

Chapter 7

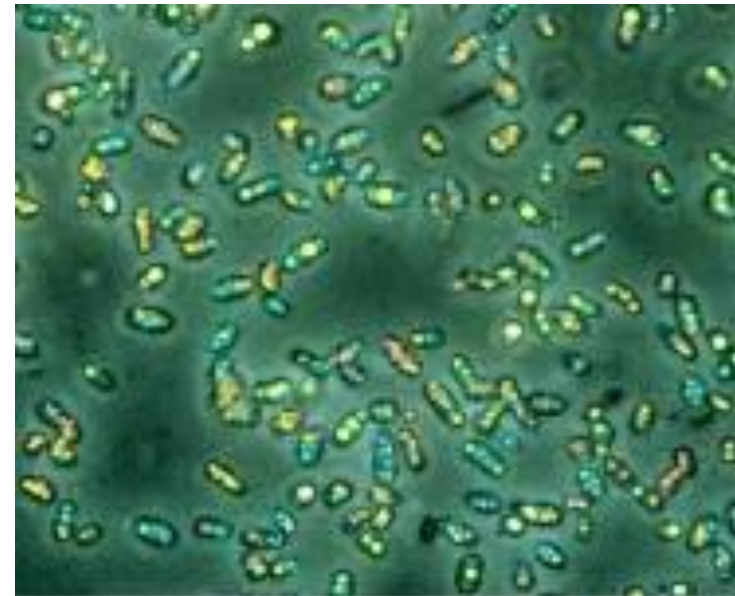
Photosynthesis: The Light Reactions

Outline

- History and intro
- Properties of light and pigments
- Light-dependent reactions
 - photosystem II and I
 - ATP synthesis
- Light-independent reactions
 - Calvin cycle
 - Rubisco and photorespiration
 - CAM and C₄ plants
- Physiological and ecological considerations
 - light
 - plant anatomy
 - plant responses
 - excess light and photoinhibition
 - greenhouse effect and consequences

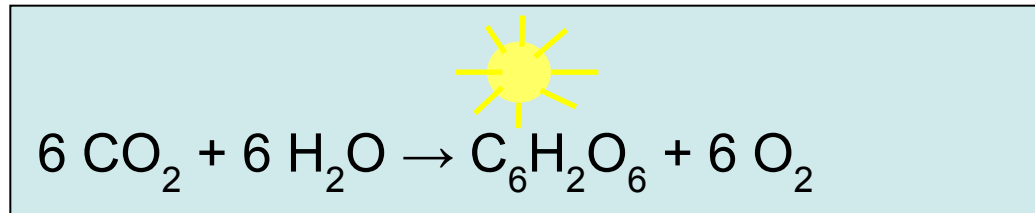
History

- 1600's **van Helmont** - soil alone does not nourish plant
- 1700's **Priestley** - plants restore air from burning candles
- 1700's **Ingenhousz** - only green parts of plants restore air, suggests CO_2 split to release O_2
- 1931 **van Niel** - Ps in purple sulfur bacteria produced S_2 instead of O_2 during Ps thus proposed O_2 released from Ps comes from H_2O , not CO_2
- 1937 **Hill** - isolated chloroplasts produced O_2 w/o CO_2 confirming O_2 released from Ps comes from H_2O , not CO_2
- 1905 **Blackman** - Ps composed of light-dep. + light-indep. rxns, enzymes involved

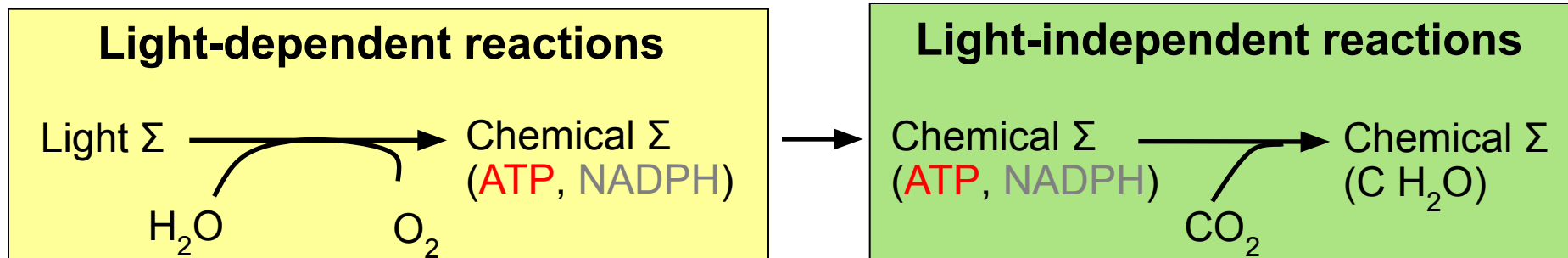


Intro

- **Photosynthesis** (Ps) = process by which plants convert sunlight into chemical Σ , how Σ enters biosphere
 - chemical Σ used to convert water and CO_2 into sugars, O_2 is produced as byproduct



- Consists of light-dependent + light-independent rxns

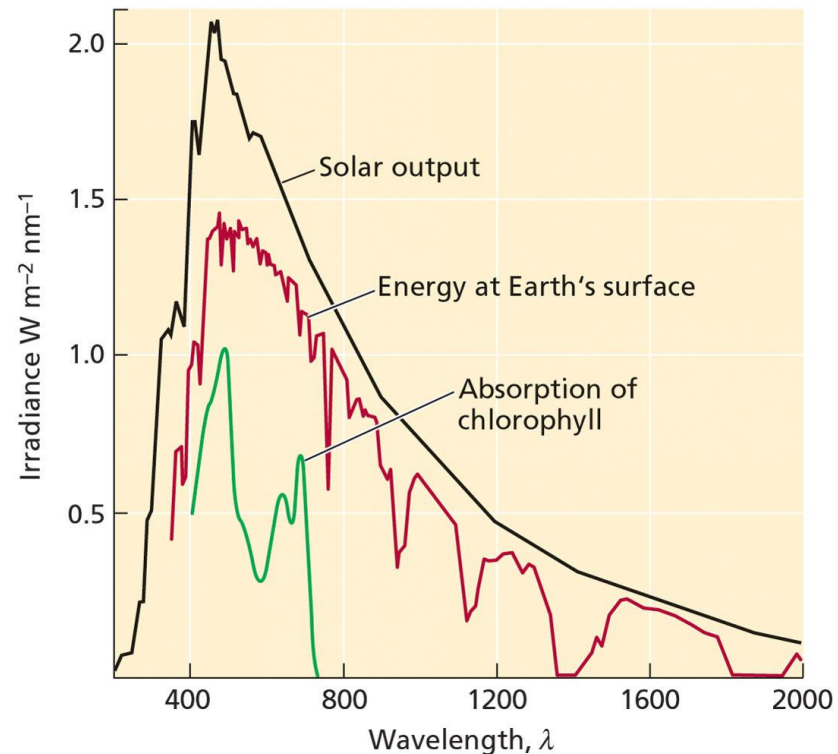


Intro

- Light-dependent rxns (a.k.a) light rxns, thylkoid rxns, light-transduction rxns
 - require light, occur on thylakoid membranes
 - split water (oxidize water to O₂)
 - produce NADPH, ATP (via PMF)
 - uses 2 photosystems
- Light-independent rxns (a.k.a) dark rxns, carbon fixation rxns, stroma rxns, Calvin cycle
 - don't require light, occur in chloroplast stroma
 - use ATP, NADPH
 - produce reduced carbon cmpds (i.e. glucose) from CO₂
- Ps primarily occurs in leaf mesophyll cells
 - mesophyll contains lots of chloroplasts

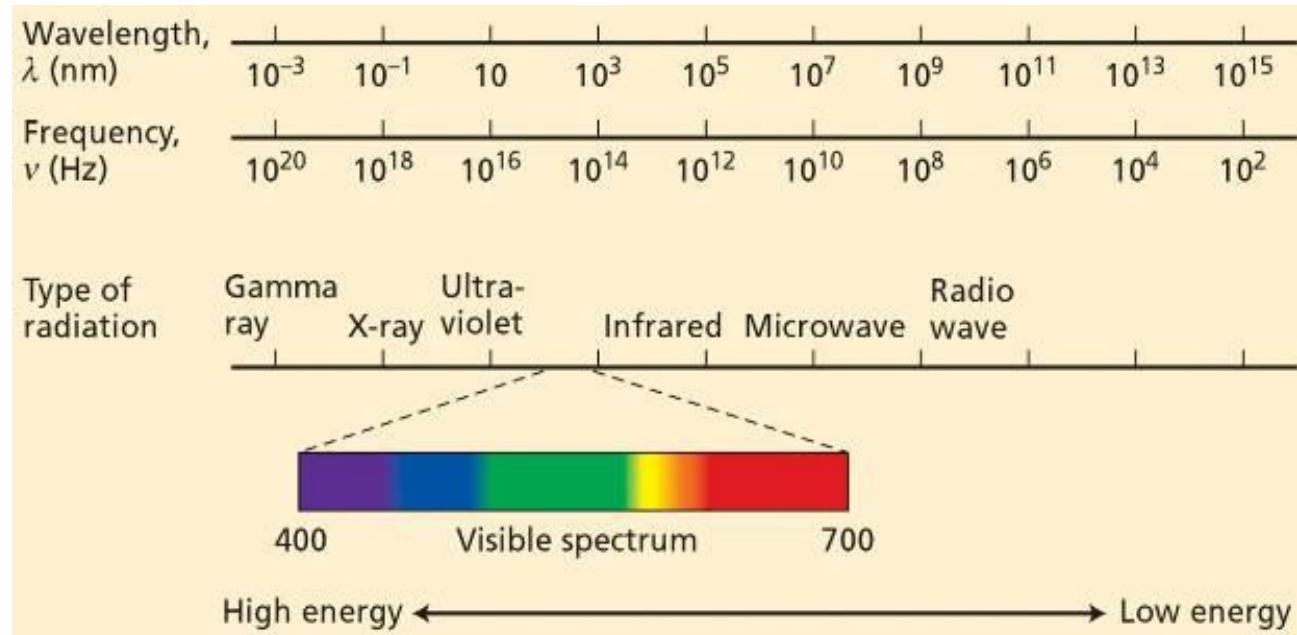
Properties of Light

- Light travels in waves
 - **wavelength** (λ) = distance btwn 2 crests
 - **frequency** (ν) = # of wave crests that pass a pt in a given time
$$c = \lambda \nu \quad \text{where: } c = \text{wave speed, } c_{\text{light}} = 3.0 \times 10^8 \text{ m s}^{-1}$$
- Light composed of particles of Σ (**photons**)
 - Σ contained in discrete packets (**quantum**)
 - Σ of photon inversely proportional to frequency
$$E = h\nu \quad \text{where: } \nu = \text{frequency of light}$$
$$h = \text{Planck's constant} = 6.626 \times 10^{-34} \text{ J s}$$



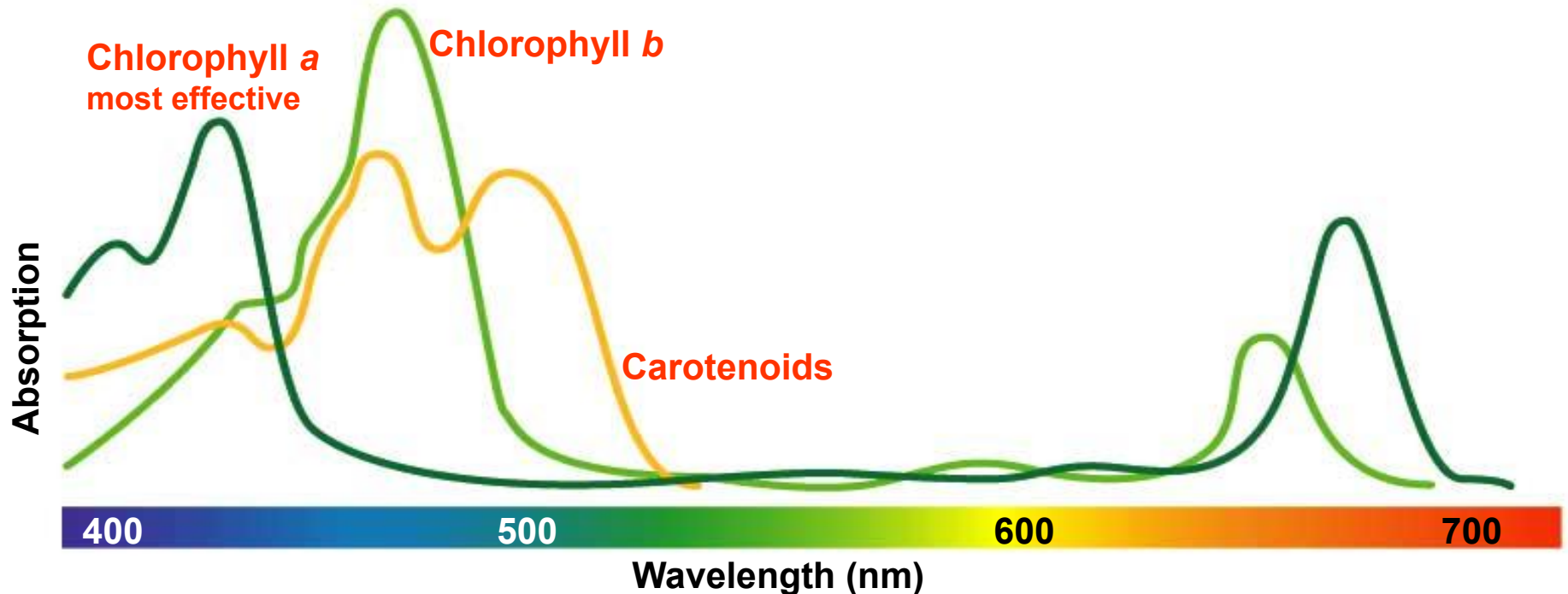
Properties of Light

- **Electromagnetic spectrum** = entire range of radiation
 - **visible spectrum** = what we can see
 - each wavelength has particular amnt Σ
 - shorter wavelength = $\uparrow \Sigma$ (violet)
 - longer wavelength = $\downarrow \Sigma$ (red)
 - UV has $\uparrow \Sigma$, infared has $\downarrow \Sigma$



Properties of Light

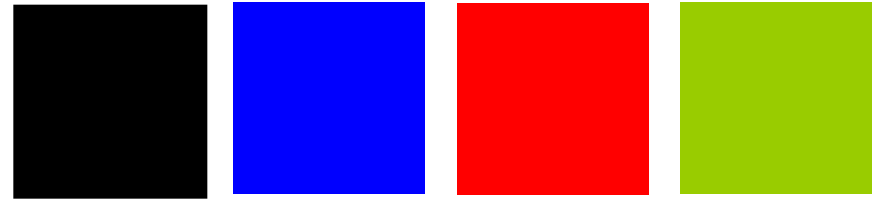
- **Absorption spectrum** = amount of light Σ absorbed by a substance as a func. of wavelength
 - chlorophyll a absorbs blue (430 nm) and red (660 nm) portion of spectrum
 - other pigments extend Ps useful portion of spectrum



Quantum Efficiency vs Energy Efficiency

- **Quantum efficiency** = fraction of absorbed photons that engage in photochemistry = 100%
 - **energy efficiency** = fraction of absorbed Σ that is stored as chemical products = 27%
 - other 73% converted to heat
 - of the 27%, most is used for R_m

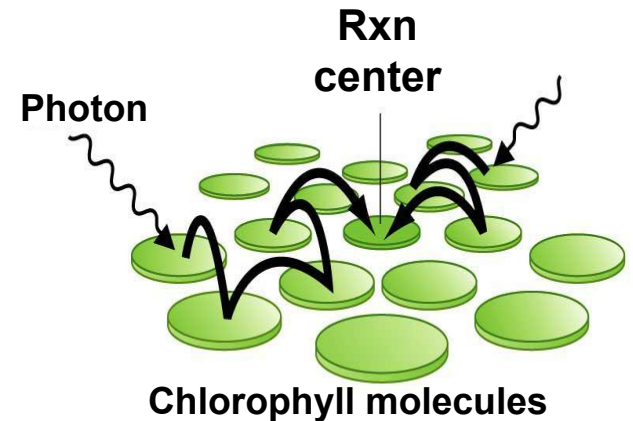
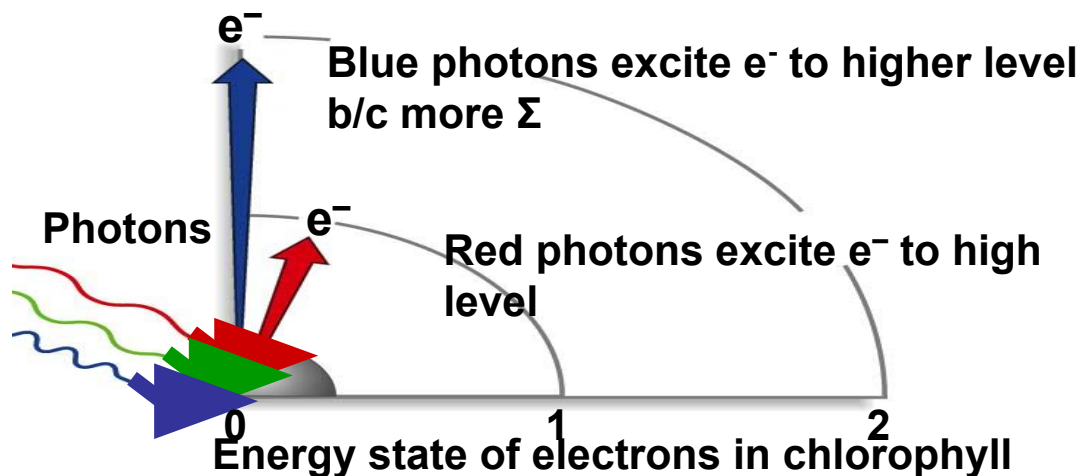
Pigments



- **Pigment** = substance that absorbs photons of light
 - photon hits pigment it can be absorbed, transmitted or reflected
 - we see transmitted or reflected
 - pigments absorb specific wavelengths of light = **absorption spectrum**
 - pigment absorbs all wavelengths in visible spectrum = black
 - pigment absorbs green and blue wavelengths but transmits or reflects red wavelengths = red (750 nm)
 - **chlorophyll** = reflects green, absorbs violet, blue and red
- **Action spectrum** = effectiveness of wavelengths

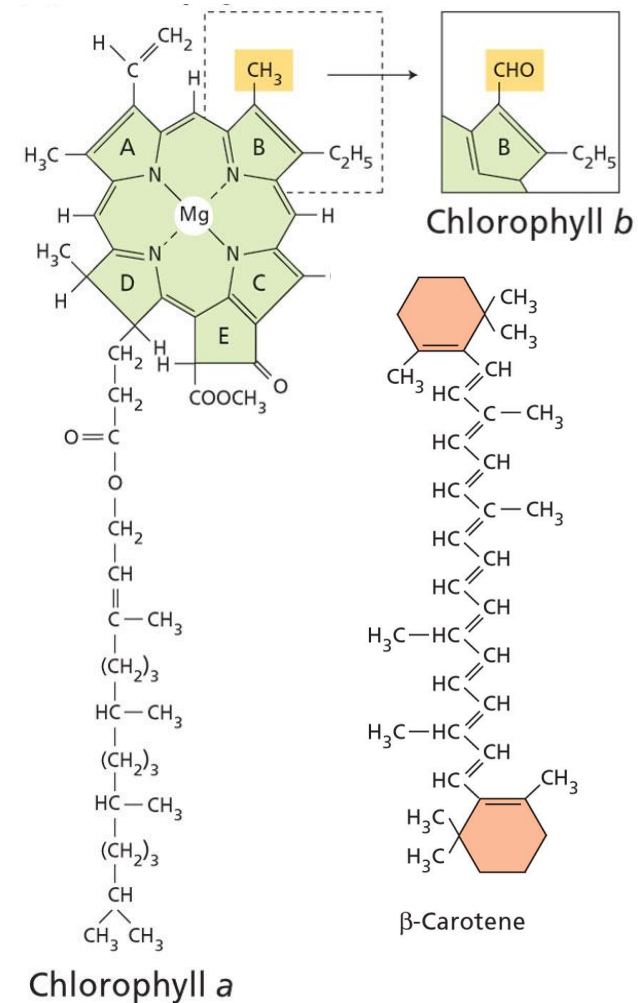
Pigments

- When photon hits pigment, e^- bumped to higher orbital (\uparrow potential Σ b/c further from nucleus) (**excited state**)
 - once e^- in higher orbital (unstable) it has 4 fates
 - re-emit photon and fall back to original position (**fluorescence** and **heat**)
 - convert Σ to heat
 - transfer Σ to another chlorophyll until reaches **reaction center** (a.k.a. **resonance energy transfer**)
 - transfer Σ to other chemical rxns in ETS



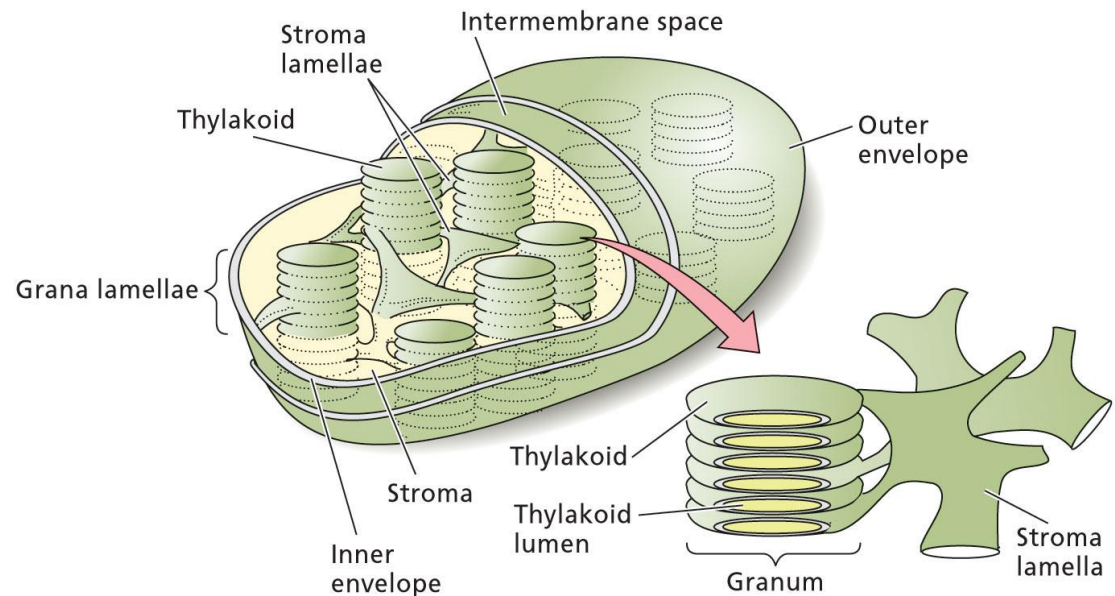
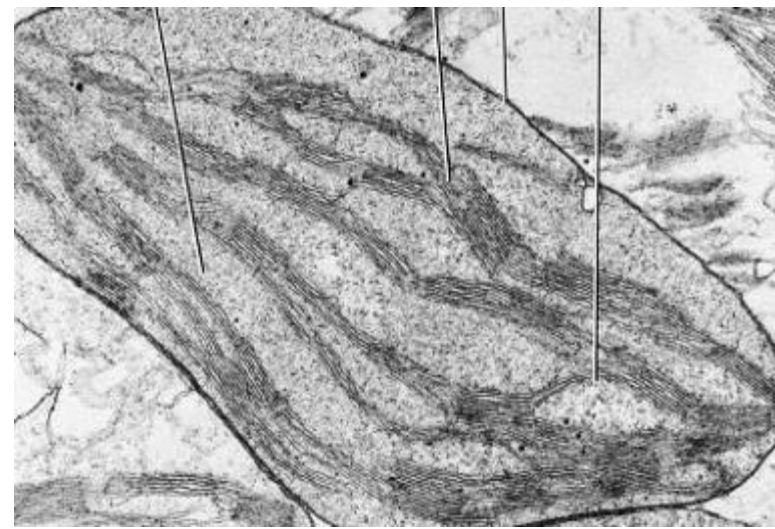
Pigments

- All Ps pigments found in chloroplast
 - primary photosynthetic pigment = **chlorophyll a**
 - must have chl. a
 - ring structure w/ Mg
 - similar to hemoglobin
 - hydrophobic tail embedded in thylakoid membrane
 - **chl. b**, **carotenoids** and **phycobilins** are accessory pigments
 - **accessory pigments** = not directly involved in Σ transduction, pass Σ to chl. a which transforms it to chemical Σ , extend useful spectrum, antioxidant func.
 - carotenoids = red/orange/yellow, embedded in thylakoid, fall color
 - 2 types carotenoids - **carotene** and **xanthophyll**



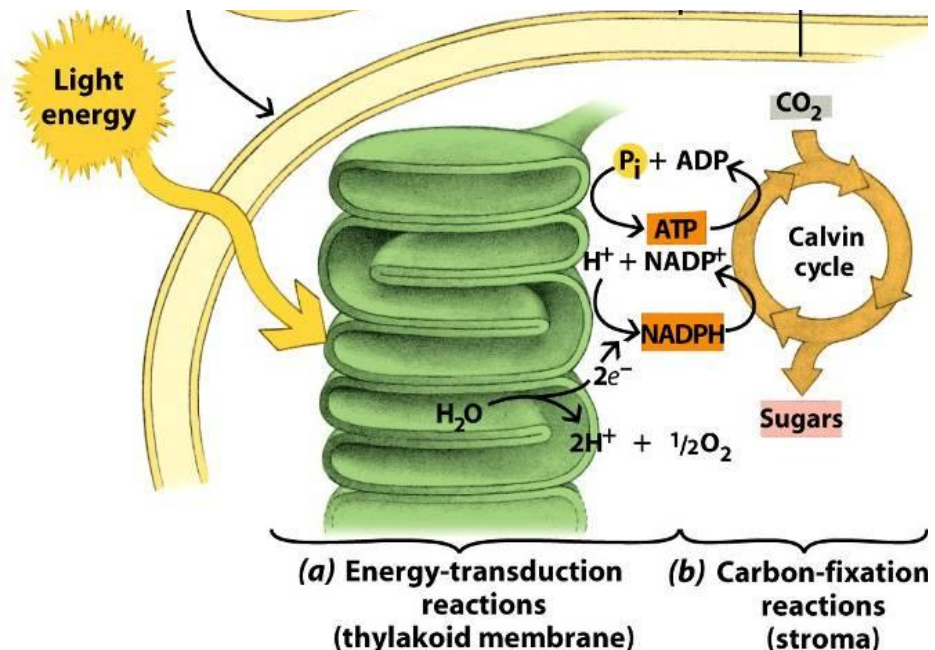
Anatomy

- Ps occurs in chloroplast
 - double-membrane, DNA, RNA, ribosomes
 - extensive 3rd membrane = **thylakoid membrane**
 - chlorophyll embedded (light-dep. rxns)
 - **stroma** (light-indep. rxns)
 - **grana lamellae** (PS II)
 - **stroma lamellae** (PS I)
 - **granum**
 - **lumen**



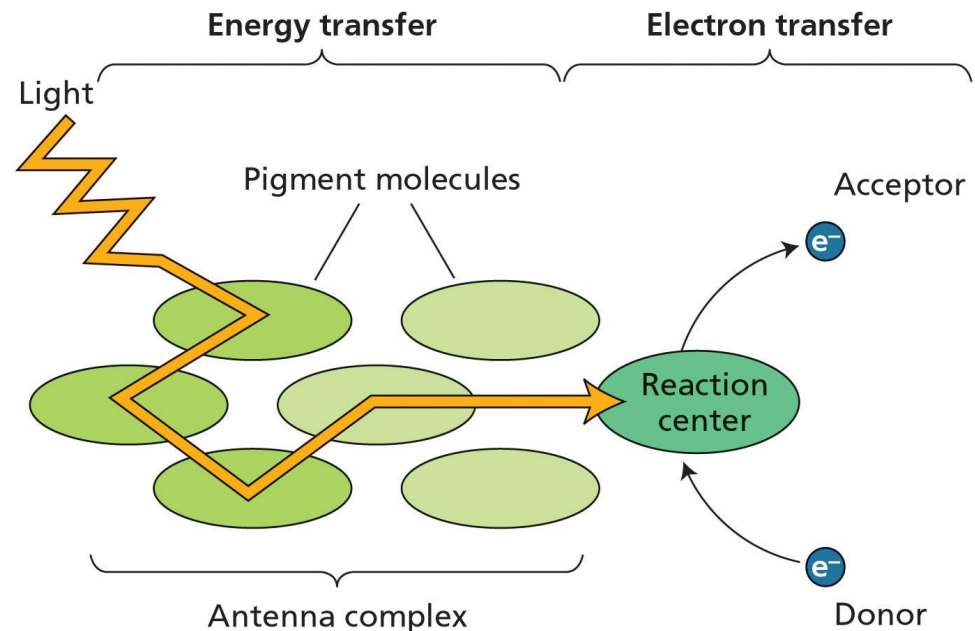
Overview of Photosynthesis

- 2 main events of Ps (+50 rxn steps in Ps discovered)
 - light-dependent rxns
 - light Σ transferred to chemical bond in ADP and reduction of NADP^+ , forming ATP and NADPH
 - thylakoid membranes
 - light-independent rxns
 - ATP used to link CO_2 to organic molecule
 - NADPH used to reduce to simple sugar
 - **carbon or CO_2 fixation** = conversion of CO_2 into organic cmpds
 - stroma



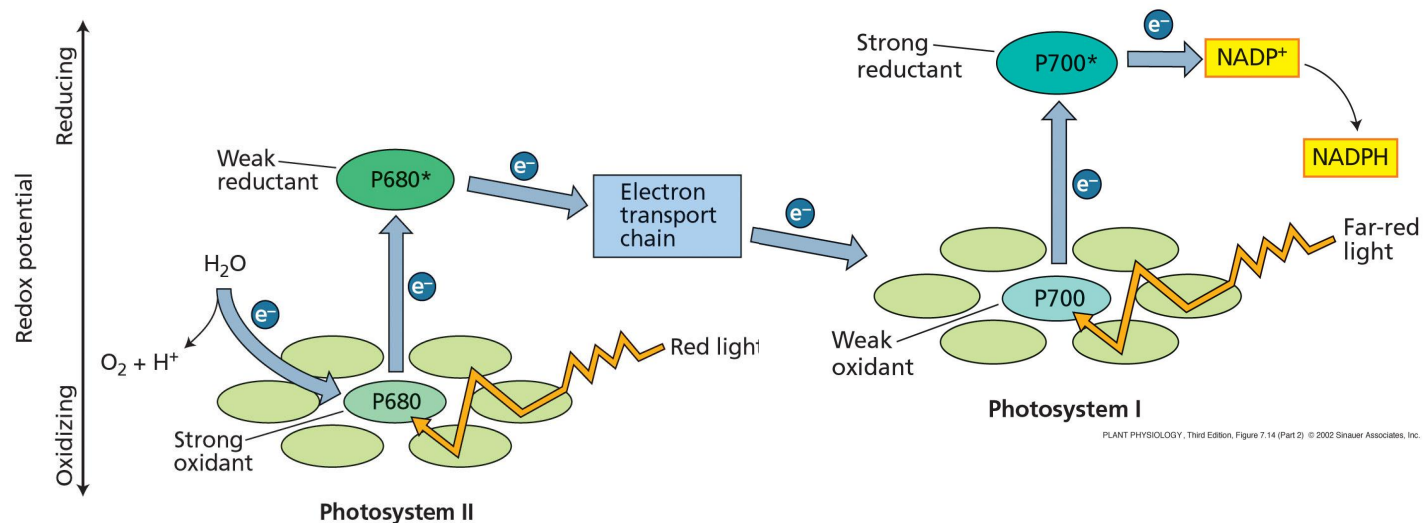
Antenna Complex and Reaction Center

- Most pigments serve as antenna
 - **antenna** collect light and transfer its Σ to reaction center
 - **antenna complex** = group of antenna molecules
 - means of increasing efficiency
 - integral proteins
 - **reaction center complex** = Σ is stored by transferring e^- from chlorophyll to e^- acceptor (REDOX rxns)
 - e^- boosted to higher orbital
 - integral proteins



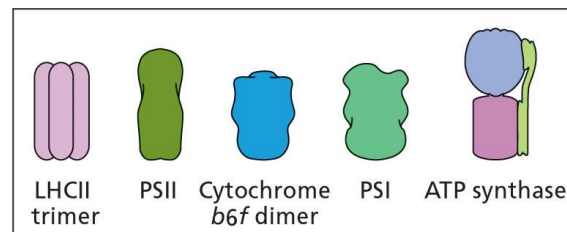
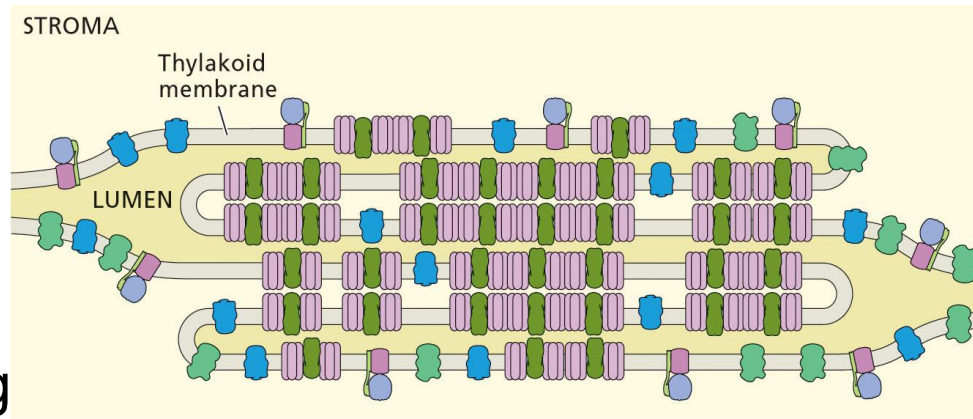
Photosystems I and II

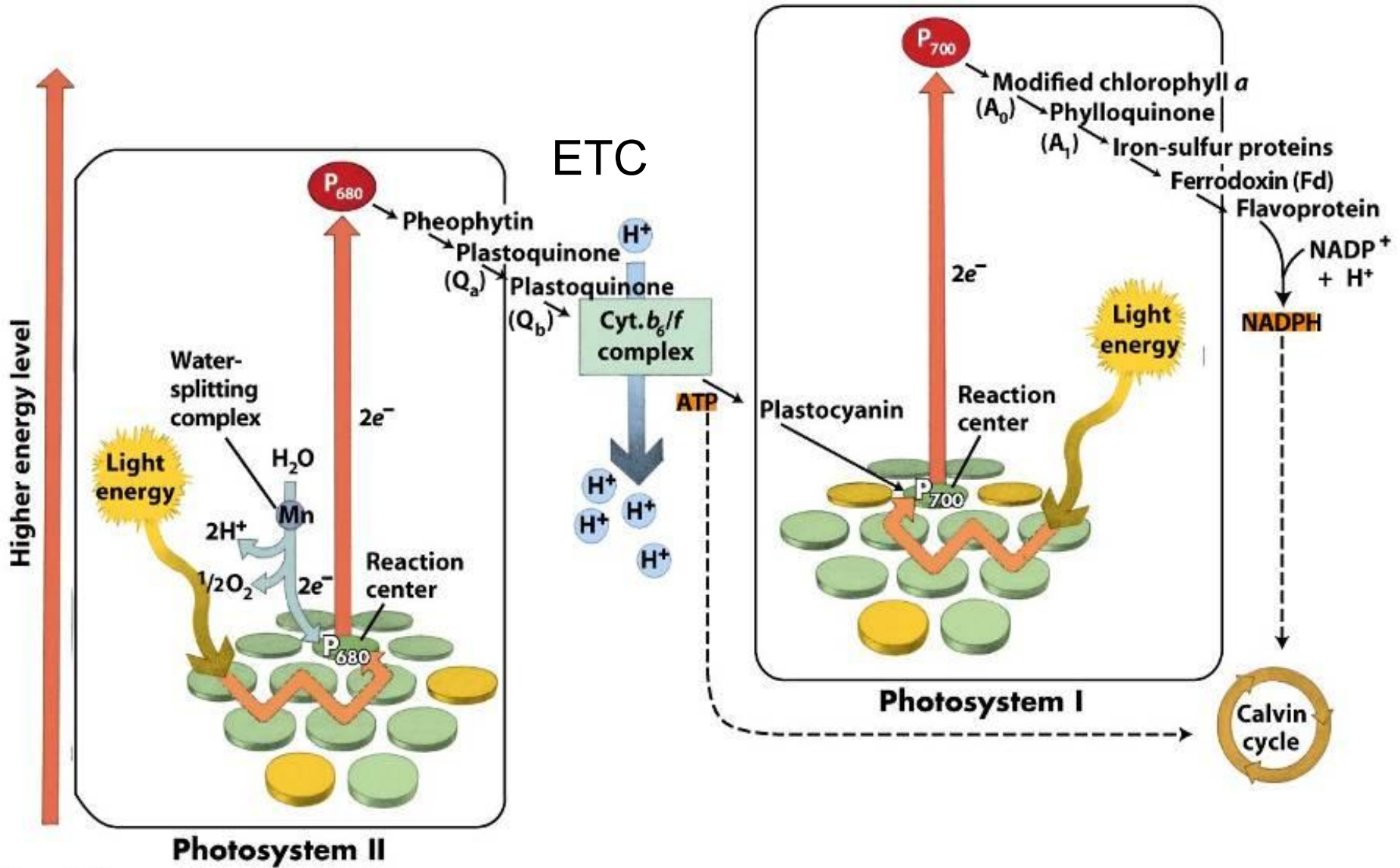
- **Enhancement effect** = Ps rate greater w/ red and far-red light together than w/ each separate
 - due to 2 photochemical complexes (photosystem I and II)
 - work in conjunction, independent antenna and rxn centers
 - linked by electron transport chain
- e^- flow = $H_2O \rightarrow PS II \rightarrow PS I \rightarrow NADP^+$ (Z scheme)
- **PSII** chl. *a* = P_{680} (red) vs **PSI** chl. *a* = P_{700} (far-red)

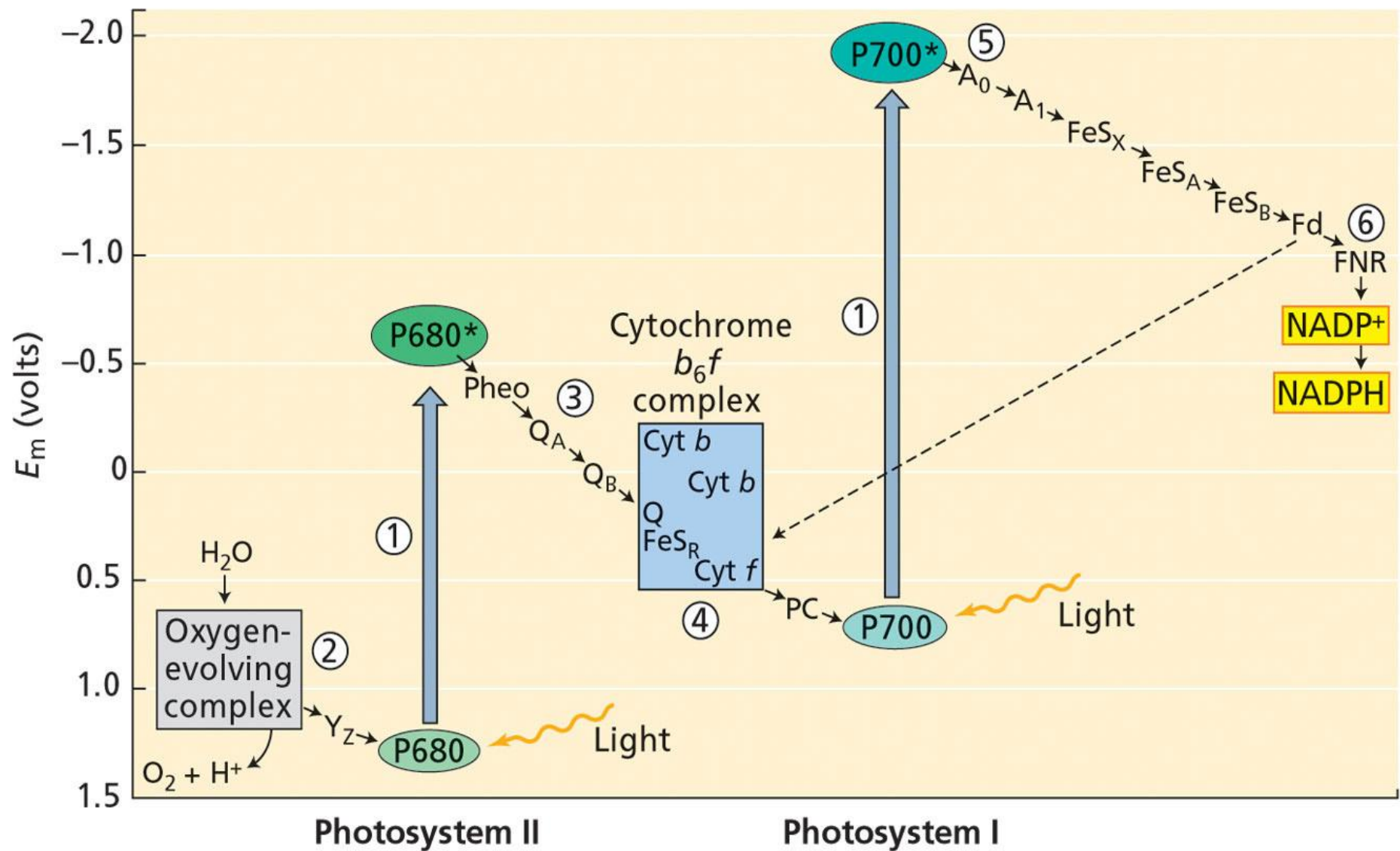


Photosystems I and II

- PS I and II spatially separated on thylakoid membrane
 - PS II on grana lamellae
 - PS I on stroma lamellae
 - ETC that connects PSII to PSI found throughout
 - PSII produces
 - $4 \text{ photons} + 2\text{H}_2\text{O} \rightarrow 4 \text{H}^+ + 4\text{e}^- + \text{O}_2$
(**photolysis**)
 - H^+ released in lumen (H^+ gradient)
 - increases efficiency b/c pool of reducers vs having to associate w/ single PS

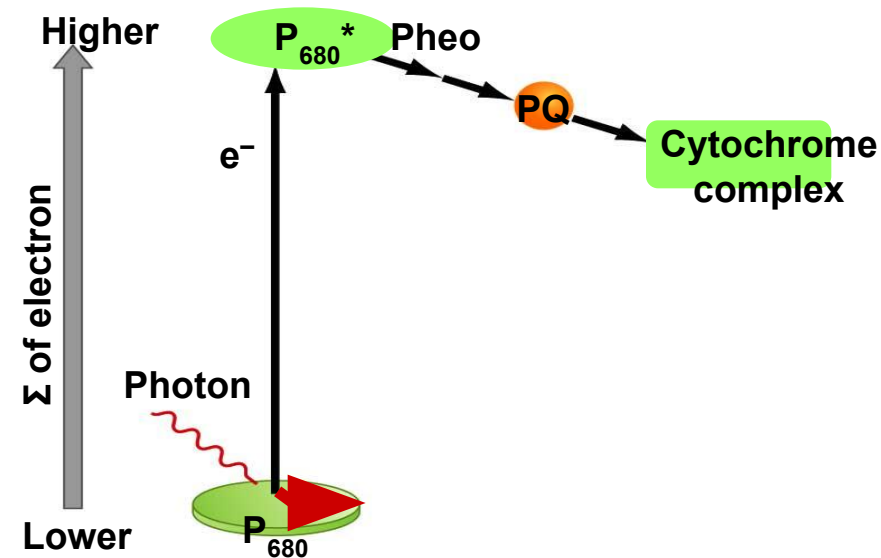






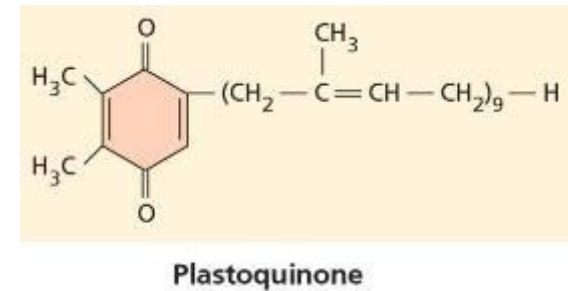
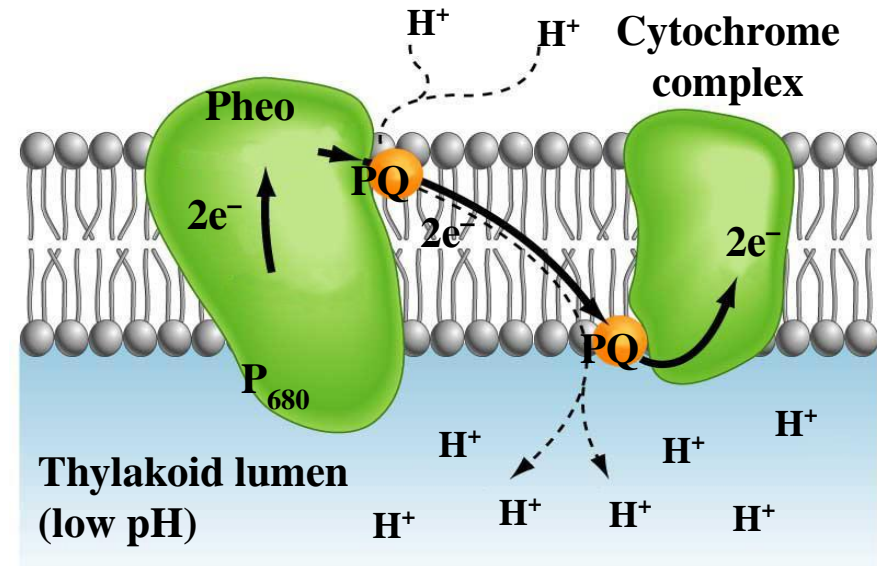
Photosystem II

- Photon absorbed by PS II
- e^- in P_{680} (chlorophyll) gets excited (P_{680}^*)
- e^- passed from P_{680}^* to Pheo (**pheophytin**)
 - e^- acceptor similar to chlorophyll but lacks a Mg, instead 2 H
 - P_{680} is oxidized as loses e^- to pheophytin
 - **NOTE:** P_{680} re-reduced by Y_z who got e^- from splitting (oxidation) water *this is where O_2 comes from!!!*
 - $4 \text{ photons} + 2\text{H}_2\text{O} \rightarrow 4 \text{ H}^+ + 4e^- + \text{O}_2$ (**photolysis**)
 - occurs in lumen (contributes to H^+ gradient (PMF) across thylakoid membrane)

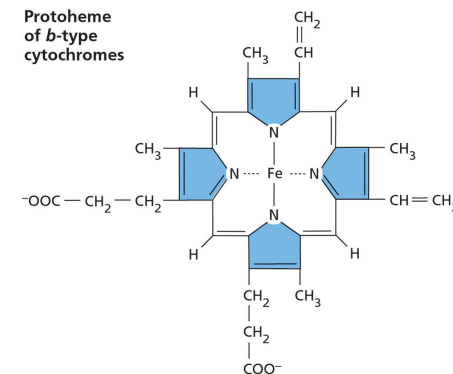


Photosystem II

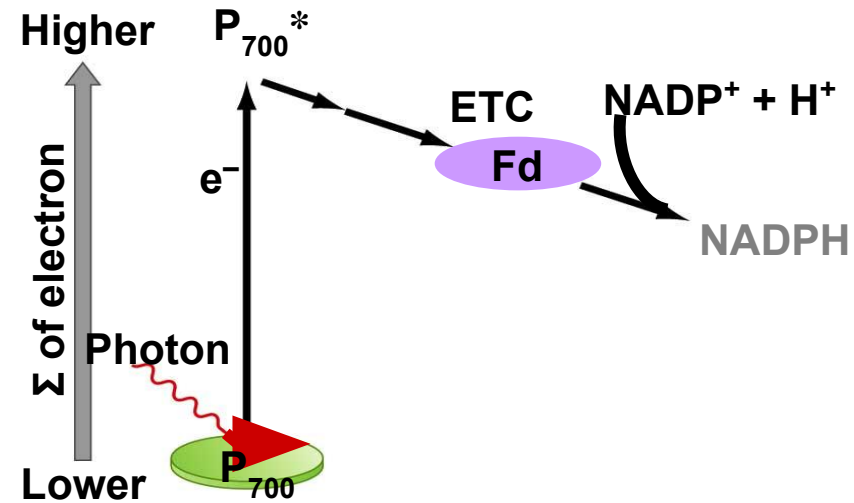
- e^- passed from Pheo to Q_A and Q_B (plastoquinones/PQ)
 - as e^- passed by Q_A and Q_B , H^+ pumped into thylakoid lumen thereby creating H^+ gradient (PMF) across thylakoid membrane
- e^- passed from PQ to **cytochrome b_6f complex**
 - large multisubunit protein w/ heme groups
- e^- passed from b_6f complex to **plastocyanin (PC)**
 - protein w/ copper
- e^- passed from PC to P_{700} (PS II)



Protoheme of b -type cytochromes



Photosystem I



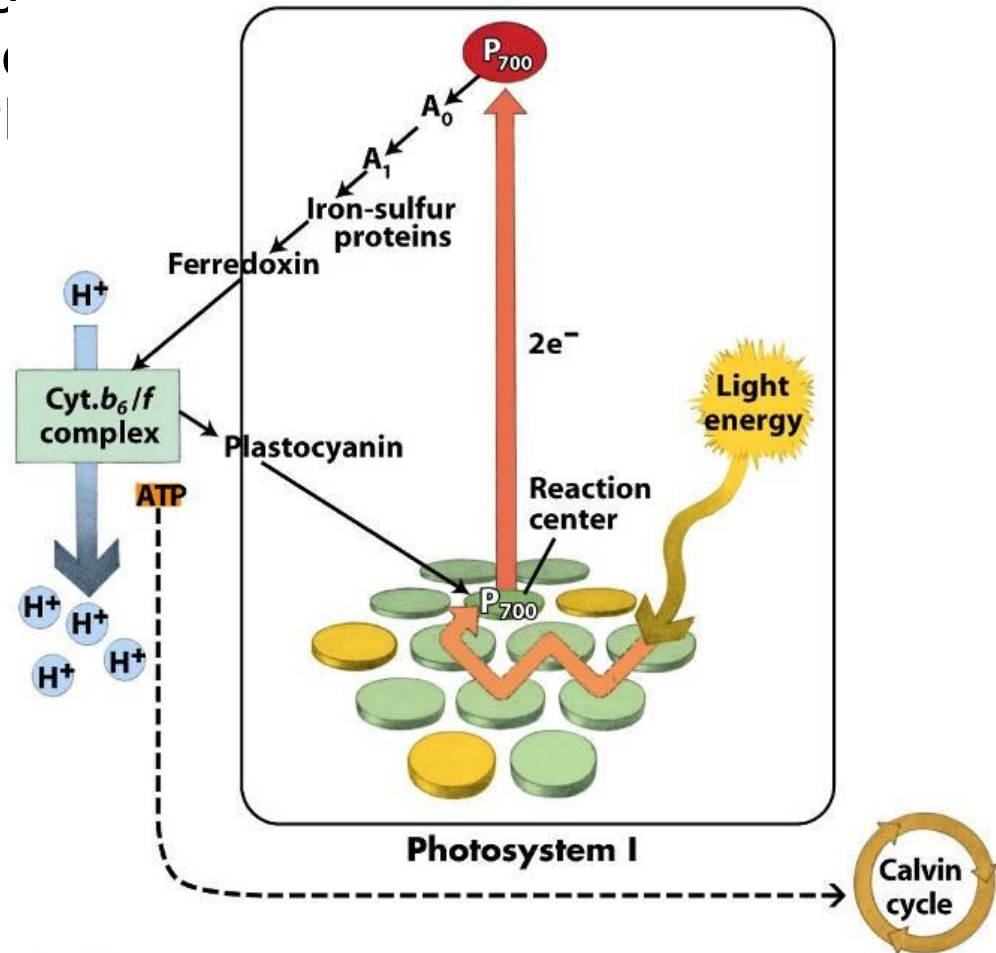
- e⁻ passed to P₇₀₀ (reduced) from PC in PS II
- Photon absorbed by reduced P₇₀₀
- e⁻ in P₇₀₀ gets excited (P₇₀₀^{*})
- e⁻ passed from P₇₀₀^{*} to A₀ (chlorophyll?) to A₁ (phylloquinone, a.k.a. vitamin A)
- e⁻ passed from A₁ to FeS_x to FeS_A to FeS_B (Fe-S proteins)
- e⁻ passed from FeS_B to Fd (ferredoxin) (Fe-S protein)
- Ferredoxin/NADP⁺ reductase (FNR) txf e⁻ and H⁺ to NADP⁺ to form NADPH
 - NADPH highly reduced, used to reduce CO₂ in Calvin Cycle
 - occurs in stroma

Noncyclic Photophosphorylation

- **Z-scheme** used to describe how PS I and II interact
- **Noncyclic photophosphorylation** (uses light to produce ATP)
 - what we've covered so far
 - 2 photons from each photosystem = 1 NADPH and 1 O
 - products go to Calvin Cycle
 - $\text{H}_2\text{O} + \text{NADP}^+ \rightarrow \text{NADPH} + \text{H}^+ + \frac{1}{2} \text{O}_2$
 - $6 e^- = 6 \text{ ATP} + 6 \text{ NADPH}$

Cyclic Photophosphorylation

- **Cyclic photophosphorylation** when extra ATP needed
 - PS I donates e^- to back to PS II resulting in production of additional ATP (no NADPH)
 - e^- txf via PQ
 - PS II generates ATP only
 - PS I generates NADPH

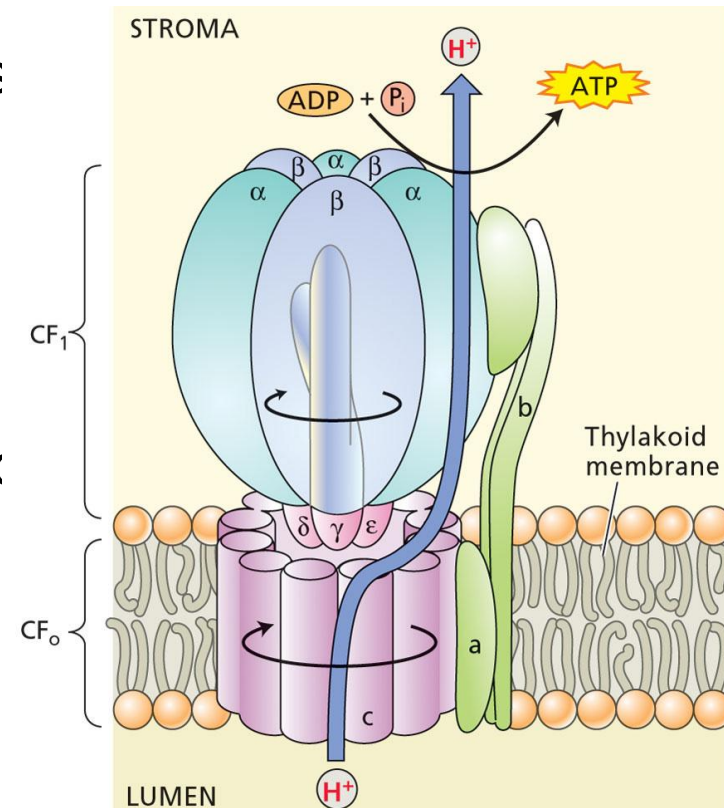


ATP Synthesis

- ATP produced via **chemiosmosis** = ion conc. differences and electric potential differences across membrane are source of free Σ that can be harnessed to do work
 - 2nd law of thermodynamics = any nonuniform distribution of matter or Σ represents a source of Σ
- **ATP synthase** (a.k.a. **ATPase**, **CF₀-CF₁**) uses PMF to generate ATP
 - H⁺ in thylakoid lumen = electrochemical gradient
 - due to splitting of H₂O, cytochrome *b₆f* complex
 - pH in stroma = alkaline, pH in lumen = acidic
 - gradient drives ATP synthesis via ATP synthase complex

ATP Synthesis

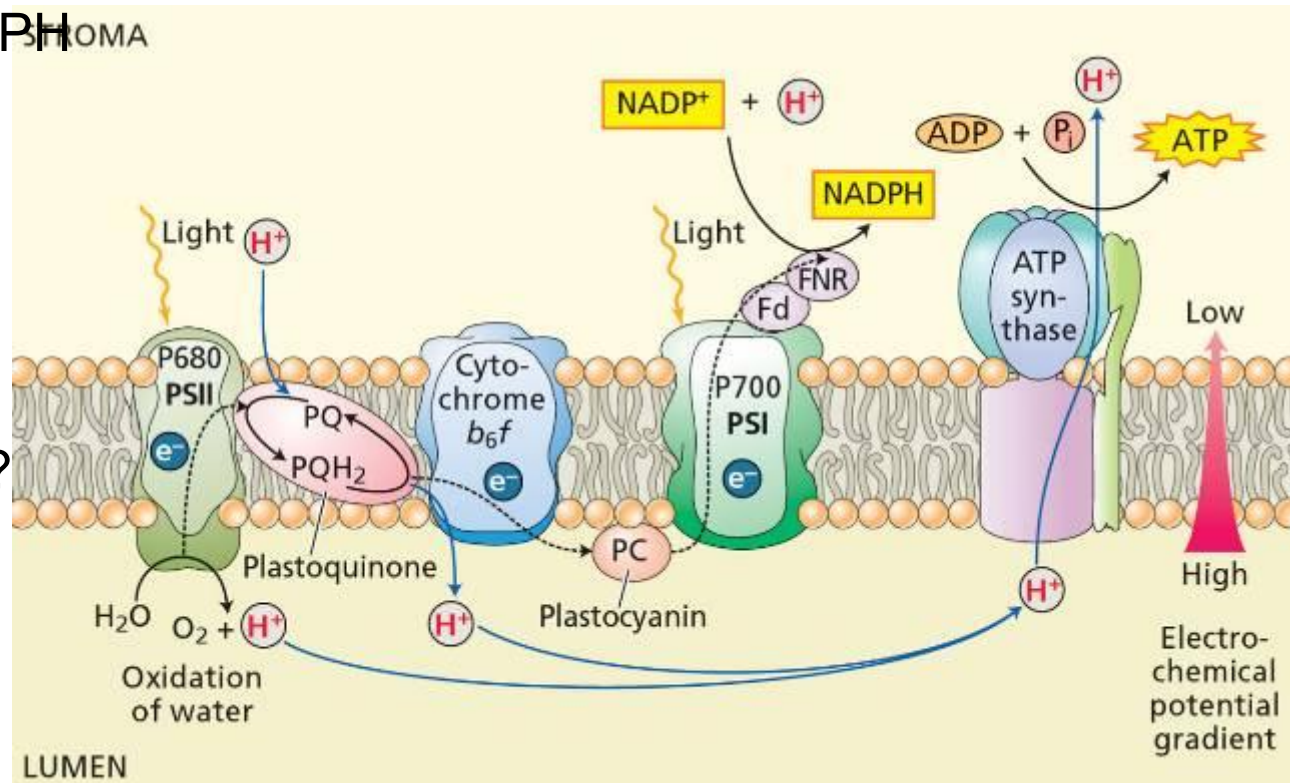
- ATP synthase consists of hydrophobic portion CF_0 (in membrane) and CF_1 (sticks out in stroma)
 - found on stroma lamellae and edge of grana of thylakoid membrane
 - CF_0 contains channel which H^+ pass
 - rotates along w/ internal stalk
 - CF_1 where ATP synthesized
 - when H^+ pass potential energy converted to kinetic
 - kinetic Σ converted to chemical bond
- 4 H^+ translocated per ATP



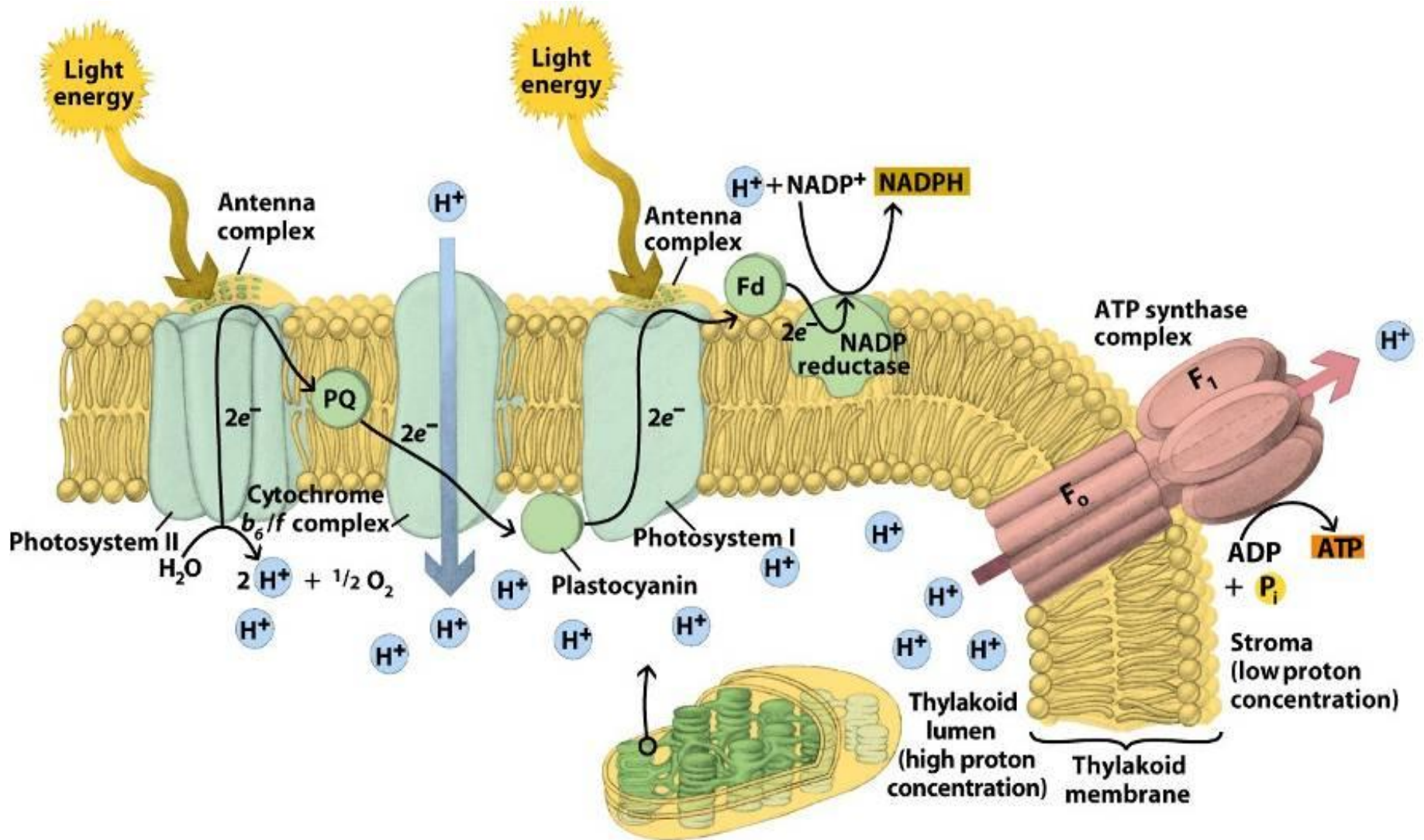
Summary

- 4 major protein complexes
 - PS II oxidizes H_2O , releases H^+ into lumen
 - b_6f complex pumps additional H^+ into lumen
 - PS I reduces NADP^+ to NADPH
 - ATP synthase produces ATP

- initial acceptor??
- final donor??

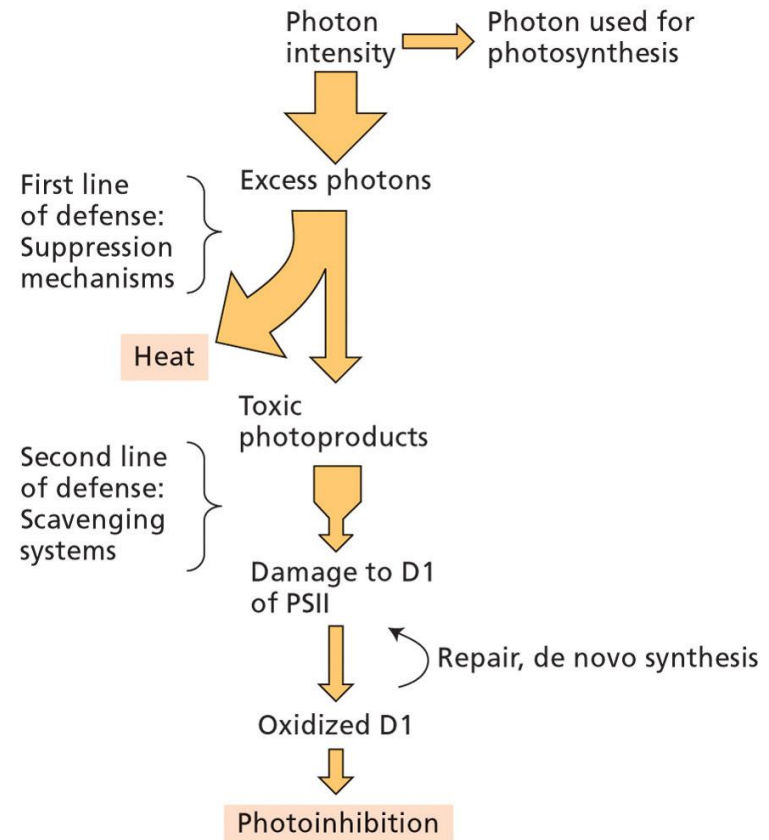


Summary II



Repair and Regulation

- Regulatory and repair mechanisms needed to safely dissipate excess Σ or repair if damaged
 - carotenoids dissipate excited state of chlorophyll
 - excited state can react w/ O_2 to produce singlet oxygen (extremely reactive, damaging to lipids)
 - xanthophylls (type of carotenoid) also help dissipate Σ and heat
 - prolonged photoinhibition (inhibition of Ps by excess light) = damage to PS II rxn center, esp. D1 protein
 - D1 protein removed and replaced



Chloroplast Genetics

- Chloroplast have their own DNA, mRNA, ribosomes
 - import some genes from nucleus
 - circular DNA
- Reproduce via division
 - chloroplasts divided btwn daughter cells
 - chloroplasts come from female plant
 - non-Mendelian genetics, maternal inheritance

Endosymbiosis

- Chloroplast is semiautonomous
 - own DNA, mRNA, ribosomes
 - descendant of symbiotic relationship btwn cyanobacteria and nonphotosynthetic eukaryotic cell (endosymbiosis)
 - genetic information lost thus needs host