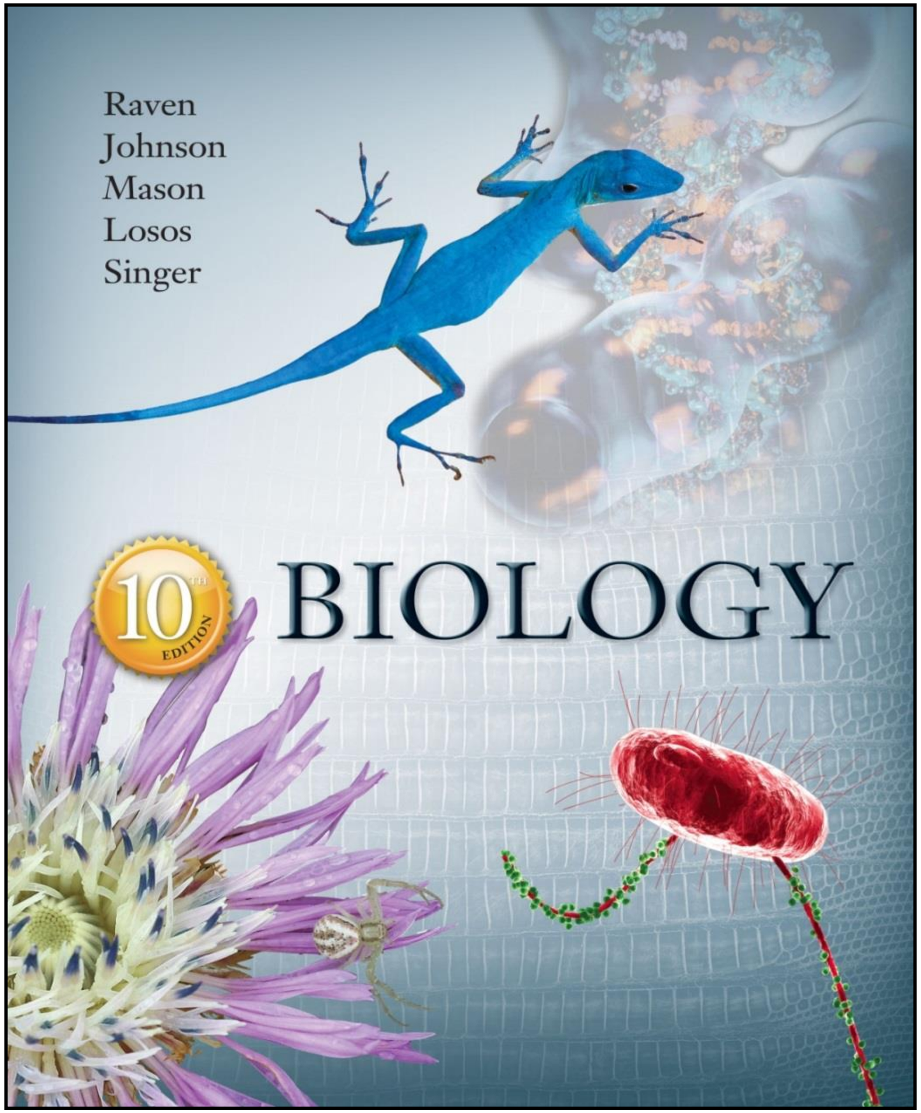


Chapter 08

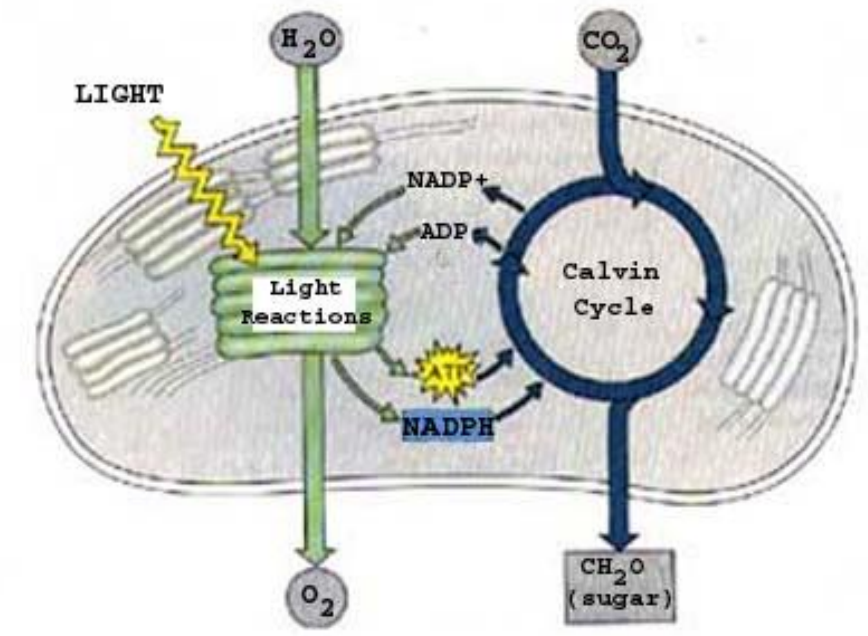
Photosynthesis

© Royalty-Free/Corbis

Important study hints

- Draw out processes on paper and label structures and steps

- Accckkk! More flash cards!!!



http://www.bio.umass.edu/biology/conn.river/photosyn.html

8.1 Photosynthesis Overview

- Ultimate source of energy is the Sun
  - Captured by plants, algae, and bacteria through the process of **photosynthesis**

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

Know this equation!!

- Oxygenic photosynthesis is carried out by
  - Cyanobacteria
  - 7 groups of algae
  - All land plants
    - photosynthesis takes place in **chloroplasts**

Diatoms are algae in a silica shell

http://arch.ced.berkeley.edu/hiddenecologies/?page_id=78

8.1 Photosynthesis Overview

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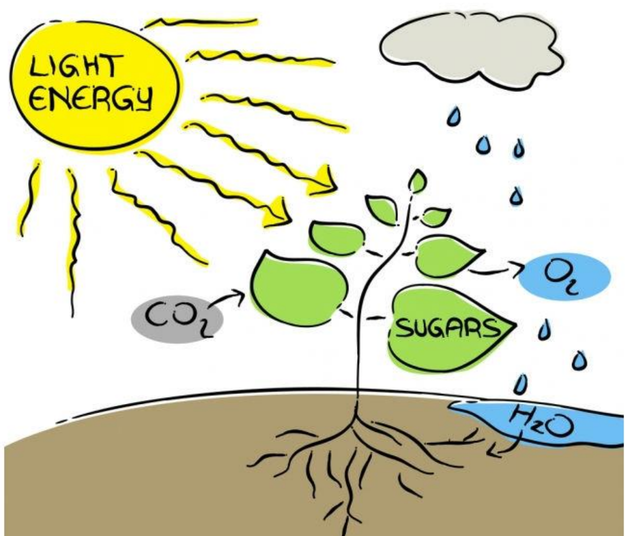
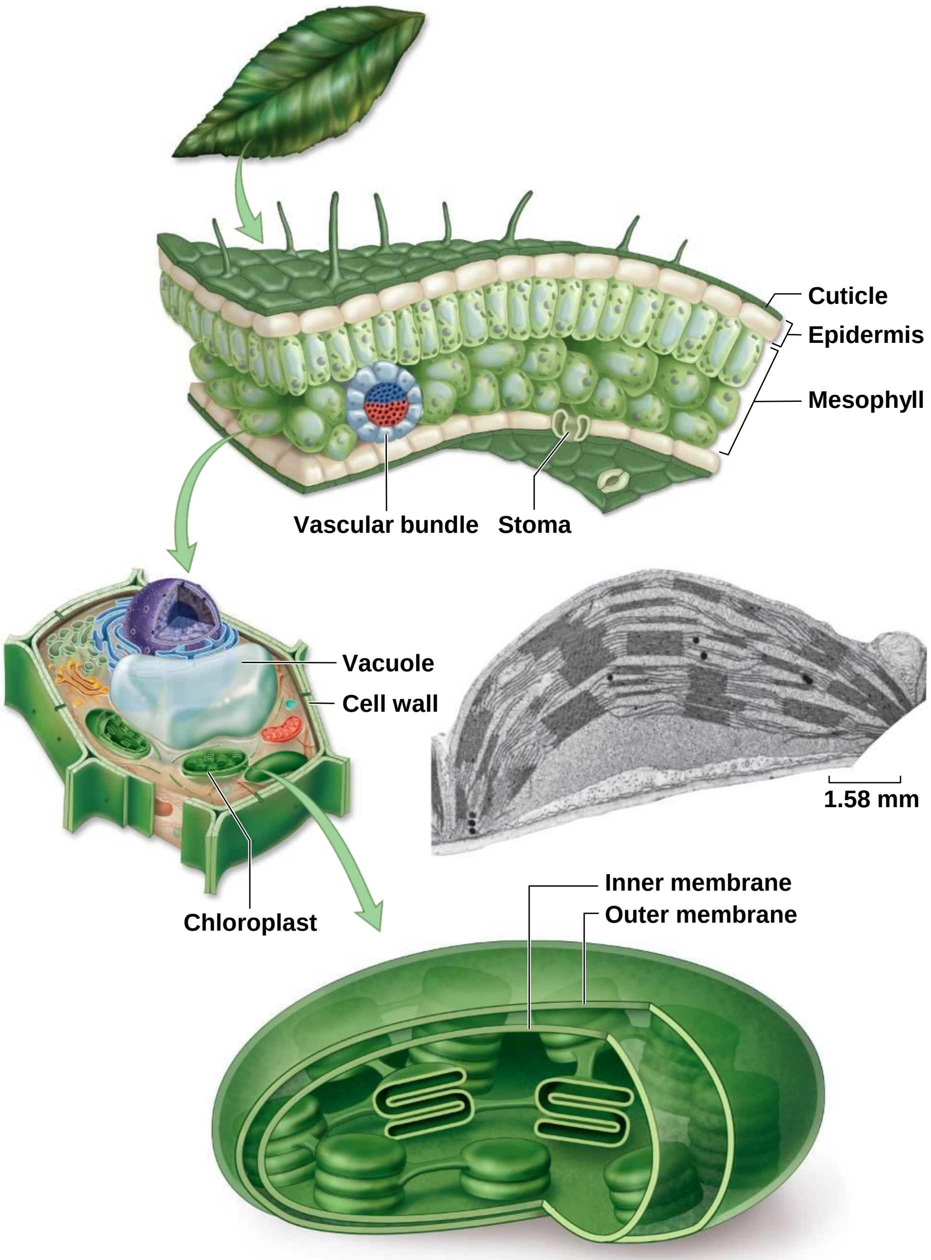


Know this equation!!

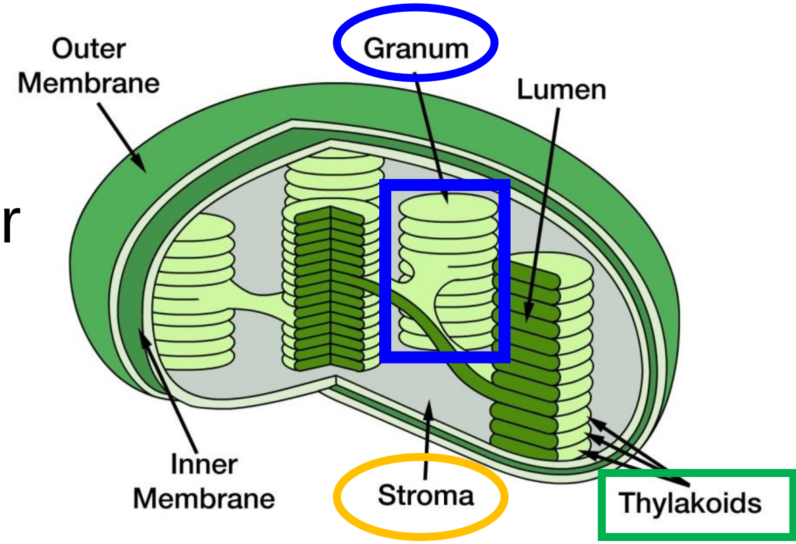
http://www.earthtimes.org/energy/photosynthesis-dream-renewable-energy/1956/



Courtesy Dr. Kenneth Miller, Brown University http://www.glogster.com/packerfan7/chloroplasts/g-6lpa2rsjd9ofnf7ov5kfra0

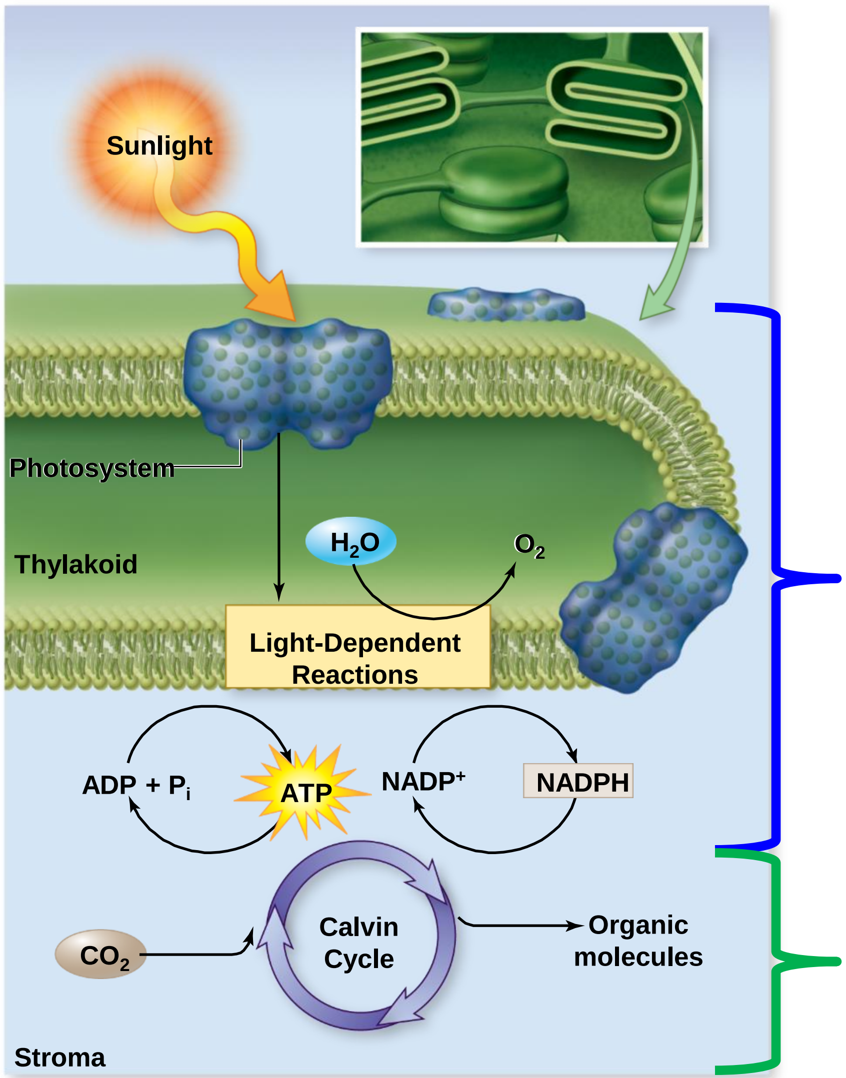
Chloroplast

- **Thylakoids** – flattened membranous sacs arranged in stacks (**grana**)
- **Thylakoid membrane** – internal membrane
  - Contains chlorophyll and other photosynthetic pigments
  - Pigments clustered into photosystems



- **Stroma** – semiliquid surrounding thylakoid membranes
- **Stroma lamella** – connect grana

Photosynthetic Processes



Light-dependent reactions

- Require light
- Capture energy from sunlight
- Make ATP and reduce $NADP^+$ to NADPH

Carbon fixation reactions

- Does not require light
- Use ATP and NADPH to synthesize organic molecules from CO_2

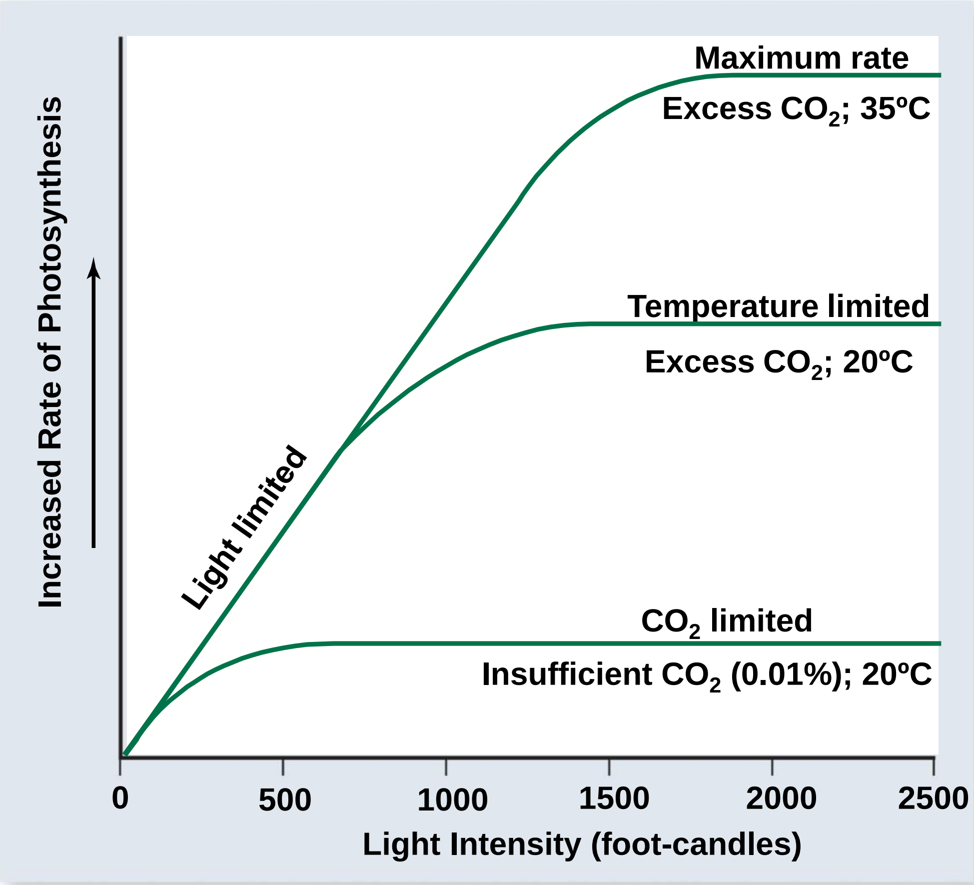
8.2 Discovery of Photosynthesis

Optional

- Jan Baptista van Helmont (1580–1644)
  - Demonstrated that the substance of the plant was not produced only from the soil
- Joseph Priestly (1733–1804)
  - Living vegetation adds something to the air
- Jan Ingenhousz (1730–1799)
  - Proposed plants carry out a process that uses sunlight to split carbon dioxide into carbon and oxygen (O_2 gas)

Optional

- F.F. Blackman (1866–1947)
  - Came to the startling conclusion that photosynthesis is in fact a multistage process, only one portion of which uses light directly
  - Light versus dark reactions
  - Enzymes involved



Optional

- C. B. van Niel (1897–1985)
  - Found purple sulfur bacteria do not release O_2 but accumulate sulfur
  - Proposed general formula for photosynthesis
    - $CO_2 + 2\ H_2A + \text{light energy} \rightarrow (CH_2O) + H_2O + 2\ A$
  - Later researchers found O_2 produced comes from water
- Robin Hill (1899–1991)
  - Demonstrated Niel was right that light energy could be harvested and used in a reduction reaction

8.3 Pigments

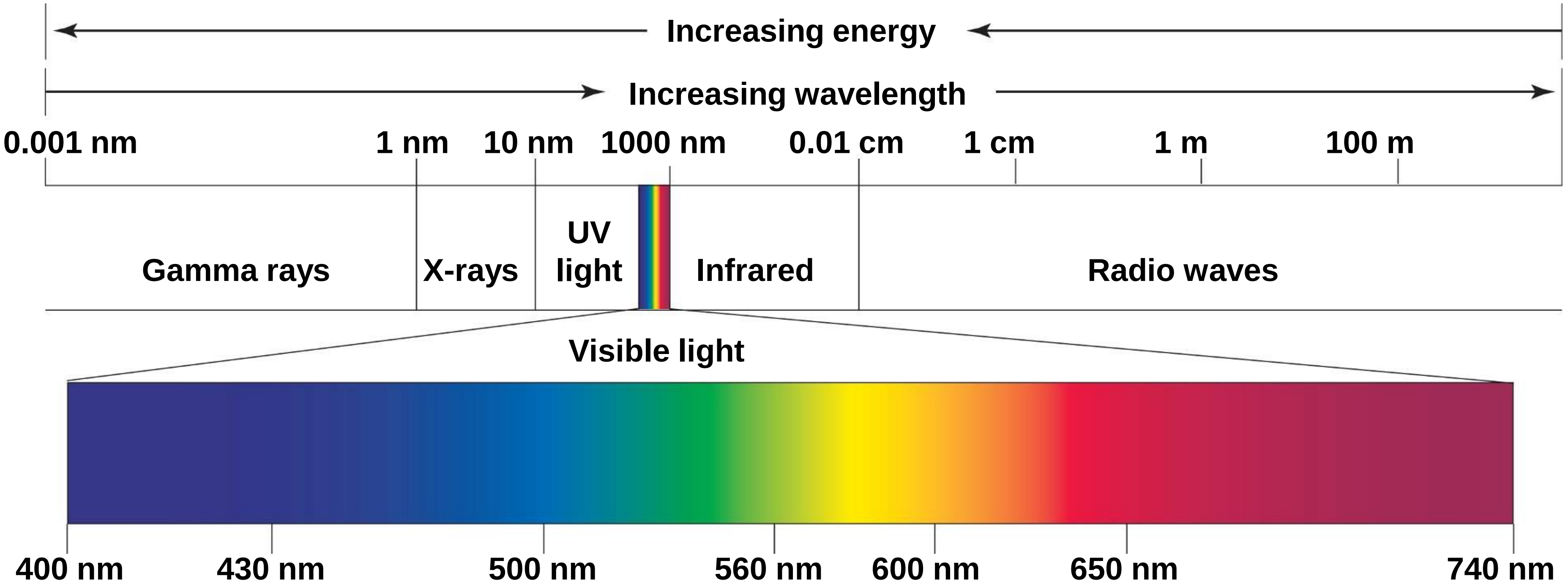
- Molecules that absorb light energy in visible range of **electromagnetic spectrum**
- **Light** is a wave form of kinetic energy
- **Photon** – particle of light
  - Acts as a discrete bundle of energy
  - Energy content of a photon is *inversely proportional to the wavelength of the light*

- **Photoelectric effect** – removal of an electron from a molecule by light

http://www.spacegrant.montana.edu/msiproject/light.html

Electromagnetic Spectrum

- Light is a form of electromagnetic energy
- *The shorter wavelength of the light, the greater is energy*
- Visible light represents only a small part of spectrum, 400 – 700 nm

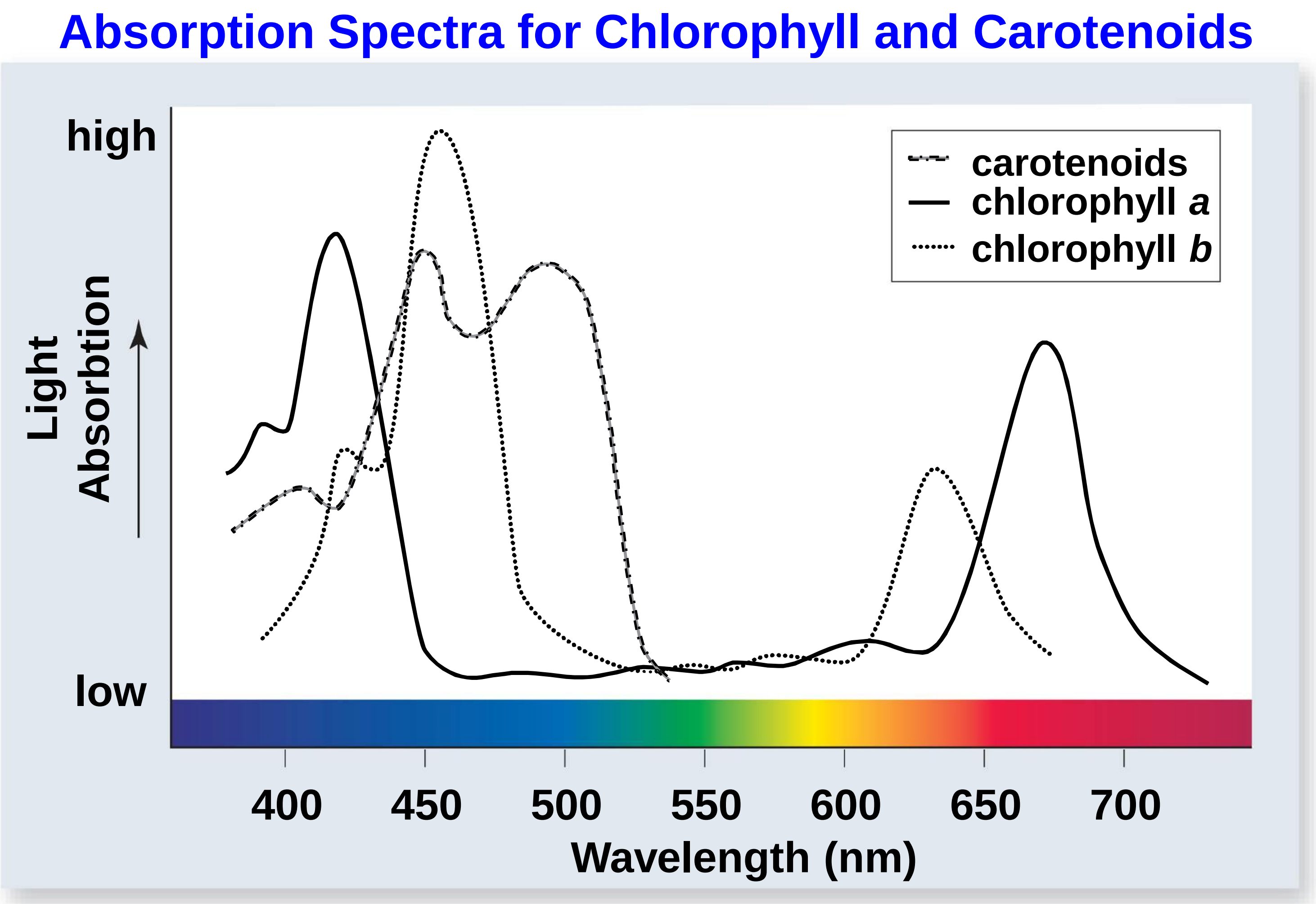


Absorption spectrum

- When a photon strikes a molecule, its energy is either
  - Lost as heat
  - **Absorbed by the electrons of the molecule**
    - *Boosts electrons into higher energy level*

- **Absorption spectrum** – range and efficiency of photons molecule is capable of absorbing

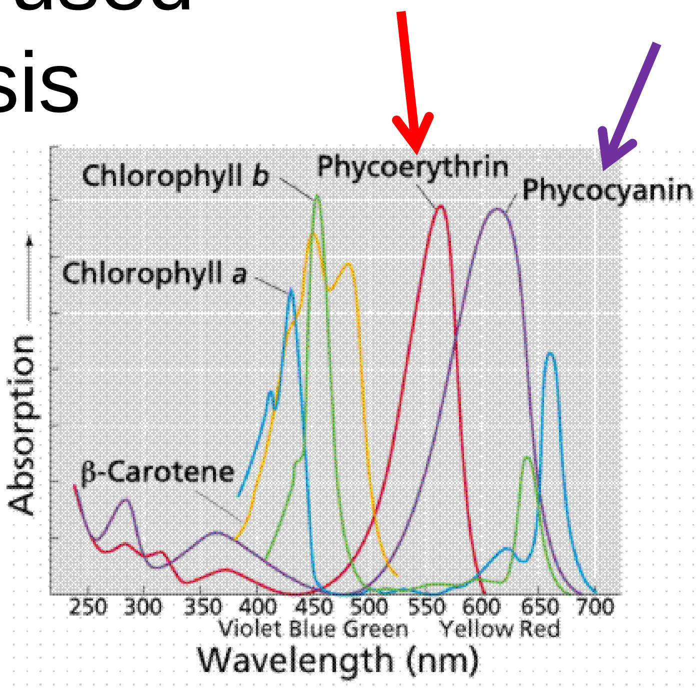
- **Absorption spectrum** – range and efficiency of photons molecule is capable of absorbing



Pigments in Photosynthesis

- Organisms have evolved a variety of different pigments
- Only two general types are used in green plant photosynthesis
  - **Chlorophylls**
  - **Carotenoids**

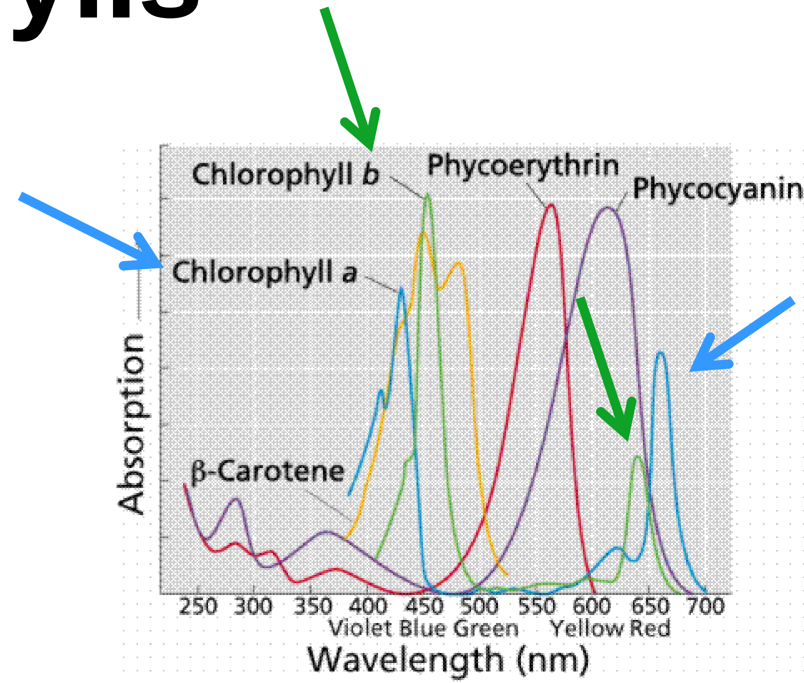
- In some organisms, other molecules also absorb light energy



http://www2.estrellamountain.edu/faculty/farabee/BIOBK/biobookps.html

http://www2.estrellamountain.edu/faculty/farabee/BIOBK/biobookps.html

Chlorophylls

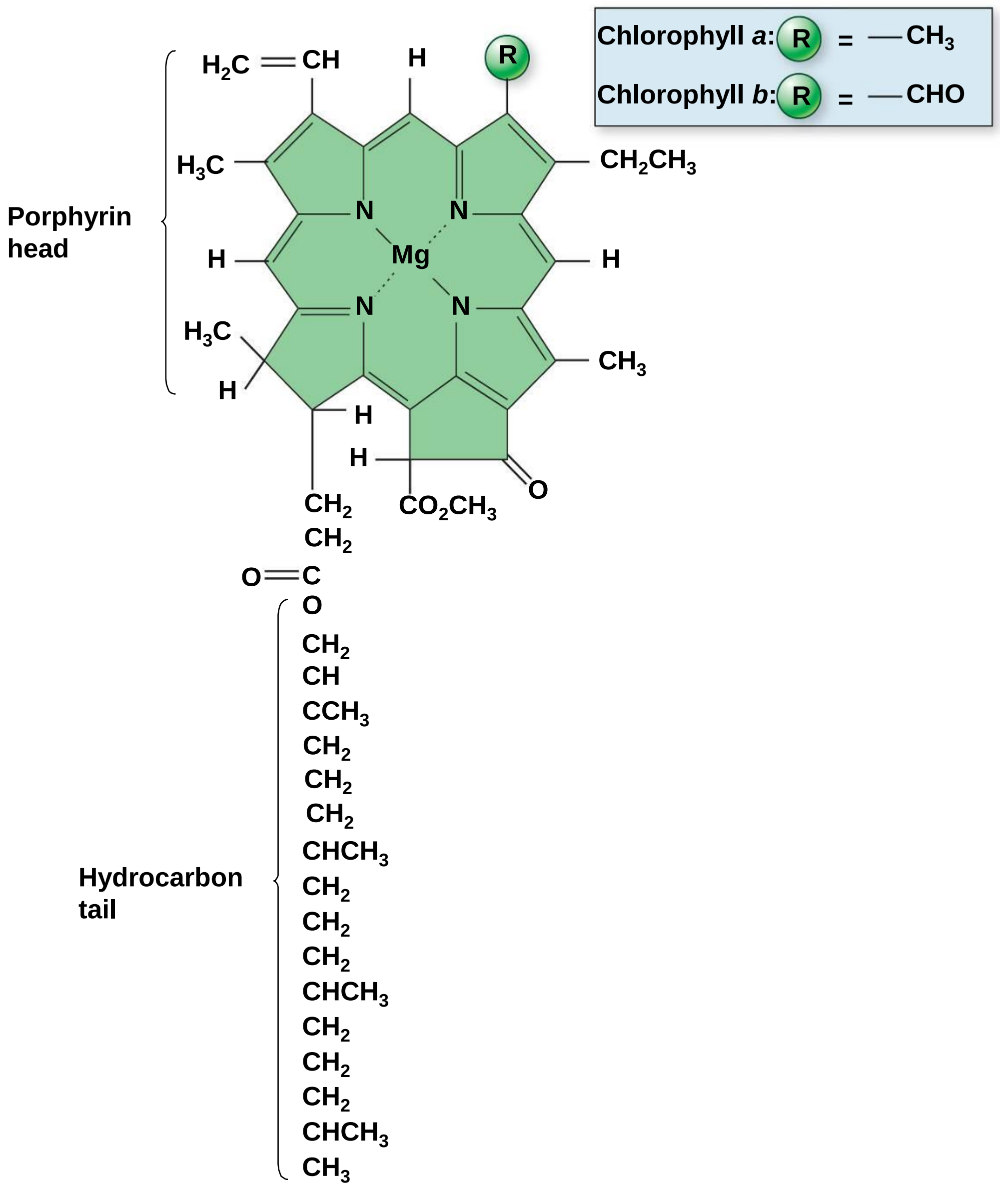


- **Chlorophyll *a***
  - Main pigment in plants and cyanobacteria
  - Only pigment that can act directly to convert light energy to chemical energy
  - Absorbs <u>*violet-blue and red light*</u>

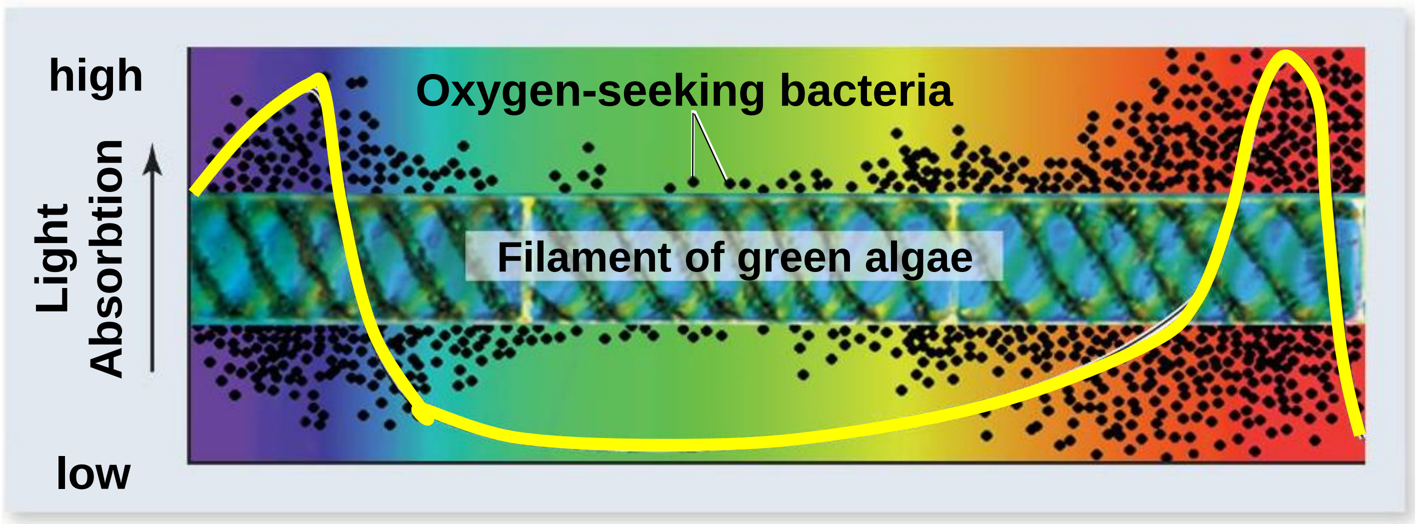
- **Chlorophyll *b***
  - Accessory pigment absorbing wavelengths that chlorophyll *a* does not absorb (<u>*blue and orange*</u>)

Structure of chlorophyll

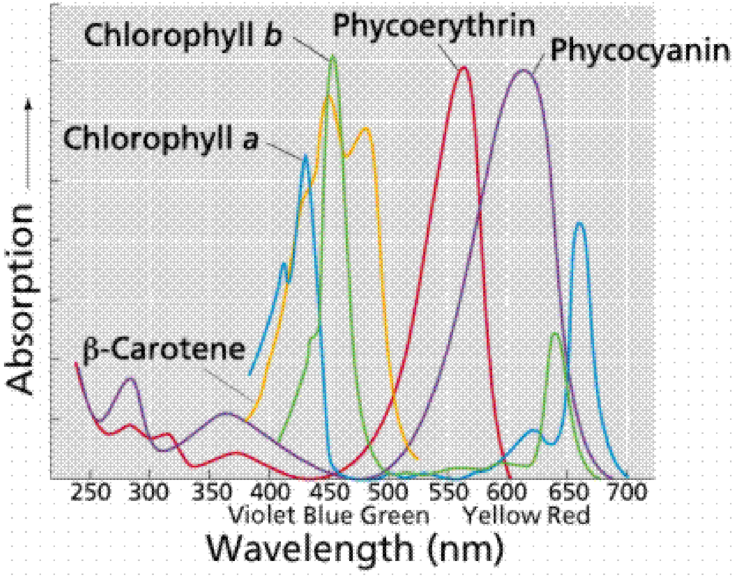
- Porphyrin ring
  - Complex ring structure with alternating double and single bonds
  - Magnesium ion at the center of the ring
- Photons excite electrons in the ring
  - Electrons are shuttled away from the ring to electron acceptor



http://www2.estrellamountain.edu/faculty/farabee/BIOBK/biobookps.html



- **Action spectrum**
  - Relative effectiveness of different wavelengths of light in promoting photosynthesis
  - Corresponds to the combined absorption spectrum of chlorophylls

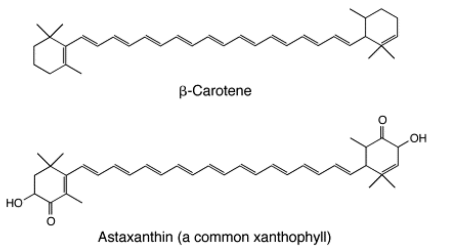


http://www.sciencedirect.com/science/article/pii/S0169534798014840

- **Carotenoids**
  - Carbon rings linked to chains with alternating single and double bonds
  - Can absorb photons… yellows - oranges - reds
  - Also scavenge free radicals – antioxidants
    - Protective role

- **Phycobiloproteins**
  - Important in some cyanobacteria & some algae in low-light ocean areas

Oak leaf in summer



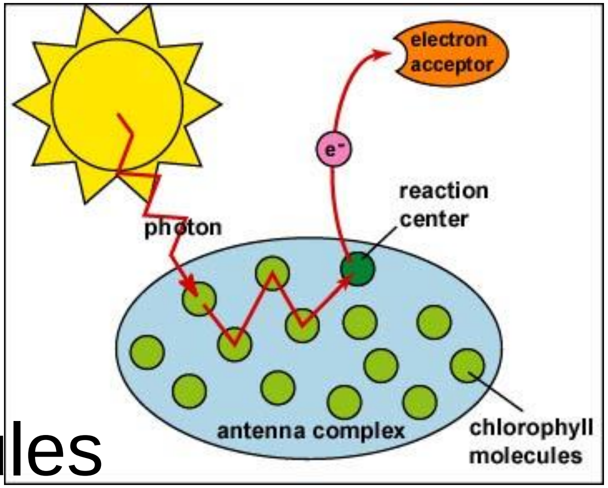
Oak leaf in autumn

Cyanobacterium: *Tolypothrix* sp.

http://en.wikipedia.org/wiki/Cyanobacteria

8.4 Photosystem Organization

- **Antenna complex**
  - Hundreds of accessory pigment molecules in thylakoid membrane
  - Gathers photons and feeds captured light energy to **reaction center**



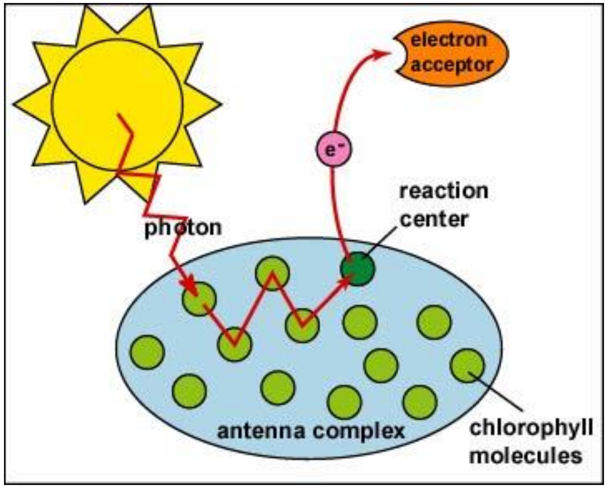
- **Reaction center**
  - 1 or more chlorophyll *a* molecules
  - Passes excited electrons out of photosystem to electron acceptor

http://student.ccbcmd.edu/~gkaiser/biotutorials/photosyn/fg3.html

Antenna complex

- Captures photons from sunlight and channels energy to reaction center chlorophylls

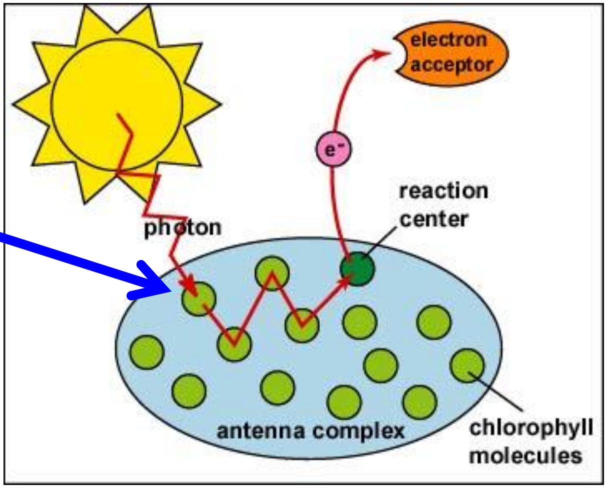
- In chloroplasts, antennae complexes consist of a web of chlorophyll molecules linked together and held tightly in the thylakoid membrane by a matrix of proteins



http://student.ccbcmd.edu/~gkaiser/biotutorials/photosyn/fg3.html

How the Antenna Complex Works

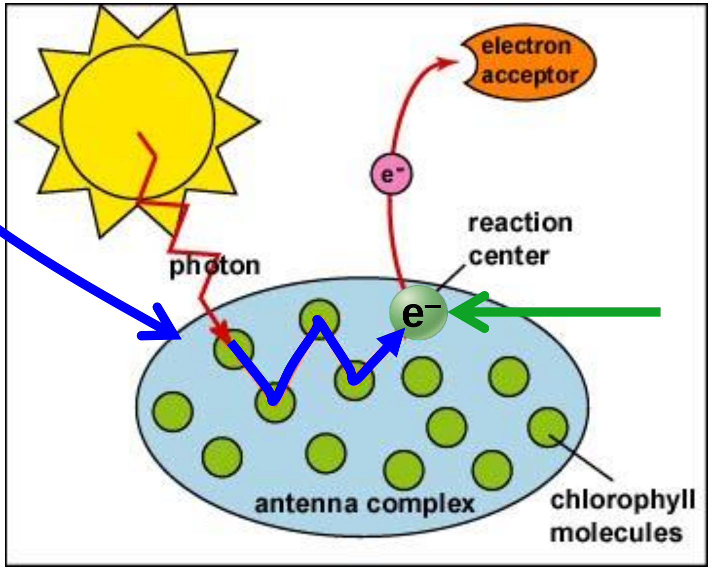
- When light of proper wavelength strikes any pigment molecule within a photosystem, the light is absorbed by that pigment molecule



http://student.ccbcmd.edu/~gkaiser/biotutorials/photosyn/fg3.html

How the Antenna Complex Works

- The excitation energy is then transferred from one molecule to another within the cluster of pigment molecules until it encounters chlorophyll a at the **reaction center**
- When excitation energy reaches the reaction center chlorophyll, electron transfer is initiated



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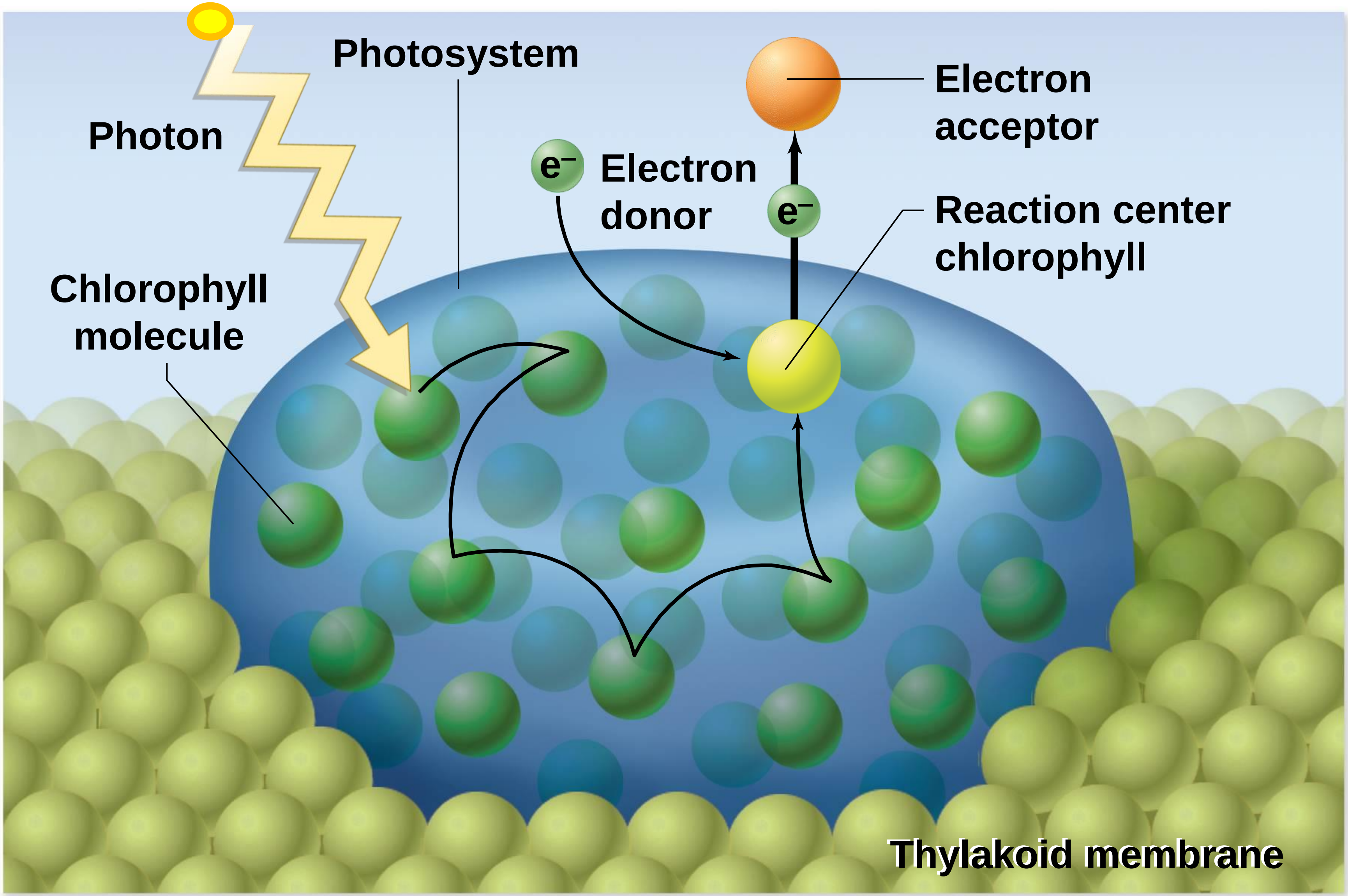
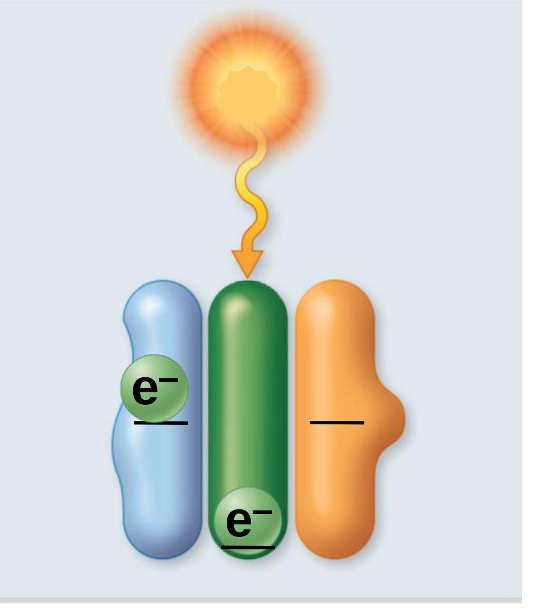
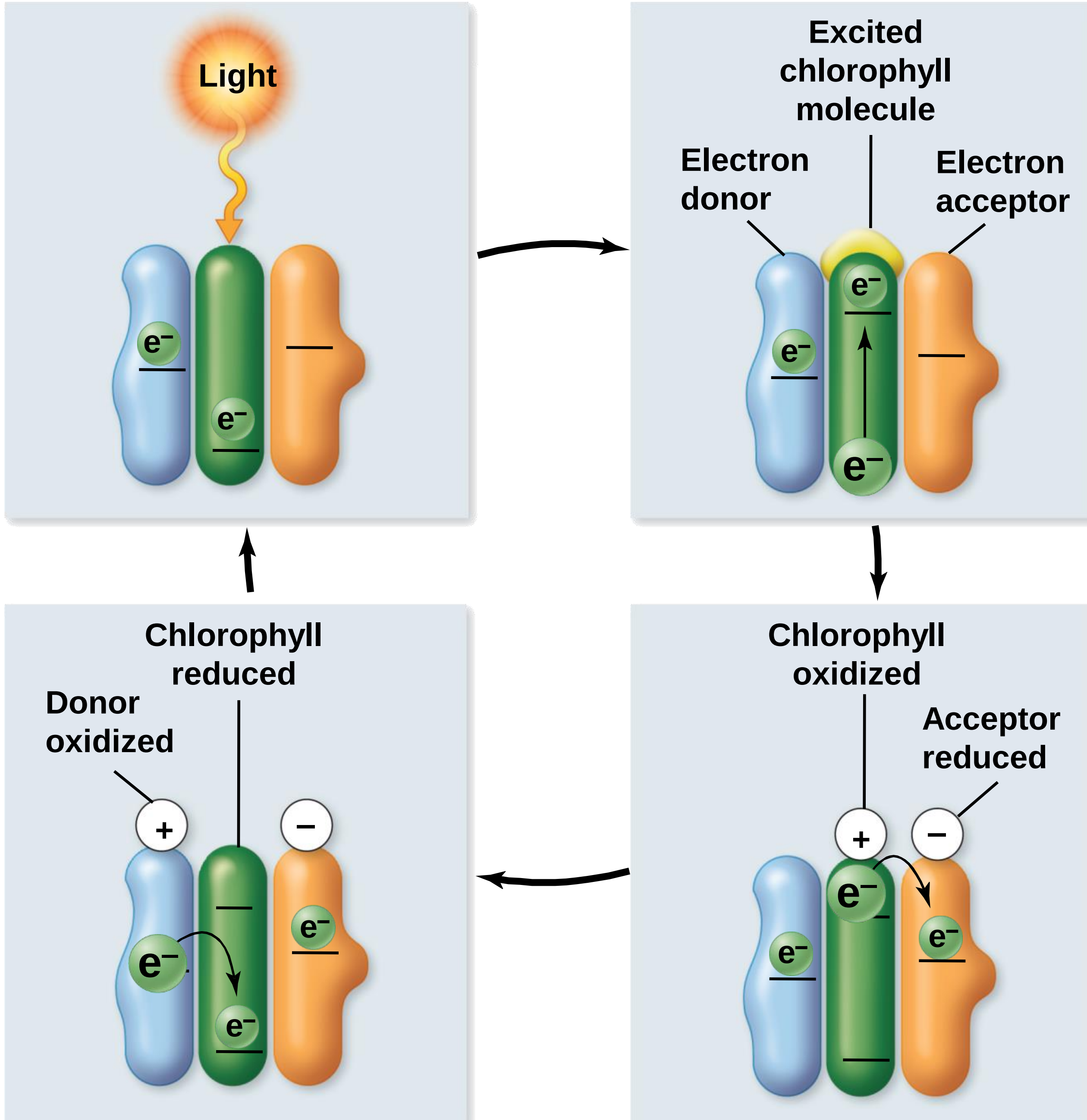
How the Antenna Complex Works



Reaction center

- Transmembrane protein–pigment complex
- When a chlorophyll in the reaction center absorbs a photon of light…
- an electron is excited to a higher energy level
- Light-energized electron can be transferred to the primary electron acceptor, reducing it
- Oxidized chlorophyll then fills its electron “hole” by oxidizing a donor molecule




Light
e⁻
e⁻
Excited chlorophyll molecule
Electron donor
Electron acceptor
e⁻
e⁻
e⁻
Chlorophyll oxidized
Acceptor reduced
+
−
e⁻
e⁻
e⁻
Chlorophyll reduced
Donor oxidized
+
−
e⁻
e⁻
e⁻

8.5 Light-Dependent Reactions

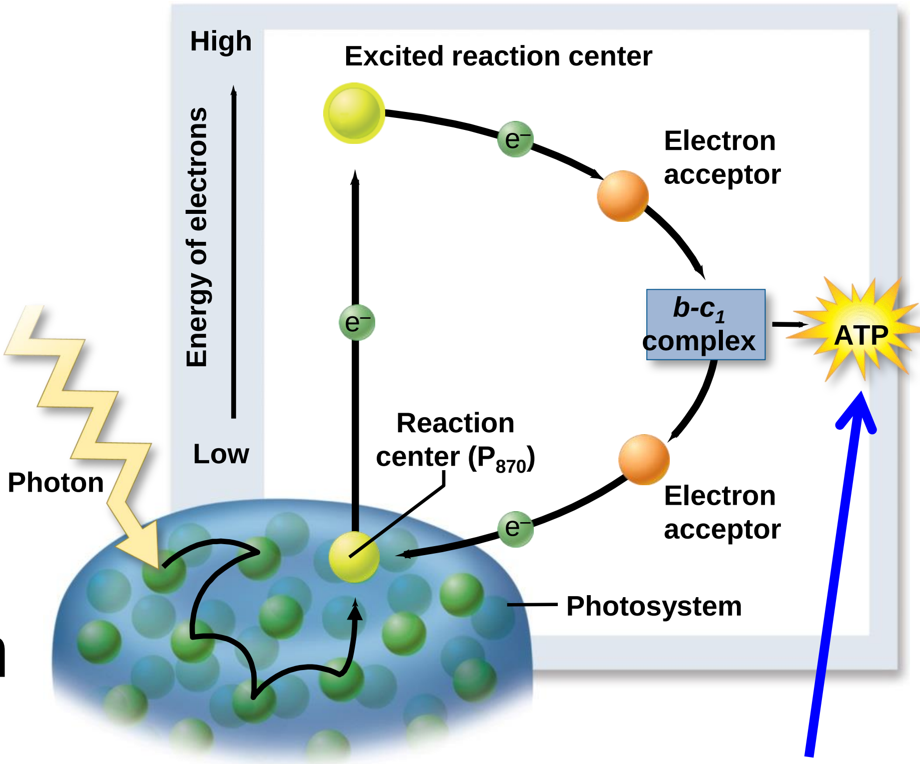
Series of steps…

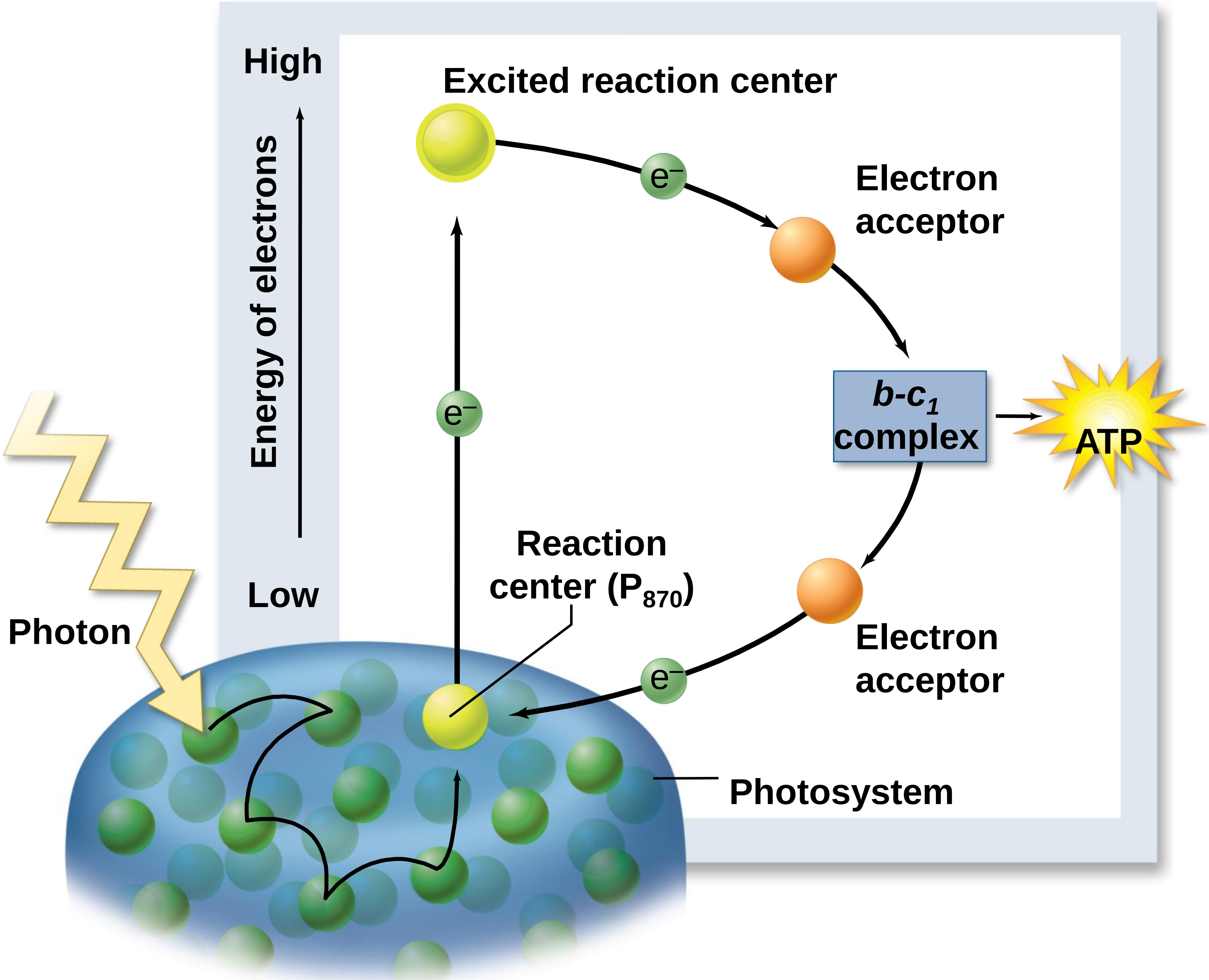
1. **Primary photoevent**
   - Photon of light is captured by a pigment molecule
2. **Charge separation**
   - Energy is transferred to the reaction center; an excited electron is transferred to an acceptor molecule
3. **Electron transport**
   - Electrons move through carriers to reduce $NADP^+$
4. **Chemiosmosis**
   - Produces ATP

Capture of light energy (steps 1–3)

Cyclic Photophosphorylation

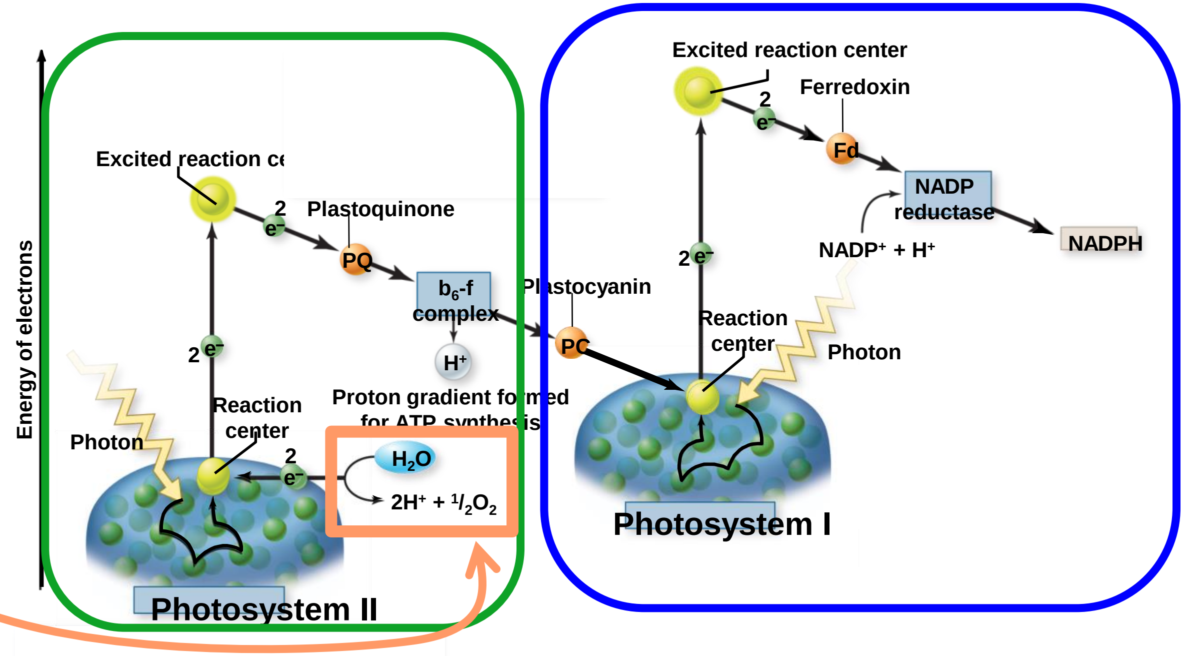
- In sulfur bacteria, only one photosystem is used
- Generates *only ATP* via electron transport
- Anoxygenic (no O_2) photosynthesis
- Excited electron passed to electron transport chain
- Generates a proton gradient for ATP synthesis




High
Energy of electrons
Low
Excited reaction center
e⁻
Electron acceptor
b-c1 complex
ATP
Reaction center (P870)
Electron acceptor
Photon
Photosystem

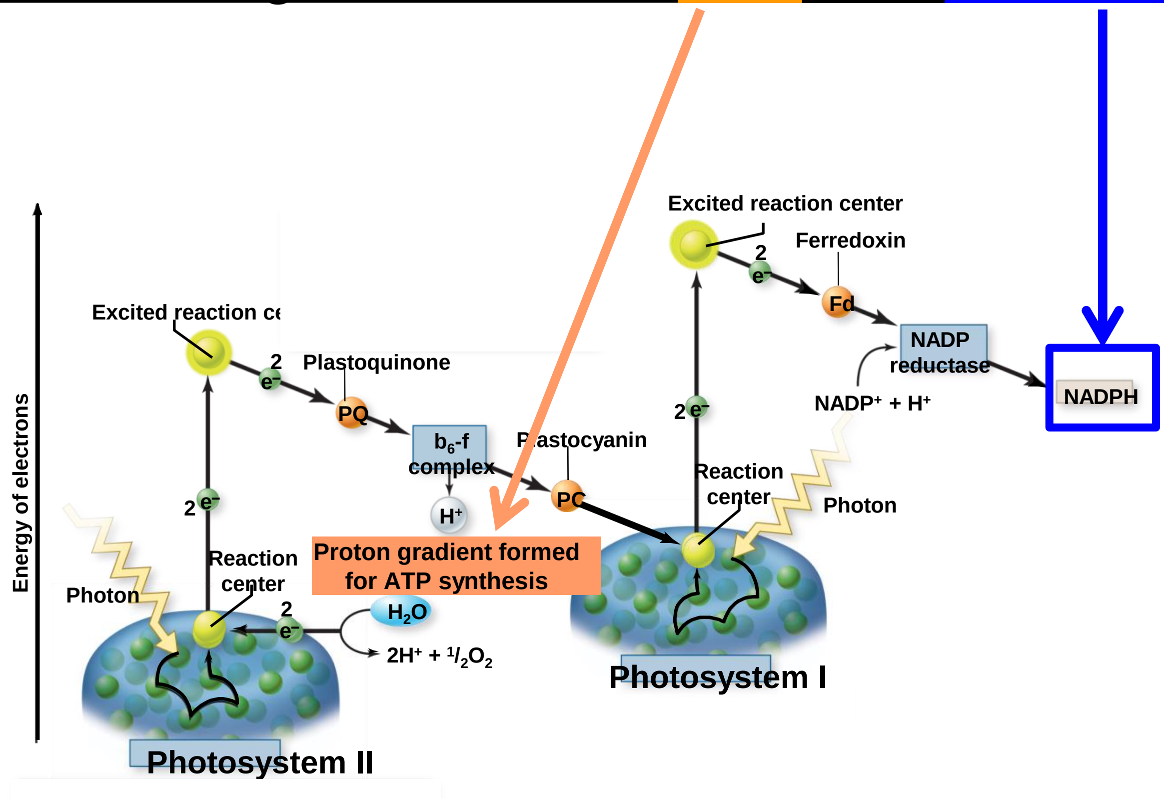
Chloroplasts Have Two Connected Photosystems

- Oxygenic (makes O_2) photosynthesis
- **Photosystem I** (P_{700})… similar to sulfur bacteria
- **Photosystem II** (P_{680})
  - Can generate an oxidation potential high enough to *oxidize water*



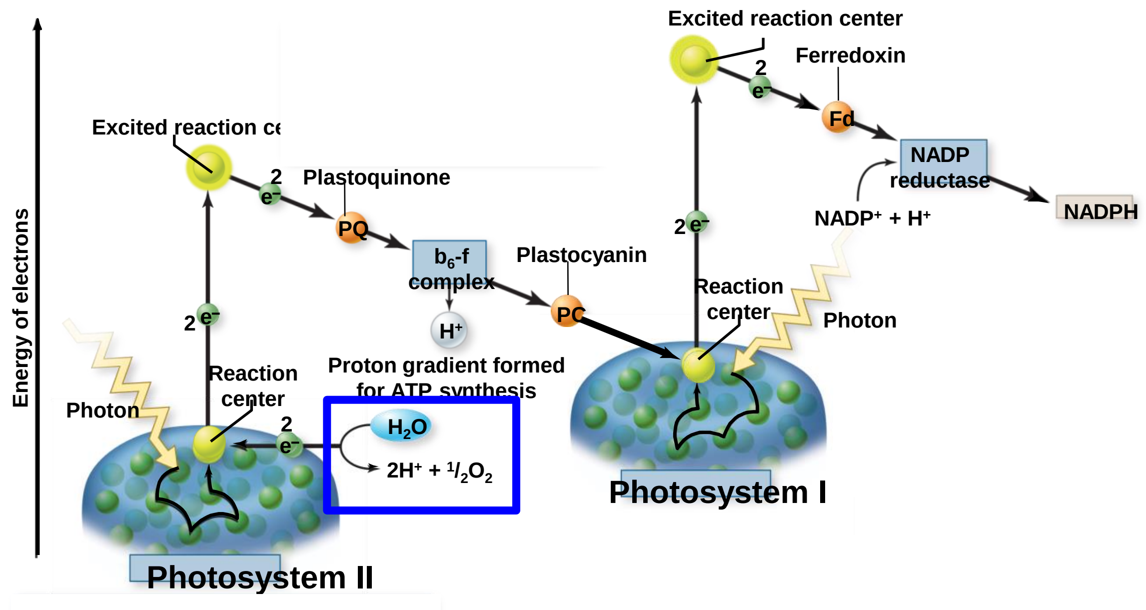
Chloroplasts Have Two Connected Photosystems

- Working together,
  - the two photosystems carry out a *noncyclic transfer of electrons that is used to generate both ATP and NADPH*



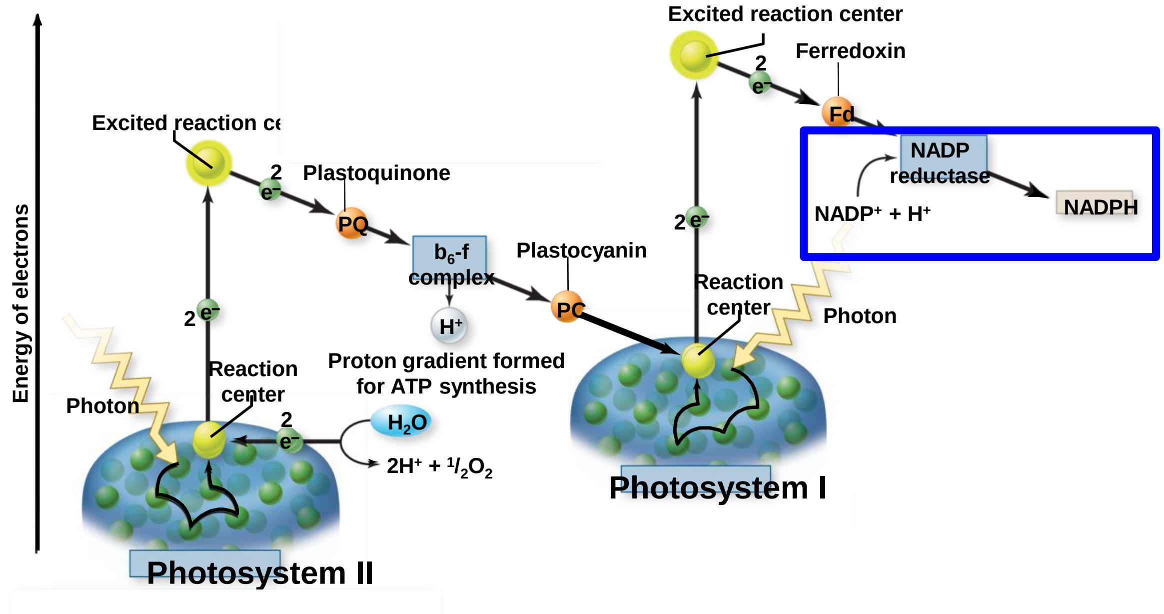
The Two Photosystems Work Together

- **Photosystem II** oxidizes water to replace the electrons transferred to photosystem I
- Two photosystems connected by cytochrome/ *b_6-f* complex



The Two Photosystems Work Together

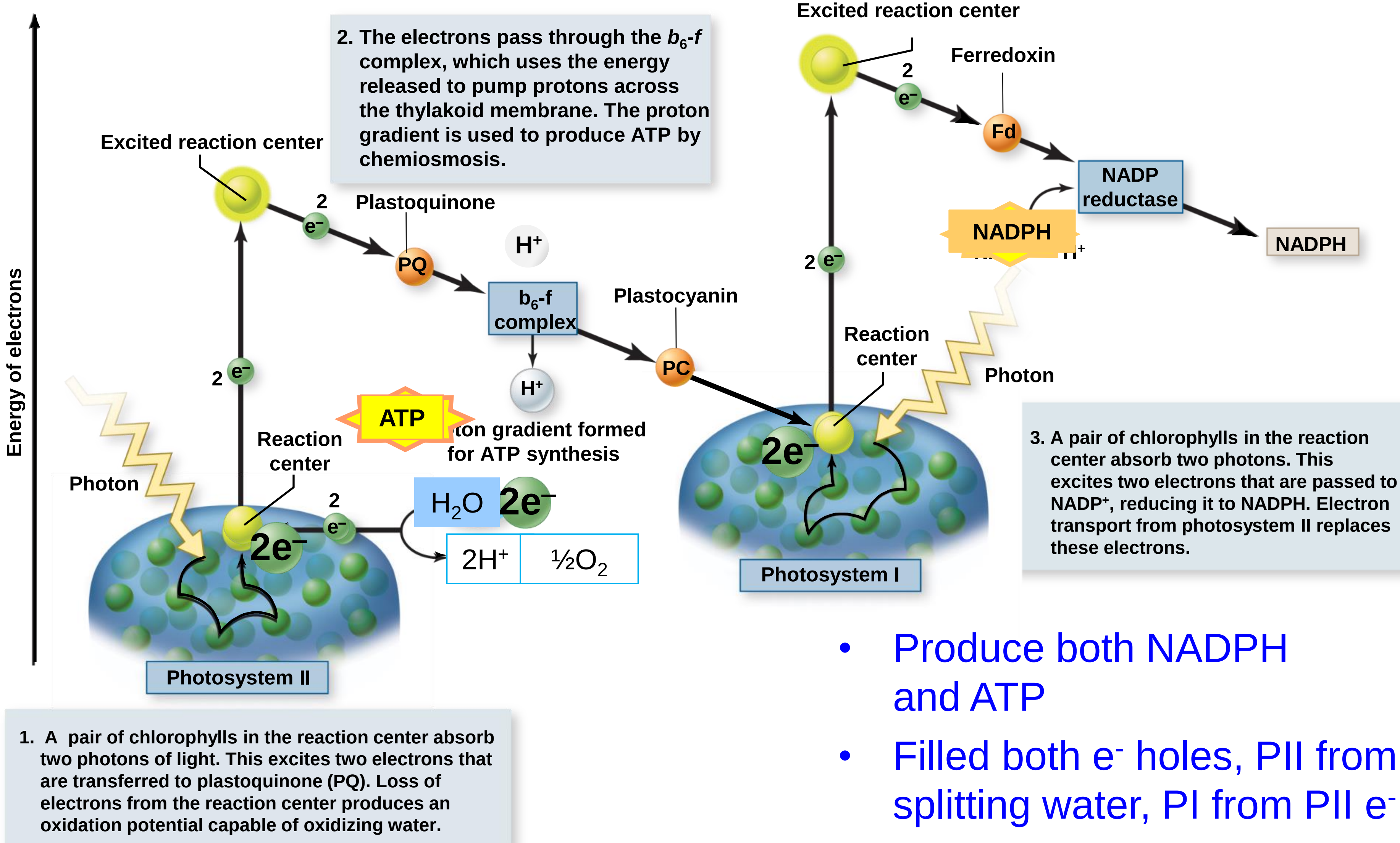
- **Photosystem I** transfers electrons ultimately to $NADP^+$, producing NADPH
- Electrons lost from photosystem I are replaced by electrons from photosystem II



Noncyclic Photophosphorylation

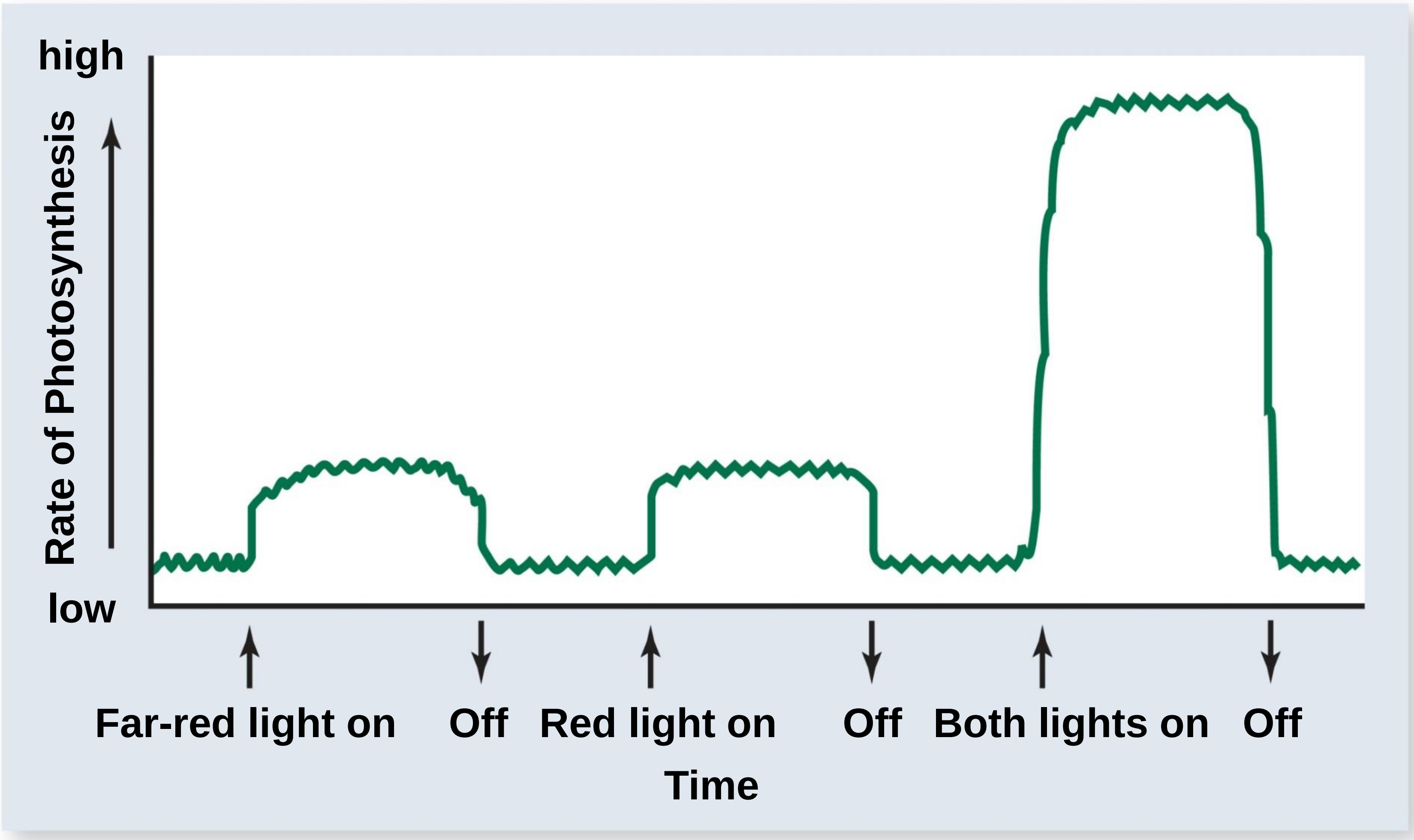
- Plants use photosystems II and I in series to produce both ATP and NADPH
- Path of electrons not a circle (“noncyclic”)
- Requires two photons (one per photosystem)
- Photosystems replenished with electrons obtained by *splitting water*
- Z diagram

Noncyclic Photophosphorylation



- Produce both NADPH and ATP
- Filled both e^- holes, PII from splitting water, PI from PII e^-

- The enhancement effect: photosynthesis is carried out by two systems that acts in series



Photosystem II

Optional

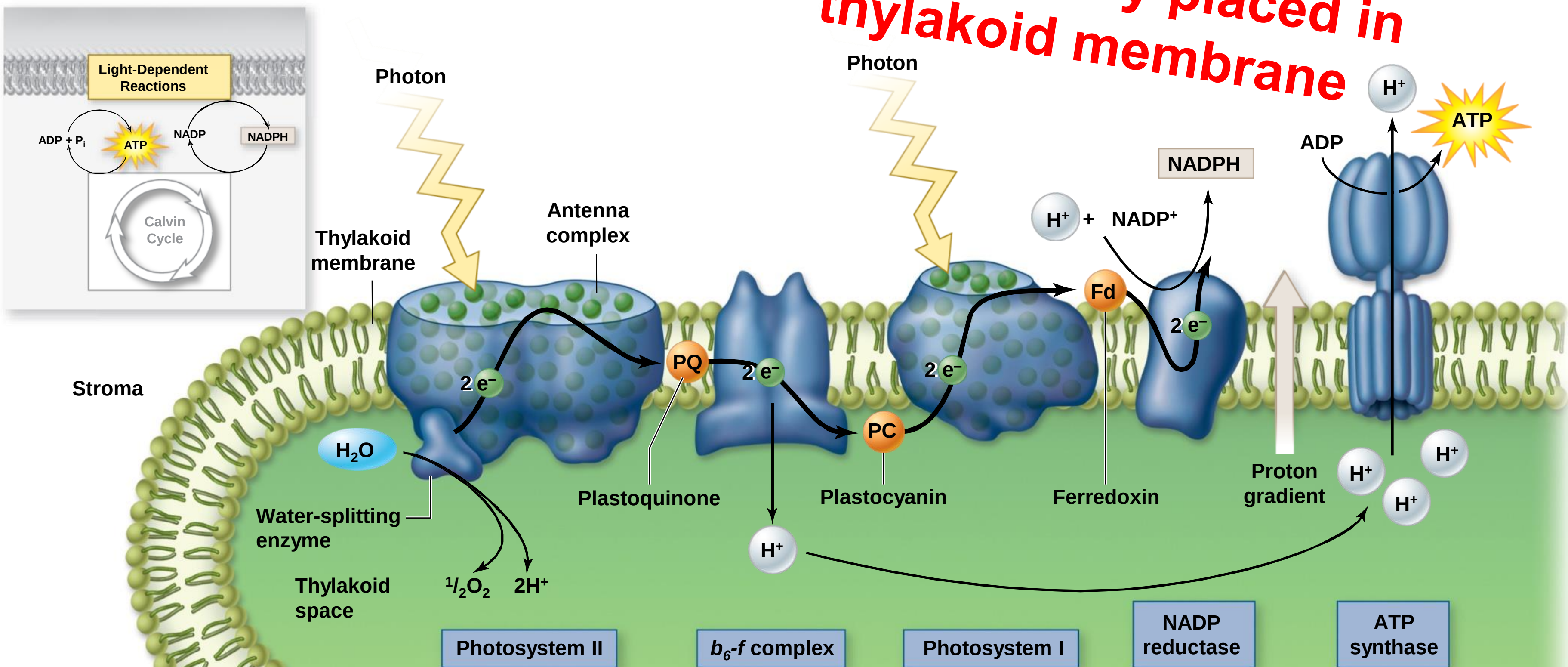
- Resembles the reaction center of purple bacteria
- Core of 10 transmembrane protein subunits with electron transfer components and two P_{680} chlorophyll molecules
- Reaction center differs from purple bacteria in that it also contains four manganese atoms
  - Essential for the oxidation of water
- b_6-*f* complex
  - Proton pump embedded in thylakoid membrane

Photosystem I

Optional

- Reaction center consists of a core transmembrane complex consisting of 12 to 14 protein subunits with two bound P_{700} chlorophyll molecules
- Photosystem I accepts an electron from plastocyanin into the “hole” created by the exit of a light-energized electron
- Passes electrons to $NADP^+$ to form NADPH

Nice summary placed in thylakoid membrane



1. Photosystem II absorbs photons, exciting electrons that are passed to plastoquinone (PQ). Electrons lost from photosystem II are replaced by the oxidation of water, producing O_2

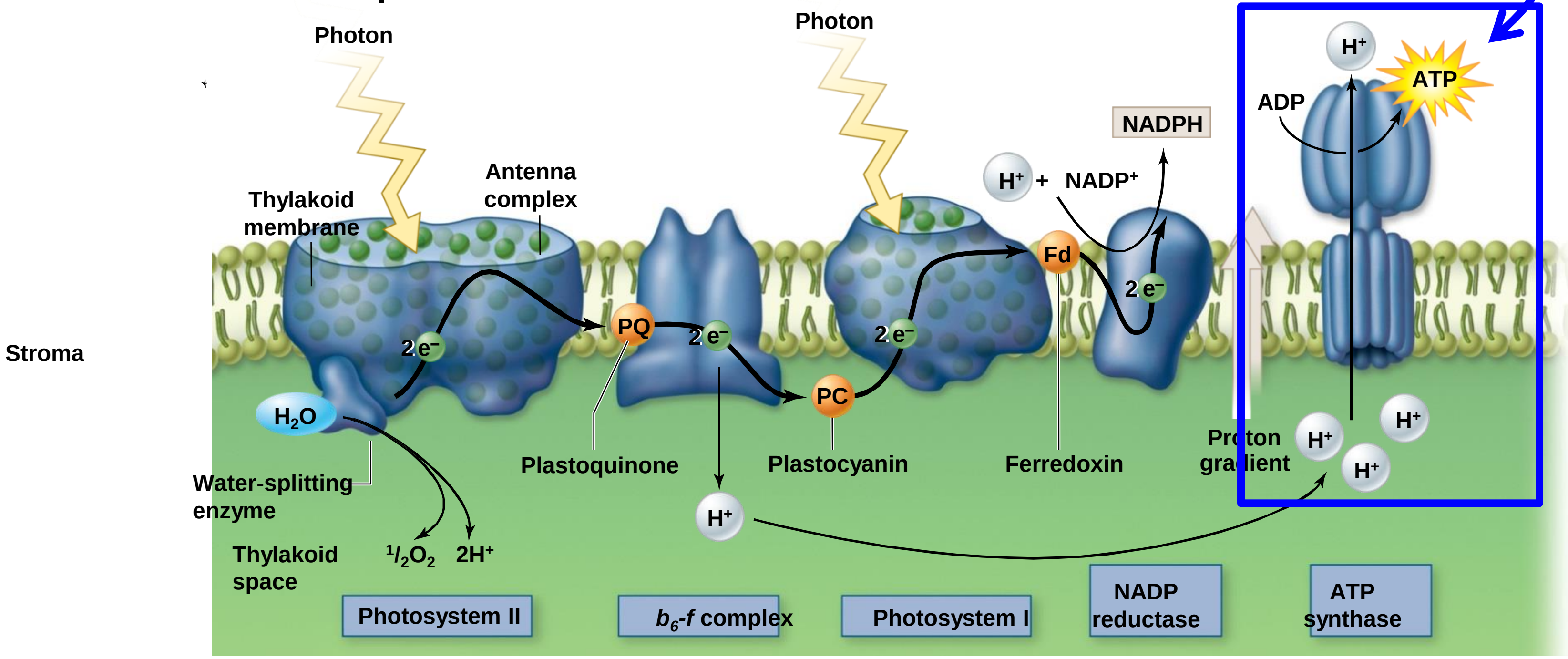
2. The b_6-f complex receives electrons from PQ and passes them to plastocyanin (PC). This provides energy for the b_6-f complex to pump protons into the thylakoid.

3. Photosystem I absorbs photons, exciting electrons that are passed through a carrier to reduce $NADP^+$ to NADPH. These electrons are replaced by electron transport from photosystem II.

4. ATP synthase uses the proton gradient to synthesize ATP from ADP and P_i enzyme acts as a channel for protons to diffuse back into the stroma using this energy to drive the synthesis of ATP.

Chemiosmosis

- Electrochemical gradient can be used to synthesize ATP (ETC between photosystems)
- Chloroplast has ATP synthase enzymes in the thylakoid membrane to produce ATP
  - Allows protons back into stroma

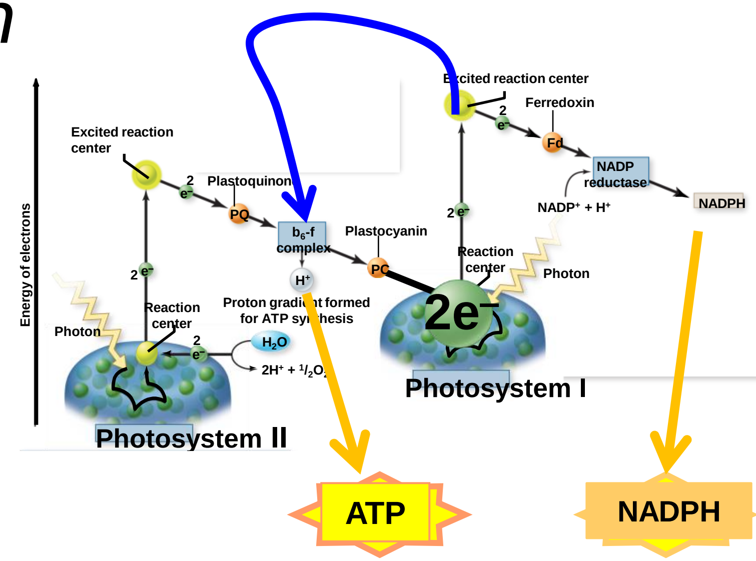


Production of additional ATP

- *Noncyclic photophosphorylation* *<u>generates both</u>*…
  - **NADPH**
  - **ATP**

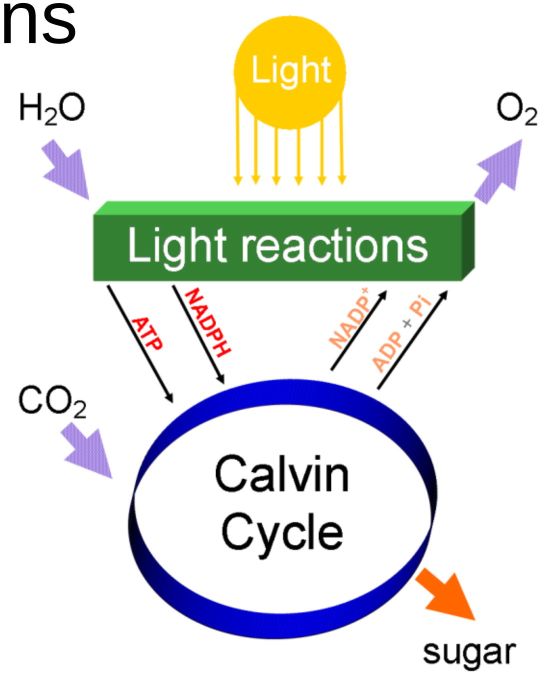
In equal amounts

- Building organic molecules takes more energy than that alone
- *Cyclic photophosphorylation* used to produce *<u>additional ATP</u>*
  - Short-circuit photosystem I to make a larger proton gradient to make more ATP



8.6 Carbon Fixation – Calvin Cycle

- To build carbohydrates cells use…
- Energy
  - ATP from light-dependent reactions
  - Cyclic and noncyclic photophosphorylation
  - Drives endergonic reaction



- Reduction potential
  - NADPH from photosystem I
  - Source of protons & energetic electrons

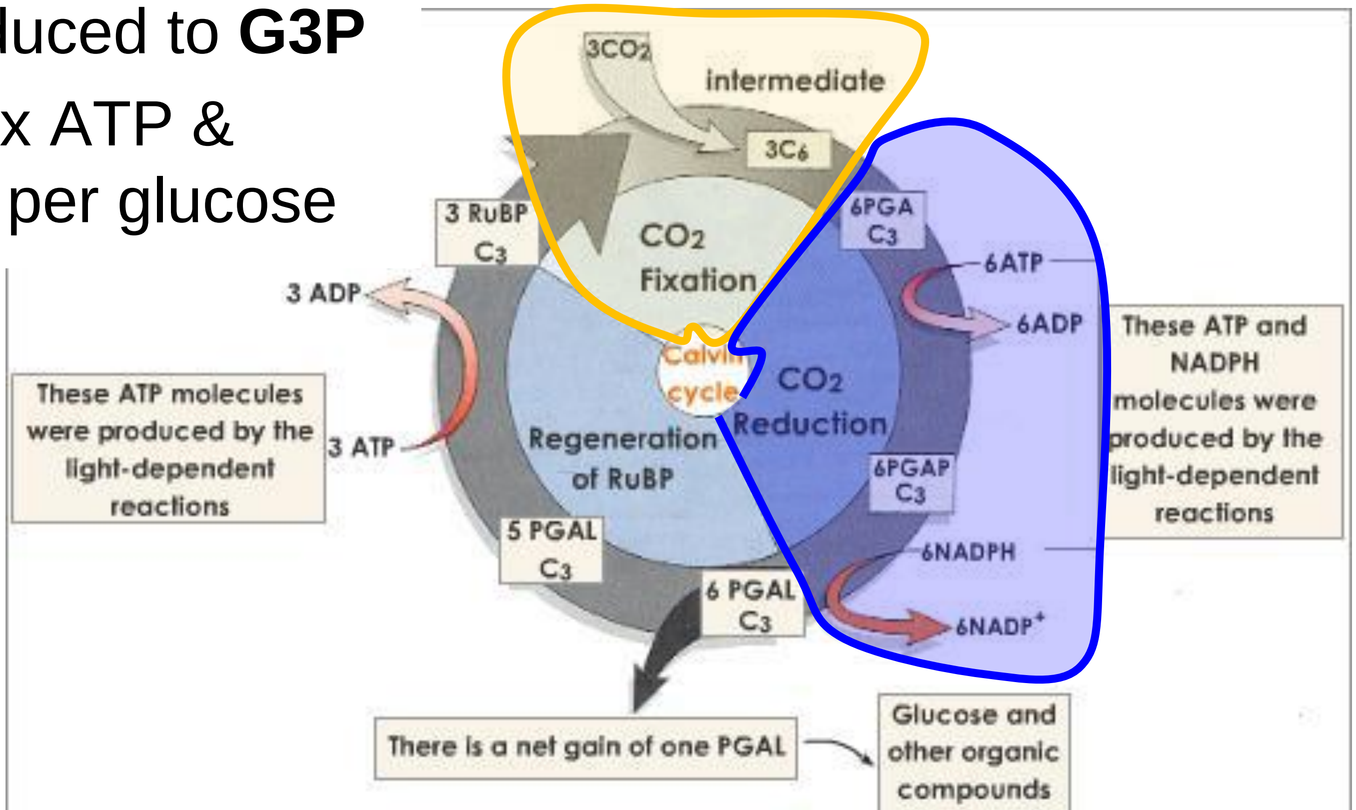
http://shappellecology.blogspot.com/2012/03/calvin-cycle-clarification.html

Calvin Cycle

- Named after Melvin Calvin (1911–1997)
- Also called **C_3 photosynthesis**
- Key step is attachment of CO_2 to **RuBP** to form **PGA**
- Uses enzyme **rubisco** (a.k.a. ribulose bisphosphate carboxylase/oxygenase)

Three Phases of Calvin Cycle

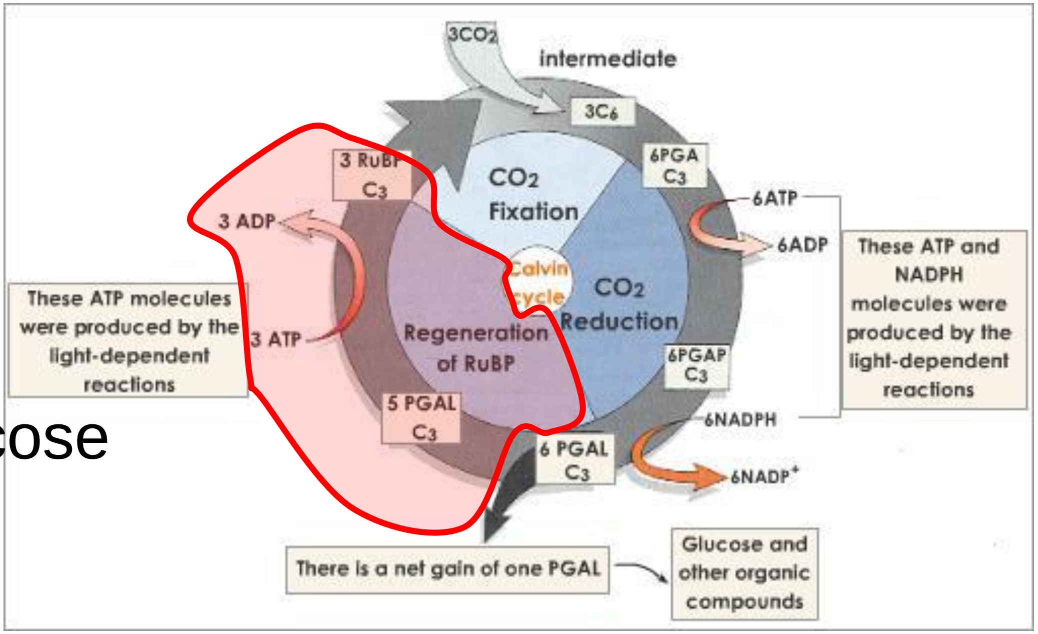
1. **Carbon fixation**
   - **RuBP** + **CO_2** → PGA
2. **Reduction**
   - PGA reduced to **G3P**
   - Uses 12x ATP & NADPH per glucose



http://www.tutorvista.com/content/biology/biology-ii/nutrition/photosynthesis-steps.php

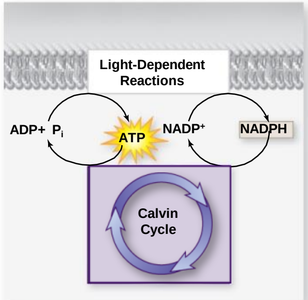
Three Phases of Calvin Cycle

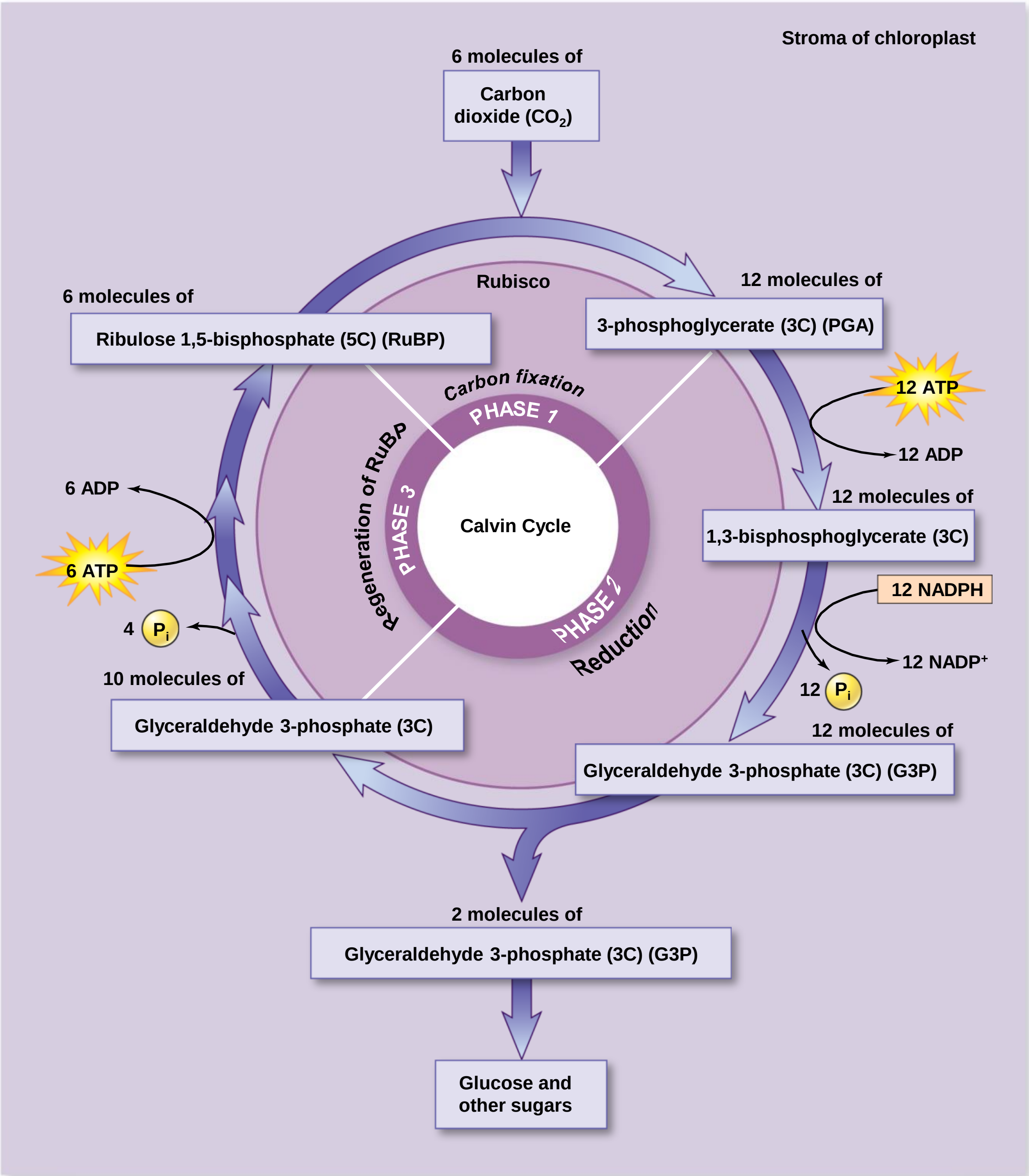
1. **Regeneration of RuBP**
   – PGA is used to regenerate RuBP
   – Use 6 ATPs per glucose



- 3 turns incorporate enough carbon to produce a new G3P
- 6 turns incorporate enough carbon for 1 glucose

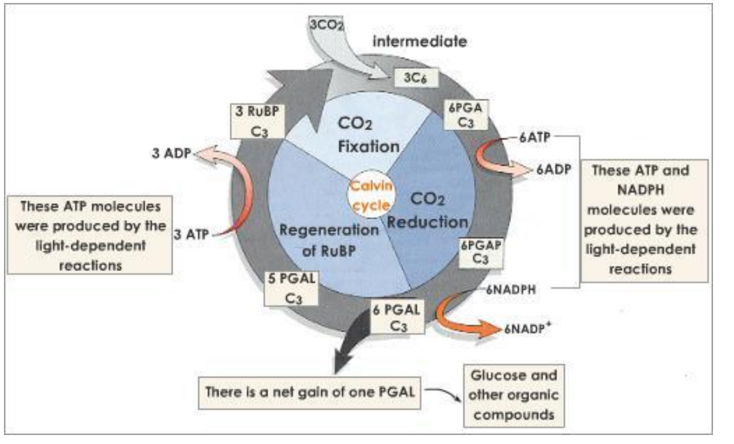
http://www.tutorvista.com/content/biology/biology-ii/nutrition/photosynthesis-steps.php


Light-Dependent Reactions
ADP+ Pi
ATP
NADP+
NADPH
Calvin Cycle


Stroma of chloroplast
6 molecules of
Carbon dioxide (CO2)
Rubisco
12 molecules of
3-phosphoglycerate (3C) (PGA)
6 molecules of
Ribulose 1,5-bisphosphate (5C) (RuBP)
Carbon fixation
PHASE 1
12 ATP
12 ADP
12 molecules of
1,3-bisphosphoglycerate (3C)
Regeneration of RuBP
PHASE 3
Calvin Cycle
6 ADP
6 ATP
4 Pi
PHASE 2
Reduction
12 NADPH
12 NADP+
12 Pi
10 molecules of
Glyceraldehyde 3-phosphate (3C)
12 molecules of
Glyceraldehyde 3-phosphate (3C) (G3P)
2 molecules of
Glyceraldehyde 3-phosphate (3C) (G3P)
Glucose and other sugars

Output of Calvin Cycle

- *<u>Glucose is not a direct product</u>* of the Calvin cycle, G3P is
- G3P is a 3 carbon sugar
  - Used to form sucrose
    - Major transport sugar in plants
    - Disaccharide made of fructose and glucose
  - Used to make starch
    - Insoluble glucose polymer
    - Stored for later use

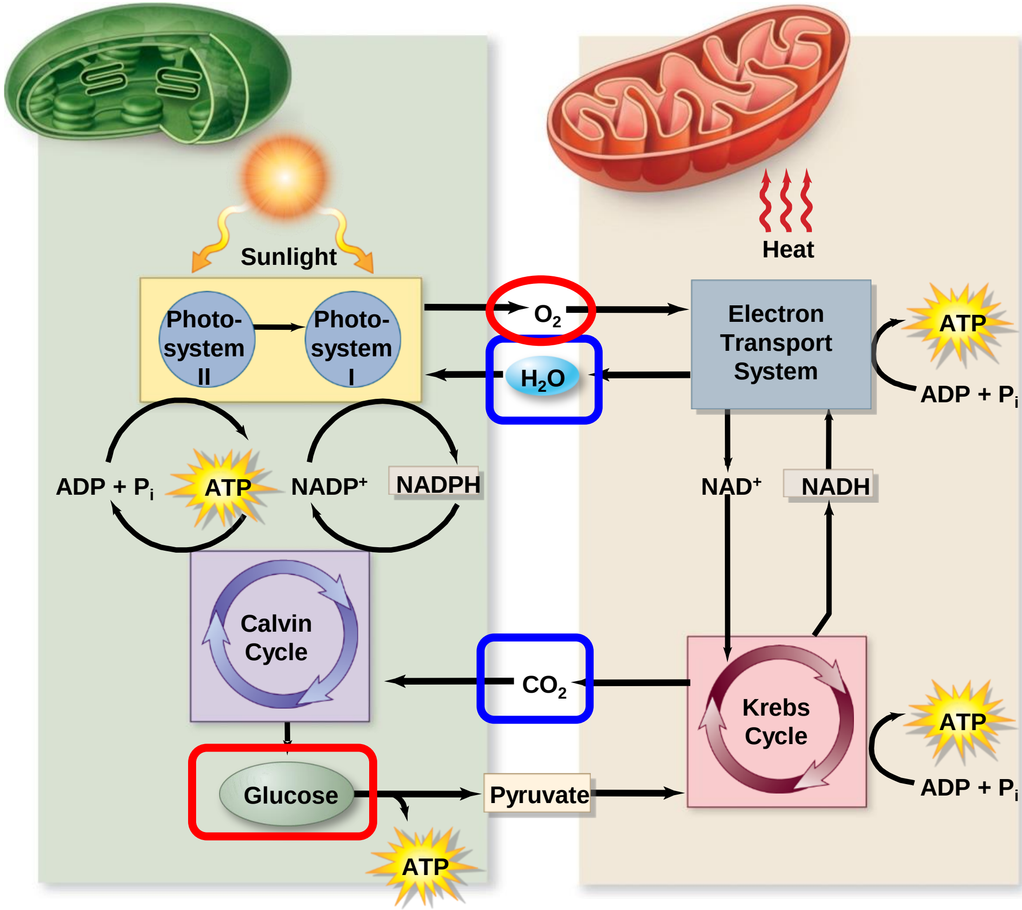


http://www.tutorvista.com/content/biology/biology-ii/nutrition/photosynthesis-steps.php

Energy Cycle

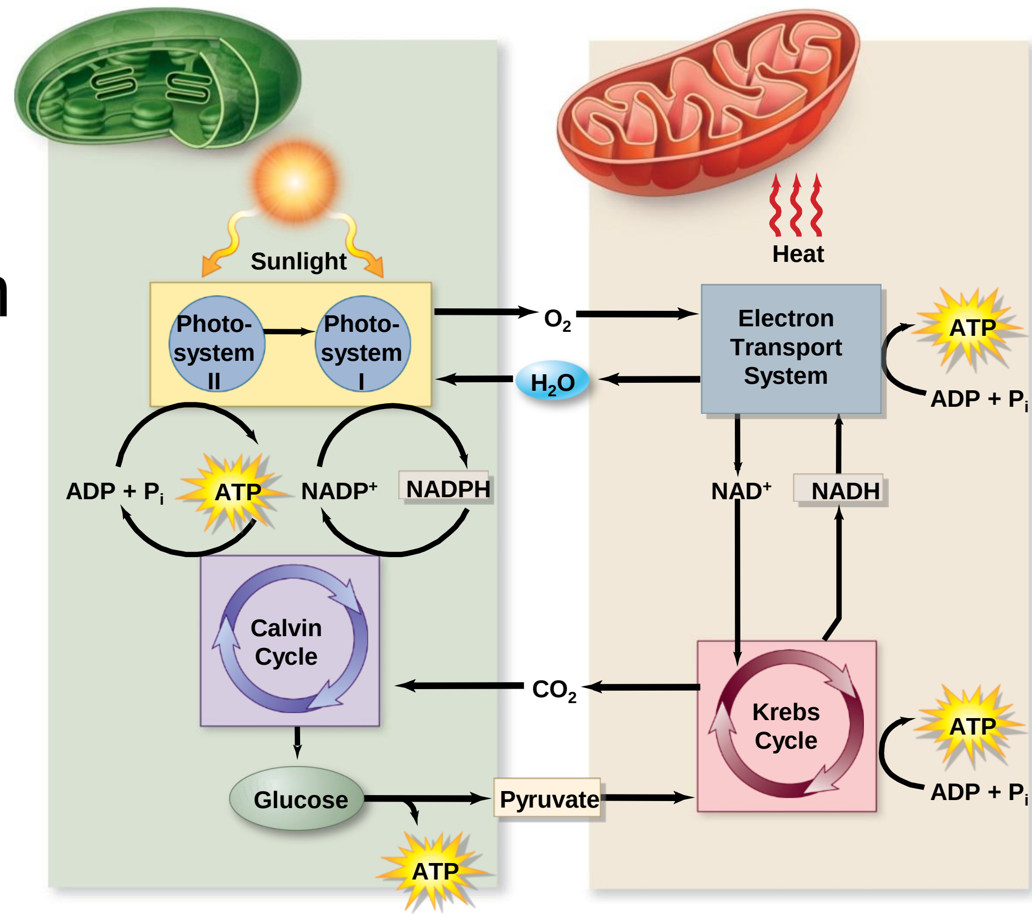
- Photosynthesis uses the products of respiration as starting substrates

- Respiration uses the products of photosynthesis as starting substrates

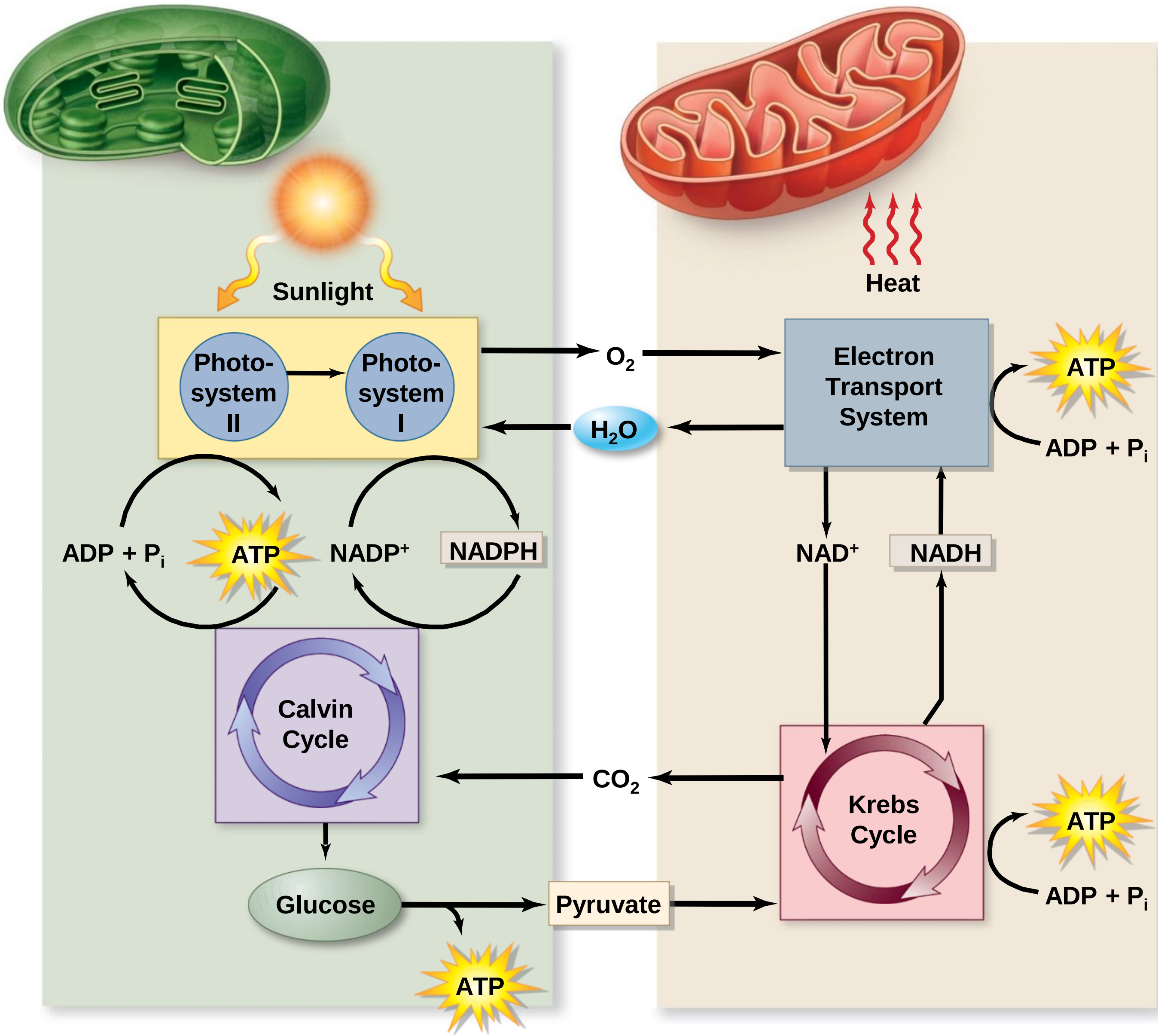


Energy Cycle

- Production of glucose from G3P even uses part of the ancient glycolytic pathway, run in reverse
- Principal proteins involved in electron transport and ATP production in plants are evolutionarily related to those in mitochondria

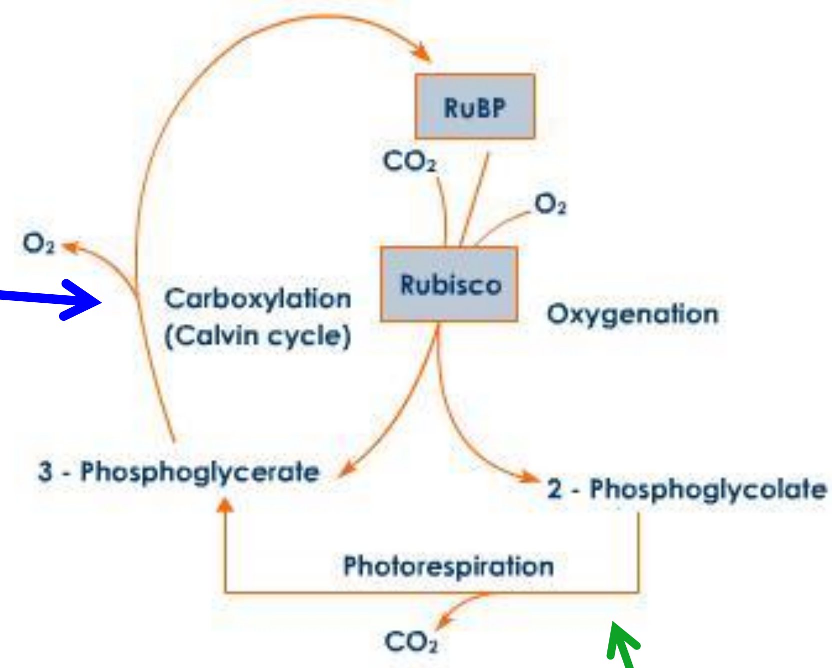


- Remember…plants use photosynthesis *and* respiration; animals only use respiration

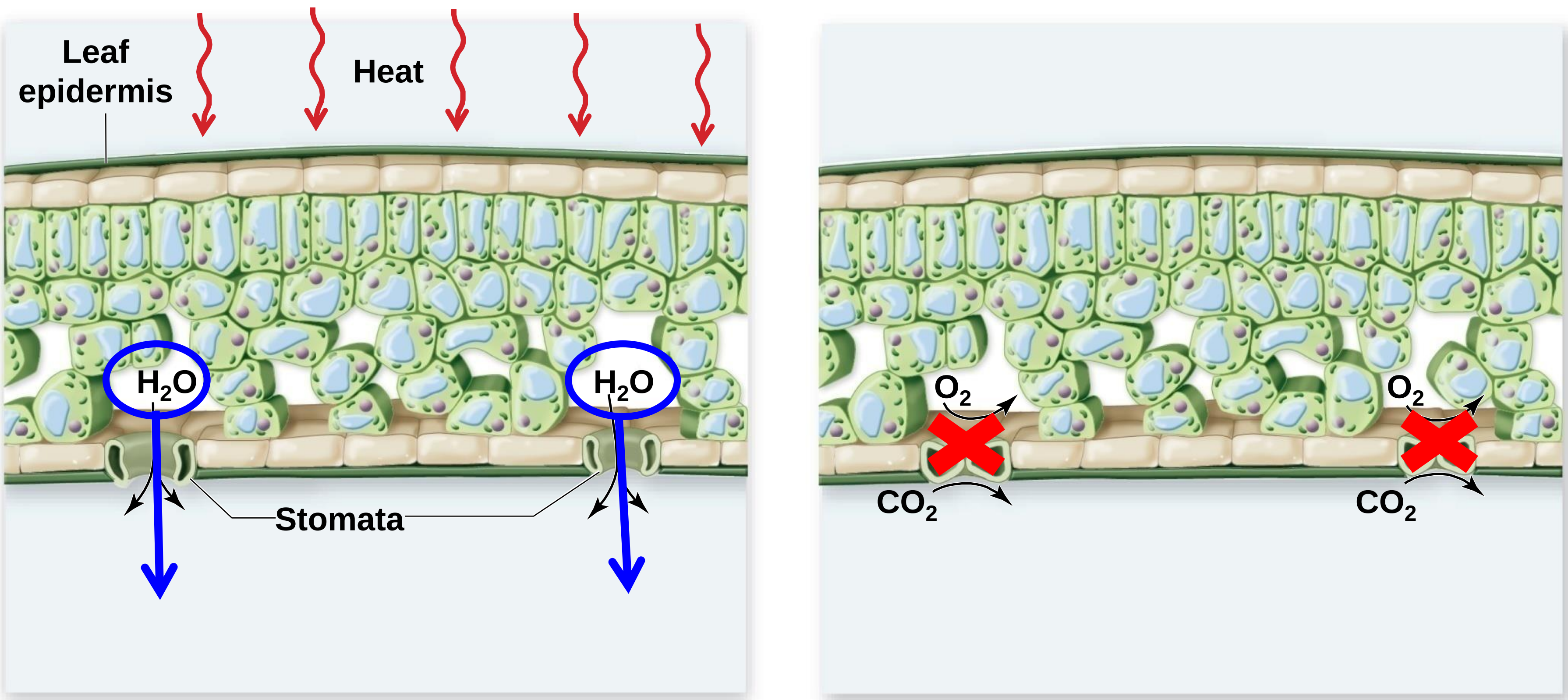


Photorespiration

- **Rubisco has 2** enzymatic **activities**
  - **Carboxylation**
    - Addition of CO_2 to RuBP
    - Favored under "normal" wet conditions
  - **Photorespiration**
    - Oxidation of RuBP by the addition of O_2
    - Favored when *stoma are closed in hot conditions* →creates low-CO_2 & high-O_2
    - CO_2 & O_2 compete for RuBP's active site
    - Photorespiration reduces carbohydrate yield of photosynthesis

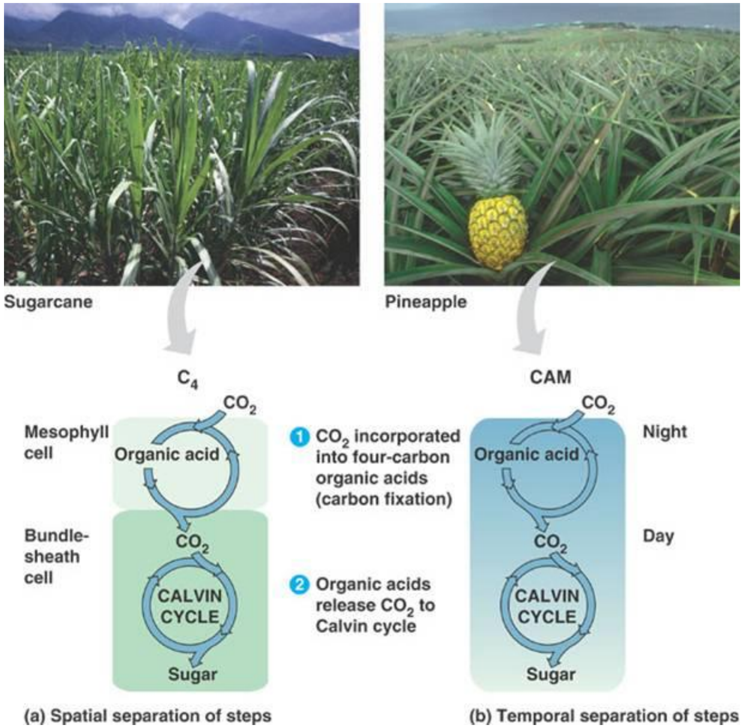


- Under hot, arid conditions, leaves lose water by evaporation through openings in the leaves called **stomata**
    - Stomata close to conserve water but as a result,…
    - O_2 builds up inside the leaves, and…
    - CO_2 cannot enter the leaves, favoring photorespiration



Many groups of plants have evolved other pathways to *reduce photorespiration*

- **C_4 plants**
  - Corn, sugarcane, many grasses
  - Separate C-fixation from Calvin cycle (rubisco) in bundle sheath cells
- **CAM plants**
  - Cacti, pineapple
  - Open stomata at night to reduce desiccation
  - Perform Calvin cycle in light



http://schoolworkhelper.net/c4-and-cam-plants/