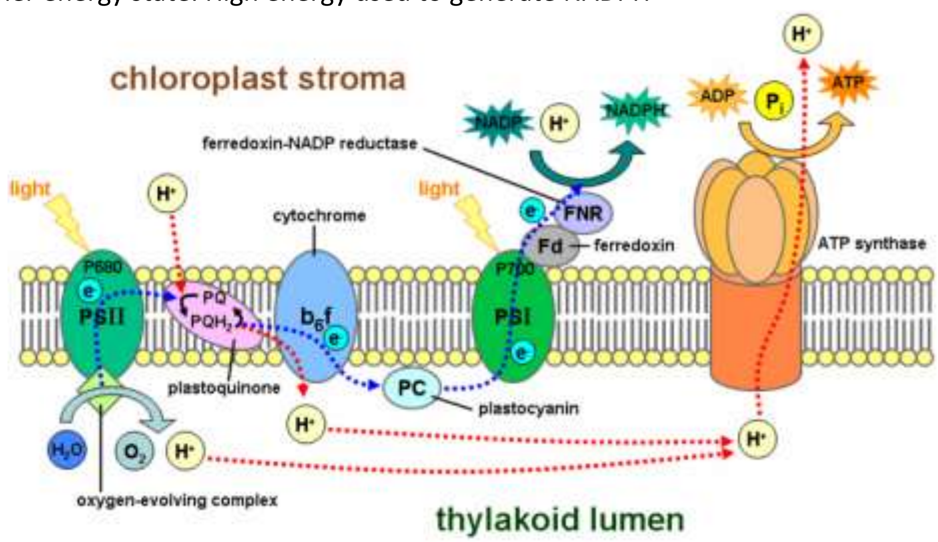
Light reactions

We went through this series of reactions in great detail because they comprise (in my opinion!) one of the most elegant systems in all of biology. Again we met the concept of "form = function" when we examined the chloroplast…

<u>**Chloroplast structure** (important attributes you need to know):</u>
Two membranes surround the chloroplast (the outer and inner membranes): we'll address the significance of this later in the semester
Thylakoids: membrane-bound structures inside chloroplasts
Granum (pl = grana): a vertical "stack" of thylakoids
Lumen: the space inside grana/thylakoids
Stroma: the space outside the thylakoids/grana but inside the chloroplast membranes
Thylakoid membrane: the membrane of the thylakoid, physically separates the stroma and lumen.



<u>**Thylakoid membrane structure** (including all protein complexes, electron carriers, etc., that you need to know):</u>
Photosystem II (PSII): Light reactions begin when pigments (mostly chlorophyll a) in PS II absorb light energy and e^- are excited.
Plastiquinone (PQ): Shuttles excited e^- from PS II to *Cyt* b_6/f complex. (PQ shuttles 2e- simultansously).
Cytochrome b_6/f complex (Cyt b_6/f): Large multi-protein complex that accepts high energy e- from PQ, and allows the e^- to fall to a lower energy state. The falling of the e^- is harnessed by *Cyt* b_6/f to do work, namely the pumping of H^+ (protons) from the stroma (outside the thylakoid) to the lumen (inside the thylakoid). Afterwards, b_6/f donates the low energy e^- to the e^- shuttle called plastocyanin.
Plastocyanin: Shuttles low energy e- from *Cyt* b_6/f to PS I.
Photosystem I: Receives low energy e^- from *Cyt* b_6/f; pigments in PSI then harness light energy to elevate the low energy e^- to a higher energy state. High energy used to generate NADPH *(NADP reductase: uses high energy e^- to produce NADPH from $NADP^+$ and H^+. (note: e^- shuttled from PS I to NADP reductase via ferrodoxin – you don't need to know this or NADP reductase!).*
ATP synthase: The high [proton] inside vs outside the lumen generates a chemical and electrical gradient across the membrane. As H^+ flow through a channel in ATP synthase, their motion is used to do work, namely the conversion of ADP + P to ATP.



Steps of the light reactions that you need to know *(note: you are responsible for details presented in lecture that might not necessarily appear here – but this summary represents nearly all of the material that I presented. Note also, the summary presented here will vary in level of detail from treatments you are likely to find in the textbook and online videos. It is more simplistic than in some texts (e.g., Raven's Biology of Plants, but more sophisticated that some others…). Note also: in my opinion, our textbook does only a mediocre job of laying out the step-by step process of the light reactions – but the figures on page 244-245 are great and represent the detail you are expected to know.*

1) Light strikes pigments (mostly chlorophylls) in PS II and excites individual electrons to a higher energy state (an orbital farther away from the atomic nucleus). The position of an e^- in the higher energy state is unstable and has high potential energy (like a boulder teetering on a hilltop right before it is rolled downhill), and this high energy is eventually harnessed to do work. (Each individual e^- comes from water as it is split by PS II – see step 3, below).

2) High energy electrons are transferred from PS II to the electron shuttle molecule plastiquinone (PQ). PQ carries 2 e^- at a time. When PQ has the 2 e^- onboard, 2 H^+ (protons) from the stroma jump onboard as well. PQ then carries the 2 high energy e^- and the 2 H^+ to the cytochrome b_6/f complex (*Cyt* b_6/f).

3) Electrons that PS II donates to PQ need to be replaced. This is accomplished when PS II "splits" water (H_20) into O (often referred to as ½ of an O_2 molecule), two H^+ (protons), and two e^-. The equation for this chemical reaction is:

$$H_2O \rightarrow O + 2H^+ + 2e^-$$

(recall that the atomic number of H is 1, meaning that it has 1 proton and 1 electron. As water is split, so too is each H atom…that's where the protons and electrons come from)

What happens to the products of this water splitting reaction?

- Individual O atoms bond in pairs to form O_2 (molecular oxygen), which is then released into the atmosphere or used by the plant. Note that this is how O_2 is formed as a product in the overall equation for photosynthesis (page 1 of these notes).
- H^+ (protons) remain in the lumen (for now!)
- e^- enter PS II to replace those e^- that were donated to PQ. These "newly arrived" e^- will eventually be excited and passed on to PQ as well!

4) Upon arrival at *Cyt* b_6/f, PQ donates the high energy e^- to Cyt b_6/f . Each high energy e- falls to a lower energy state, and as it does the release of energy is used to pump the two H^+ carried by PQ from the stroma into the lumen.

5) *Cyt* b_6/f donates the low energy e- to the shuttle molecule plastocyanin (PC). PC then carries the low energy e- to PS I. (PC carries e- one at a time – but you do not need to know this!).

6) Light strikes pigments (mostly chlorophylls) in PS I and excites individual electrons to a higher energy state (an orbital farther away from the atomic nucleus).

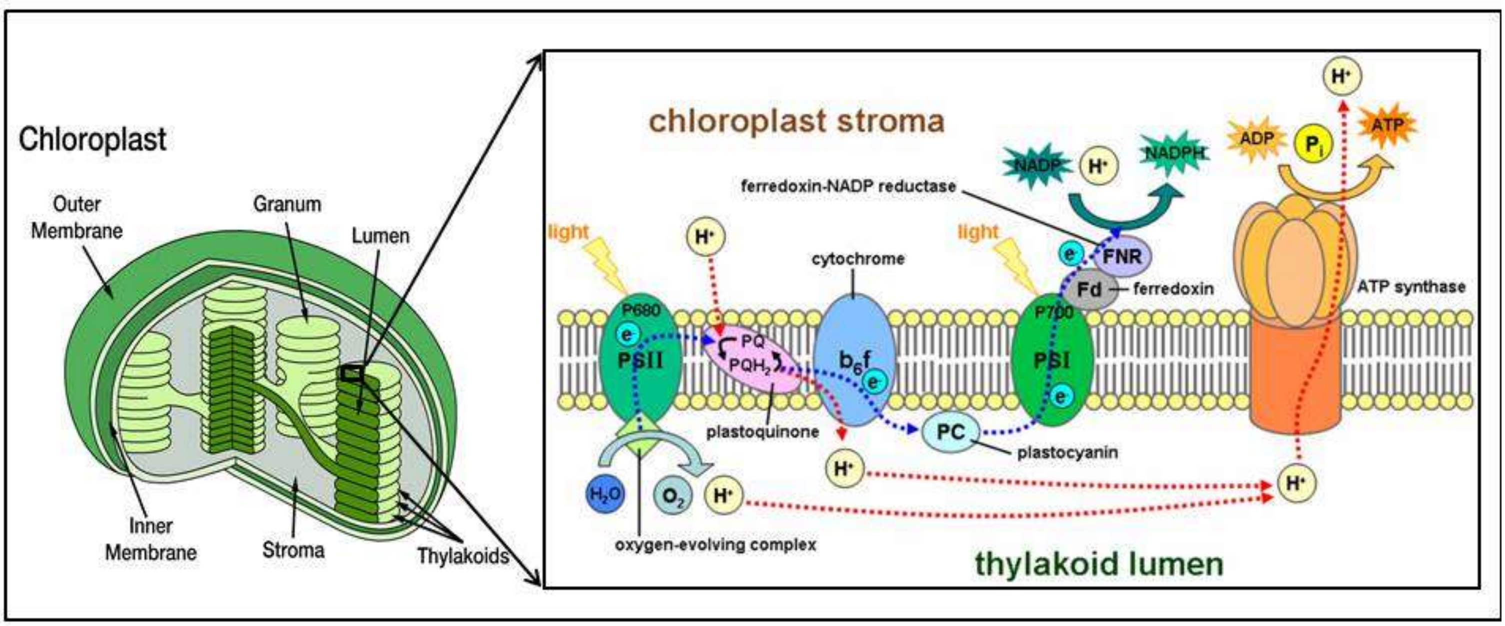
7) High energy electrons in PS I are used to drive formation of the molecule NADPH.
(You do not need to know the details of how this happens, nor do you need to know about NADPH – just think of it as an energy molecule like ATP). But – if you are interested here

are the details: high energy e^- are donated from PS I to the electron shuttle molecule Ferrodoxin, which then donates them to $NADP^+$, the energy release that accompanies this transfer is used to catalyze the formation of NADPH. (You do not need to know the name of the enzyme that catalyzes the formation of NADPH – but it is ferrodoxin-$NADP^+$ reductase [FNR]).

8) During the light reactions, a proton gradient forms across the thylakoid membrane: there is a high concentration of H^+ inside thylakoid membrane (in the lumen) and a low concentration of H^+ outside the thylakoid membrane (in the stroma). The protons that accumulate in the lumen come from <u>two sources</u>: **1)** they are created when water is split (see step 3), and; **2)** they are pumped into the lumen by *Cyt* b_6/f. This gradient is a chemical gradient, and it is also an electrical gradient because the protons have a charge. Thus, the gradient is referred to as an **electrochemical gradient**. It is used to do the last bit of work in the light reactions…

9) The electrochemical gradient across the thylakoid membrane causes protons to flow from the lumen to the stroma. The movement of protons is caused by diffusion (the movement of molecules from high concentration to low concentration) as well as the charge imbalance across the membrane (the many protons all have a positive charge and repel each other – and the higher repulsion in the lumen causes them to flow outwards into the stroma). The protons flow through specially designed channels in the protein complex ATP synthase. As they move through ATP synthase, the energy of their motion is harnessed to catalyze the formation of ATP from ADP and P. Think of ATP synthase as a water mill, and the H^+ are the water that causes it to turn. The turning of this mill then does the work (ADP + P -> ATP).

10) ATP and NADPH provide the energy required to drive carbon fixation in the light-independent reactions (Calvin cycle, C_3 cycle).



Online videos for studying the light reactions

Online videos are great tools for studying processes such as the light reactions. However, it is difficult to find videos that present information at the exact level of detail that you will be required to know for this class.

I suggest that you watch the videos I recommend below. As you watch, focus on the "big picture" concepts and processes. In each video there is vocabulary that you don't need to know, and there is vocabulary that is in your lecture notes but absent from the videos. As you watch, refer our posted lecture notes and your own handwritten notes – the level of detail that we diagrammed and discussed in class is the level of detail you need to know. "Know what you need to know".

https://www.youtube.com/watch?v=BK_cjd6Evcw

Notes about this video:

- This video is simple, which is good for overall comprehension
- PQ, PC, and Cytb6/f are not labeled…which is unfortunate!
- CAUTION! The video implies that PQ and (even worse!) PC cause pumping of H+ into the lumen (watch carefully – see that?!). Baloney! Cytb6/f does the pumping.
- The lumen is referred to as the "thylakoid space" (ok, but uncommon)

https://www.youtube.com/watch?v=YeD9idmcX0w

Notes about this video:

- Great overview, including CO_2 entering through stomata, etc.
- Stop watching at 2:10 (end of the light reactions)
- Nothing is labeled in this video (PSII, PSI, PQ, PC, etc) – so you will need to watch this with your notes by your side! If you can watch this video and name the molecules in action – you are golden! The final step in your studying is to take a blank piece of paper and draw the thylakoid membrane, and in/around it all protein complexes (PSII, PSI, Cytb6/f, ATP synthase), all shuttle molecules (you need to know PQ and PC) all smaller molecules (H_20, O_2, ATP), or subatomic particles (H^+, e^-) and explain how the system works!

https://www.youtube.com/watch?v=vEsAtC9d_MQ

Notes about this video:

- Reiterates that photosynthesis is broken into two stages: 1) Light reactions, and; 2) Light-independent reactions (in this video, called the Calvin cycle)
- The term "Light independent reactions" is not used – the more formal term "Calvin cycle" is used.
- There is some technical minutia in this video that you do NOT need to know – but this provides a great overview.
- If you watch this – do so with your notes and "know what you need to know"
- **Ignore especially the following terms:** P680, P700, "oxidize", "oxidizing agent", "reduce", "reducing agent"
- Remember, "hydrogen ion" = "proton".
- You don't need to know the "Z-scheme" energy representation that begins at 8:00, but it's a concise review.
- Khan academy, so it's good

We might not cover the following information on atrazine and paraquat until our next lecture on the light-independent reactions.

Herbicides that interrupt electron transport of the light reactions:
Herbicide : A type of pesticide used to kill unwanted plants.
Pesticide: A compound used to prevent, kill or mitigate any unwanted pest.
Pest: any organism detrimental to human interests.
The movement of electrons from one donor molecule to the next is known as an electron transport chain. In lecture, we discussed two herbicides that act on plants by interrupting the flow of electrons through the transport chain of the light reactions: 1) atrazine, and 2) paraquat.

1) Atrazine: Disables plastiquinone (PQ) such that electrons do not leave PS II, and therefore arrests the light reactions. A VERY common herbicide because it is cheap and effective (e.g., increases corn yields by 1-6%). Recent controversy has arisen because atrazine has been shown to affect hormone levels in some animals (especially amphibians) and cause males frogs to develop female reproductive characteristics. It is also suspected as a carcinogen. Atrazine does not kill crop plants because it is sprayed before crop seeds germinate (a "pre-emergence" herbicide) or because plants like corn are able to degrade it more quickly than weeds.

Video RE: atrazine (from Huffington Post)
http://www.youtube.com/watch?v=9iJQvrEOIjU
(stopped at 3:17)

2) Paraquat: Accepts (more accurately: "steals"!) high energy electrons from PS I before they can be used to drive the formation of NADPH. This arrests photosynthesis. Paraquat is a widely used and very effective herbicide. It is toxic to animals and some research links it to the development of Parkinson's disease in farmworkers and others with high exposure to paraquat. It has been used as a murder poison, and as a suicide agent in poor countries where access is easy. Gained prominence in the 1970's due to "paraquat pot", which was marijuana grown in Mexico and smuggled into the US, but that had been sprayed with paraquat by the US drug authorities in an attempt to eradicate the fields.
