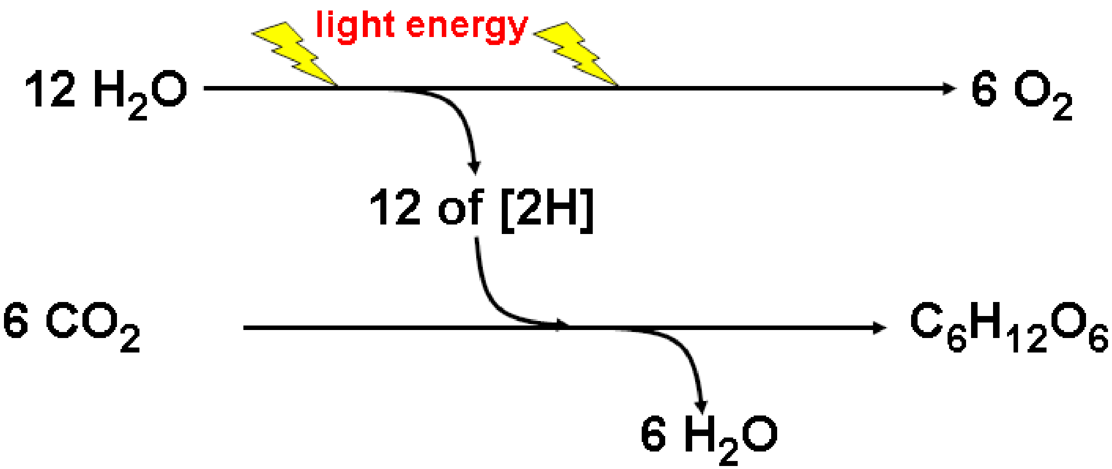
BIO 311C
Spring 2010

Exam 3: Friday 16 April

Exam 3 will cover reading assignments, lecture information and presentation slides since Exam 2.

Lecture 29 – Friday 9 Apr.

Water is oxidized during the light reactions of photosynthesis.
Carbon dioxide is reduced during the dark reactions of photosynthesis.



oxidation of water occurs as a part of the light reactions of photosynthesis

reduction of carbon dioxide occurs as a part of the dark reactions of photosynthesis

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Summary of the Light Reactions of Photosynthesis

$\geq$ 72 quanta of light

$$12\ NADP^{+} + 12\ H_2O \xrightarrow{\text{light reactions}} 6\ O_2 + 12\ (NADPH + H^{+})$$

18 ATP

The most important products of the light reactions to the plant are ATP and NADPH because they are required for the dark reactions. Oxygen is a waste product.

Summary of the Dark Reactions of Photosynthesis

$$6\ CO_2 + 12\ (NADPH + H^{+}) \xrightarrow{\text{Calvin Cycle}} C_6H_{12}O_6 + 12\ NADP^{+} + 6\ H_2O$$

18 ATP

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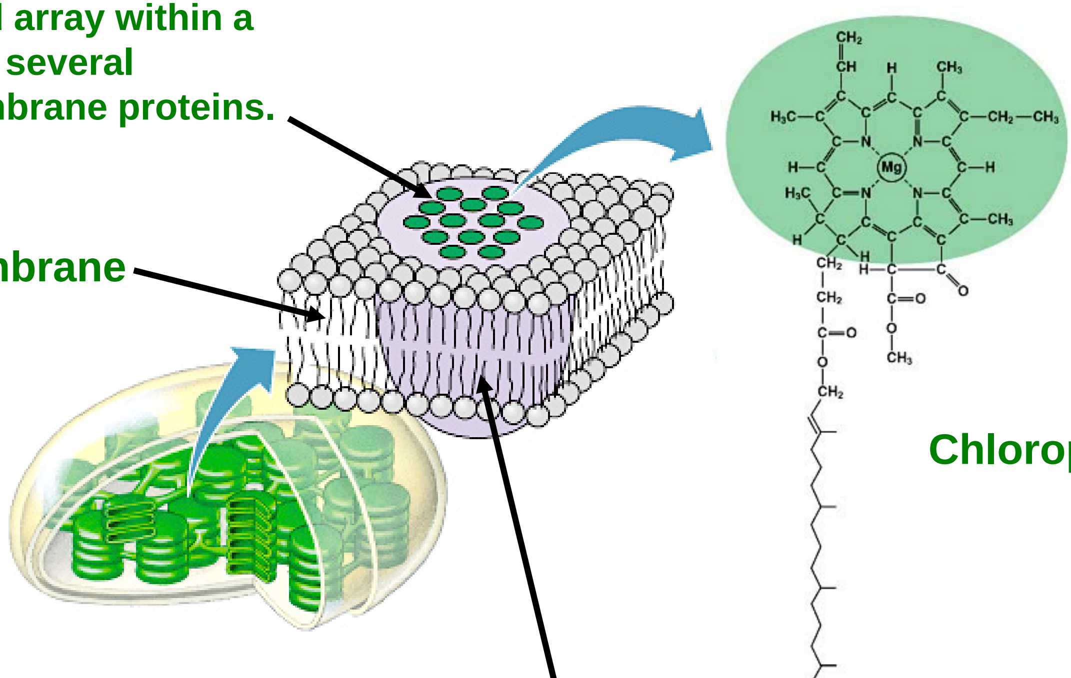
The Location of Chlorophyll Molecules Within Thylakoid Membranes

Several hundred chlorophyll molecules occur as an organized array within a cluster of several transmembrane proteins.

Thylakoid membrane



Chlorophyll molecule

Complex of several transmembrane proteins

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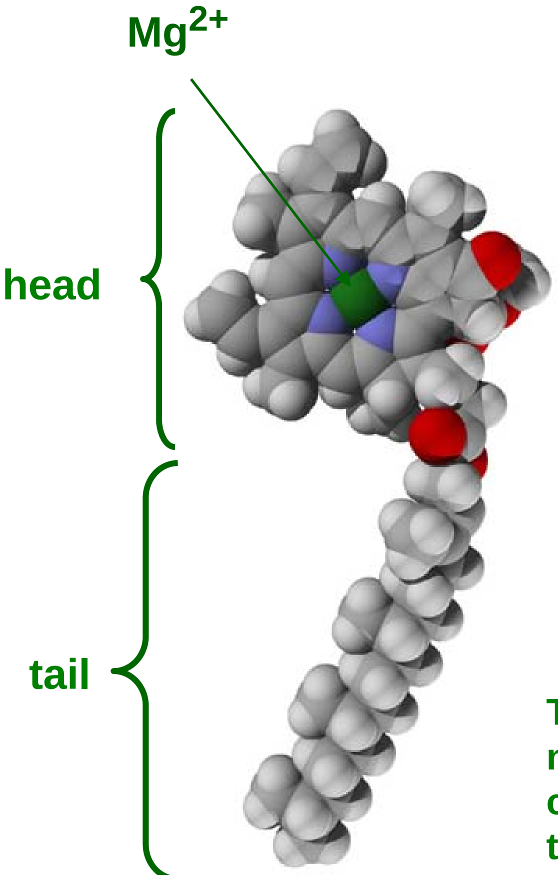
Chlorophyll Molecule

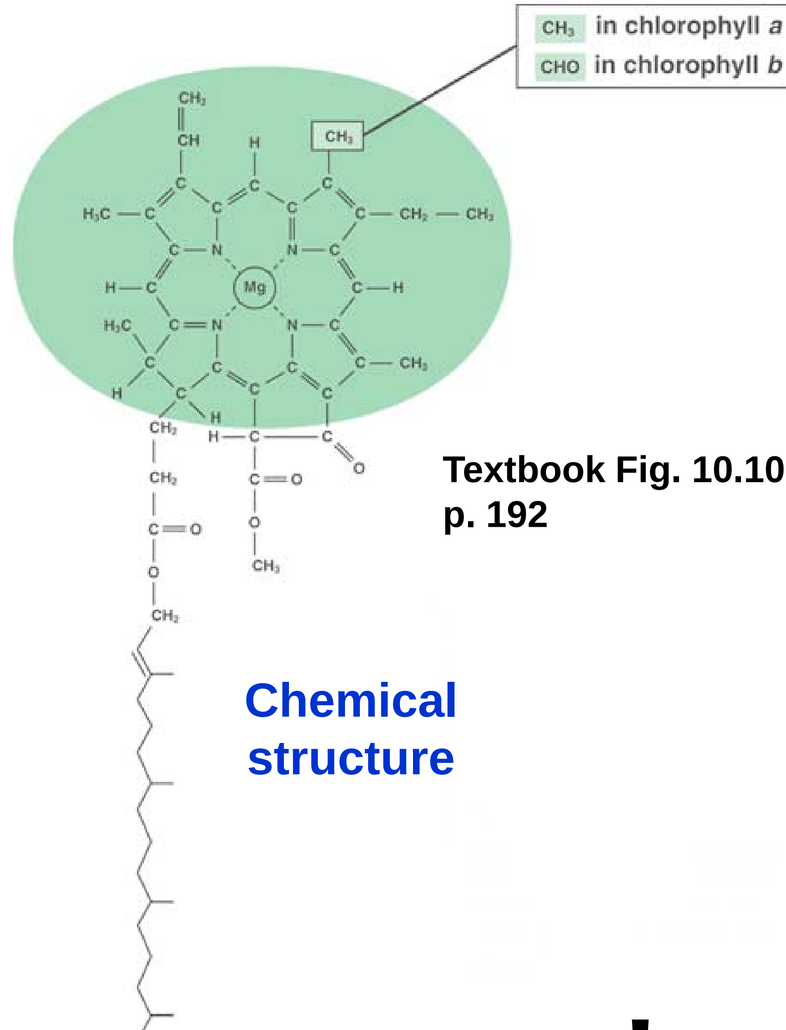


Space-filling model

(different kinds of atoms are shown in different colors)

The ring structure (head) of chlorophyll is polar and projects from the hydrophobic interior of thylakoid membranes. It is the portion of the molecule that absorbs light energy. The magnesium ion is required for its function.

The tail of chlorophyll is nonpolar. It anchors the chlorophyll in place within transmembrane proteins by hydrophobic bonding.



Textbook Fig. 10.10, p. 192

Chemical structure

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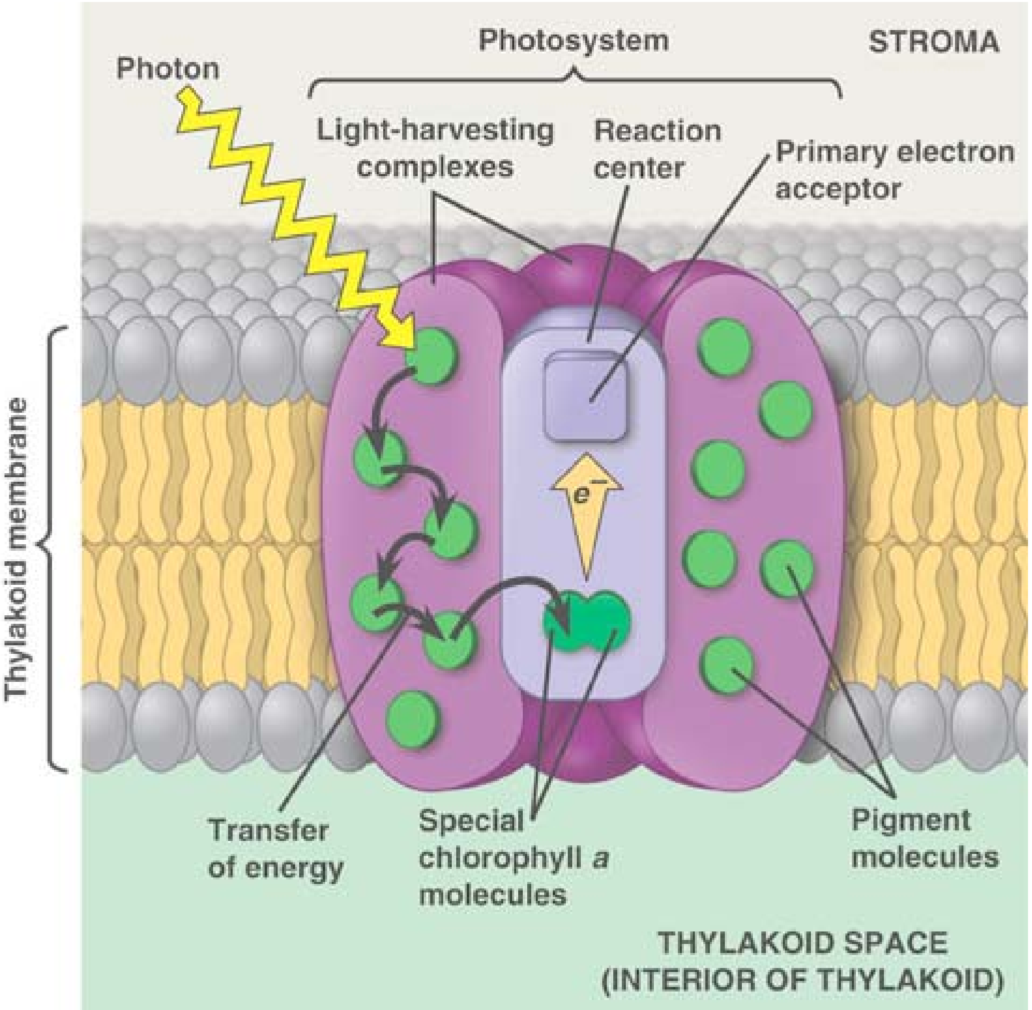
Light Harvesting in a Thylakoid Membrane

Textbook Fig. 10.12, p. 193



1. A photon of light is absorbed by any one of the chlorophyll molecules within an array.
2. The energy content of the light is transferred rapidly among the chlorophyll molecules within the array.
3. The energy eventually becomes "trapped" in a special pair of chlorophyll molecules.
4. Energized special-pair chlorophyll loses an electron to another molecule called a primary electron acceptor. This is an oxidation-reduction reaction.

<u>Energy</u> transfer among chlorophyll molecules does not involve any chemical reaction. <u>Electron</u> transfer from the "special pair" chlorophyll molecules to the primary electron acceptor is the first chemical reaction of photosynthesis.

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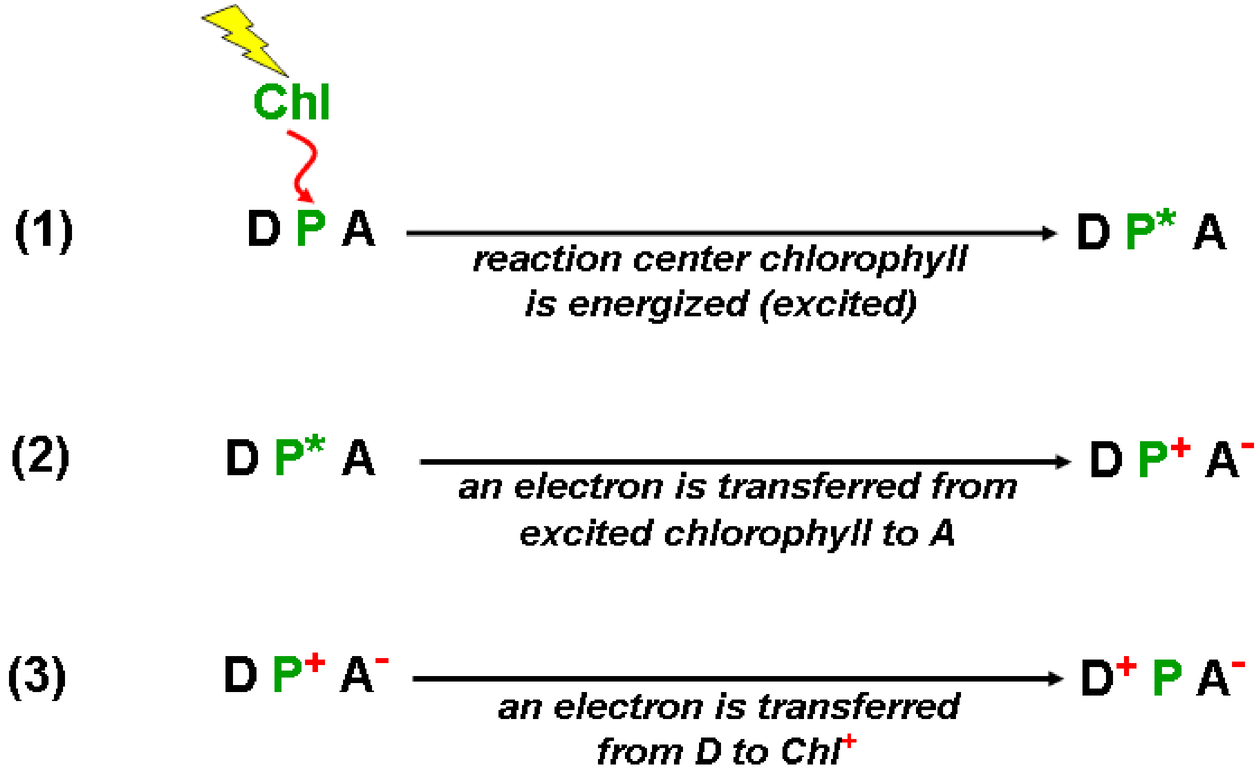
Three Steps in Primary Electrical Charge Separation in a Reaction Center



Chl: any chorophyll molecule that absorbs light energy
P: special-pair chlorophyll
A: electron acceptor
D: electron donor

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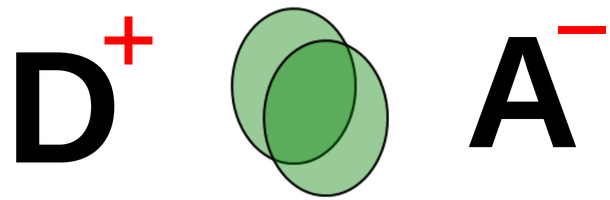
Final Result of Primary Charge Separation in a Reaction Center



Both A$^-$ and D$^+$ are very unstable molecular species.

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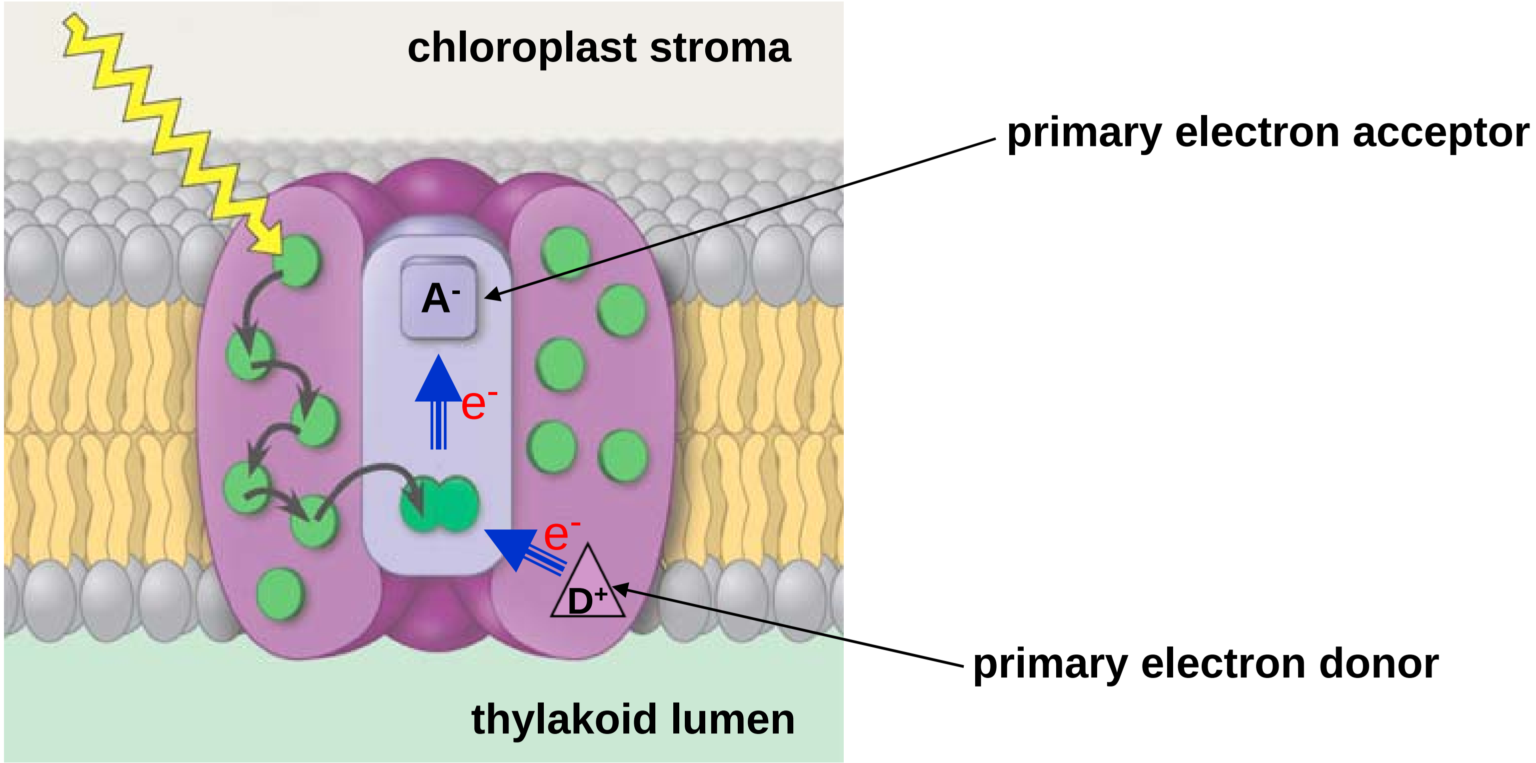
Primary charge separation in a reaction center makes the lumen of the thylakoid more positively charged and the stroma of the chloroplast more negatively charged.



Slightly modified from Fig. 10.12, p. 193.

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Connection Between the Reaction Centers of the Two Photosystems of Photosynthesis

$D_2\ P_{680}\ A_2 \xrightarrow{\text{electron transport chain}} D_1\ P_{700}\ A_1$ thylakoid membrane

$\underbrace{D_2\ P_{680}\ A_2}$ reaction center of Photosystem II (RC 2)

$\underbrace{D_1\ P_{700}\ A_1}$ reaction center of Photosystem I (RC 1)

A photosynthetic reaction center plus other molecules that interact directly with the reaction center in the thylakoid membrane is called a photosystem.

Two photosystems are embedded in the same thylakoid membrane. They are somewhat separated from each other, but are connected through an electron transport chain.

P700 and P680 are the names of the special-pair chlorophyll of Photosystem 1 and Photosystem 2, respectively. *

Primary Electrical Charge Separation in the Two Photosystems of Photosynthesis

In this illustration a quantum of light has been absorbed and primary electrical charge separation has occurred in each of the two photosystems.

The condition of separated electrical charges in a photosystem is a very unstable (high-energy) state. Thus, in this illustration both photosystems are in a high energy state.

An electron transport chain occurs between the two photosystems such that the extra electron on A_2^- can be transferred to the D_1^+.

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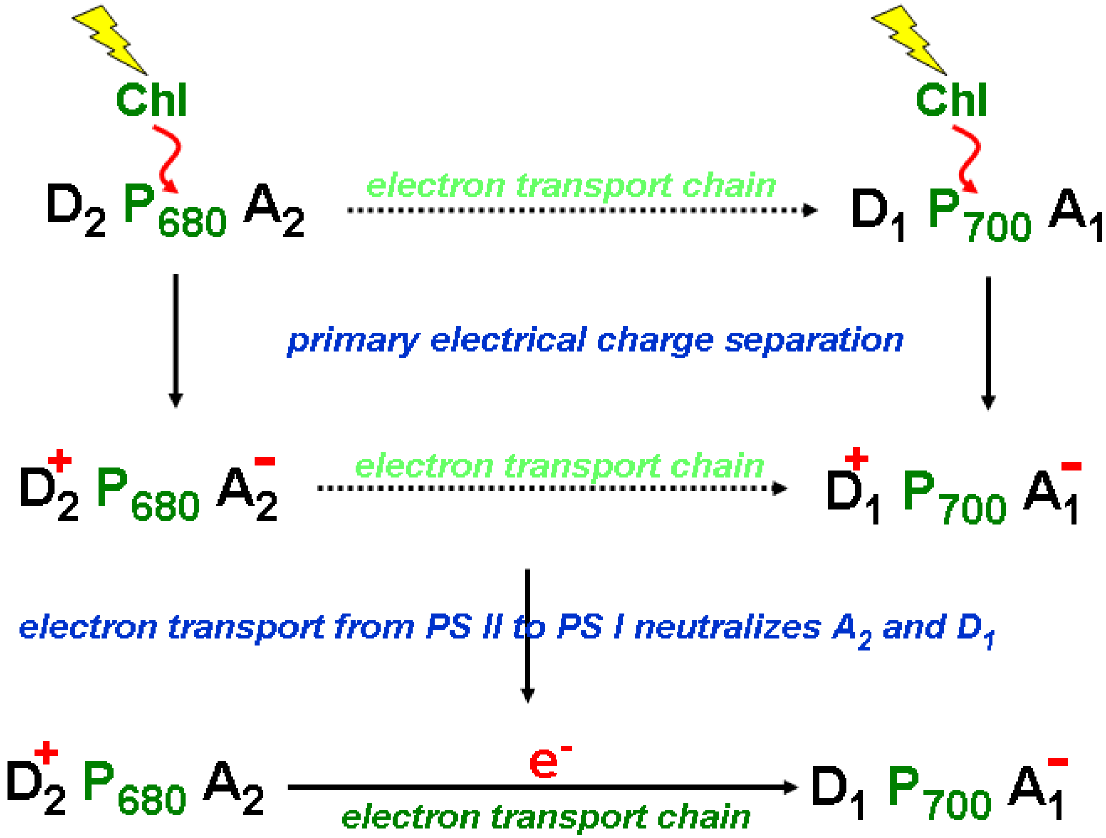
Electron Transport Between the Two Reaction Centers (RC 2 and RC 1) of Photosynthesis



RC 2 RC 1

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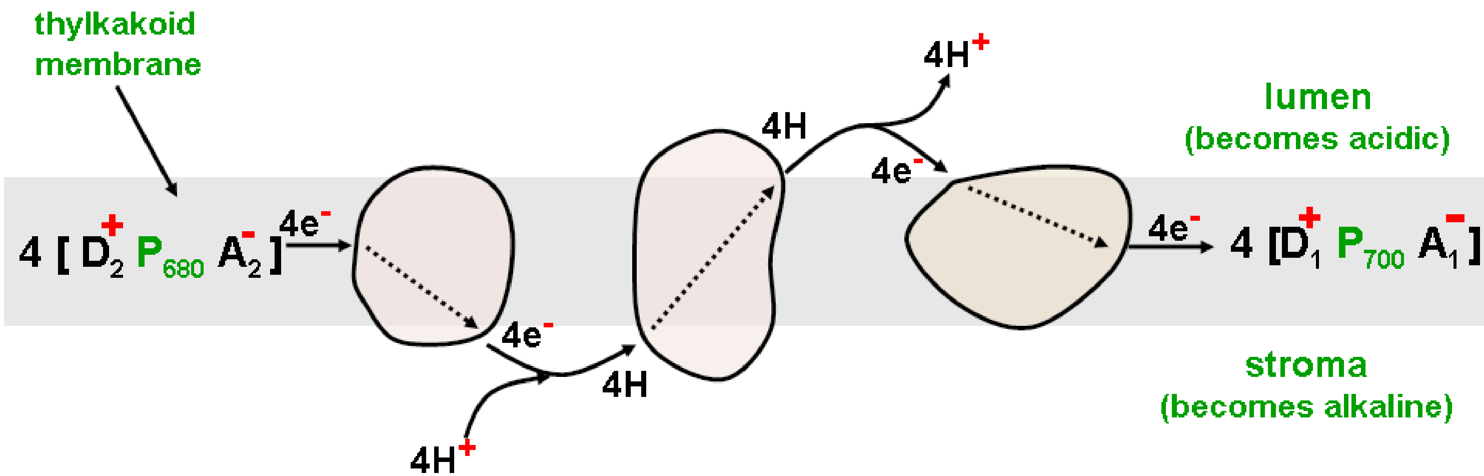
Proton transport Across the Thylakoid Membrane During Operation of the Electron Transport Chain Between the Reaction Centers of Photosystem 2 and Photosystem 1



The electron transport chain pumps protons from the stroma to the lumen of the chloroplast, creating a pH gradient across the thylakoid membranes.

Four electrons are shown moving from RC 2 to RC 1 instead of just one, in order to chemically balance this process with other reactions that are connected to it. Each photosystem would have to absorb 4 quanta of light in order to facilitate the transfer of 4 electrons.

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Electrical Charges Remaining on RC 2 and RC 1 after Electron Transfer Between the Two Photosystems

$$D_2^{+}\ P_{680}\ A_2 \longrightarrow D_1\ P_{700}\ A_1^{-}$$

Strong
oxidizing agent

Strong
reducing agent

This condition is still a very unstable. (e.g. It is in a high energy state). D_2^{+} has a strong attraction for an additional electron, while A_1^{-} has a strong tendency to lose its excess electron.

Thus, RC 2 becomes a strong oxidizing agent (oxidant) while RC 1 becomes a strong reducing agent (reductant).

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Production of O_2 from water by Photosystem 2

1. The strong oxidant D_2^+ in RC 2 removes an electron from one of the hydrogen atoms of a molecule of H_2O, leaving behind a proton (H^+) and a very unstable hydroxyl radical [OH]. The electron removed from water reduces D_2^+ to regenerate electrically neutral D_2.

2. The H^+ from the molecule of H_2O is released into the lumen of the thylakoid, making the lumen more acidic.

3. The remaining [OH] from the molecule of H_2O is temporarily stored by Photosystem 2.

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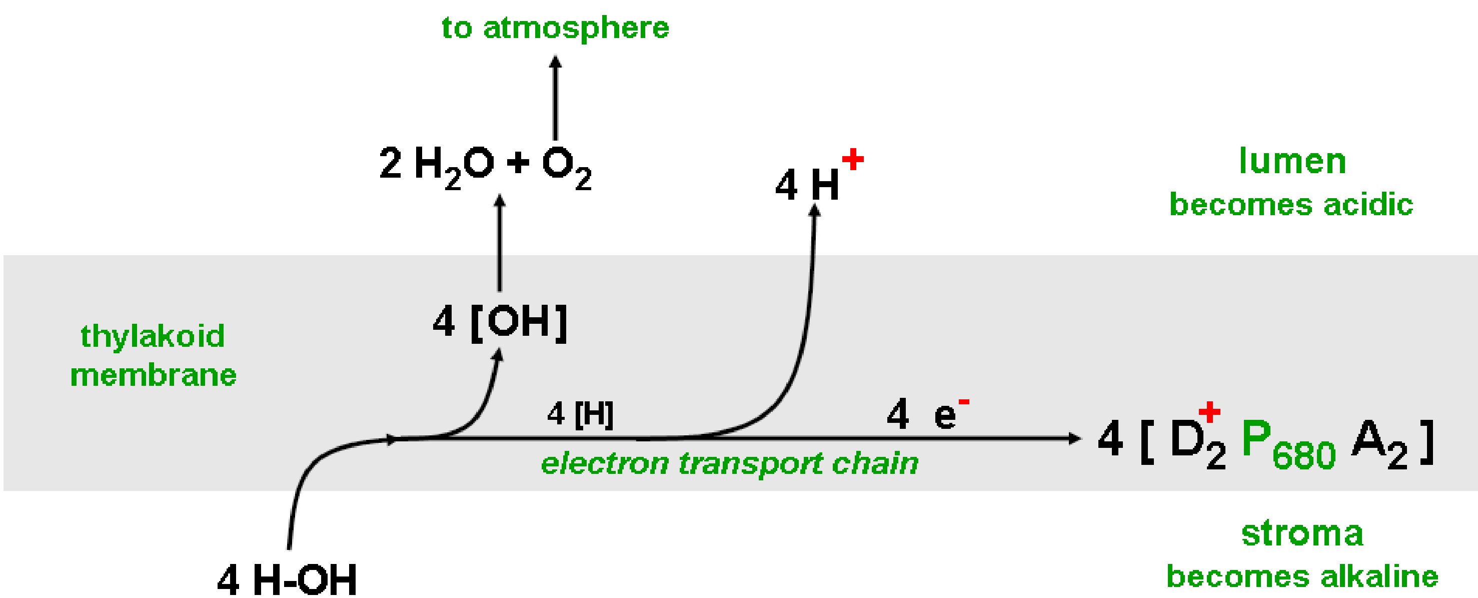
Electron Transport from Water to RC 2



net: $2\,H_2O + 4\,D^+ \longrightarrow 4\,D + O_2 + 4\,H^+$

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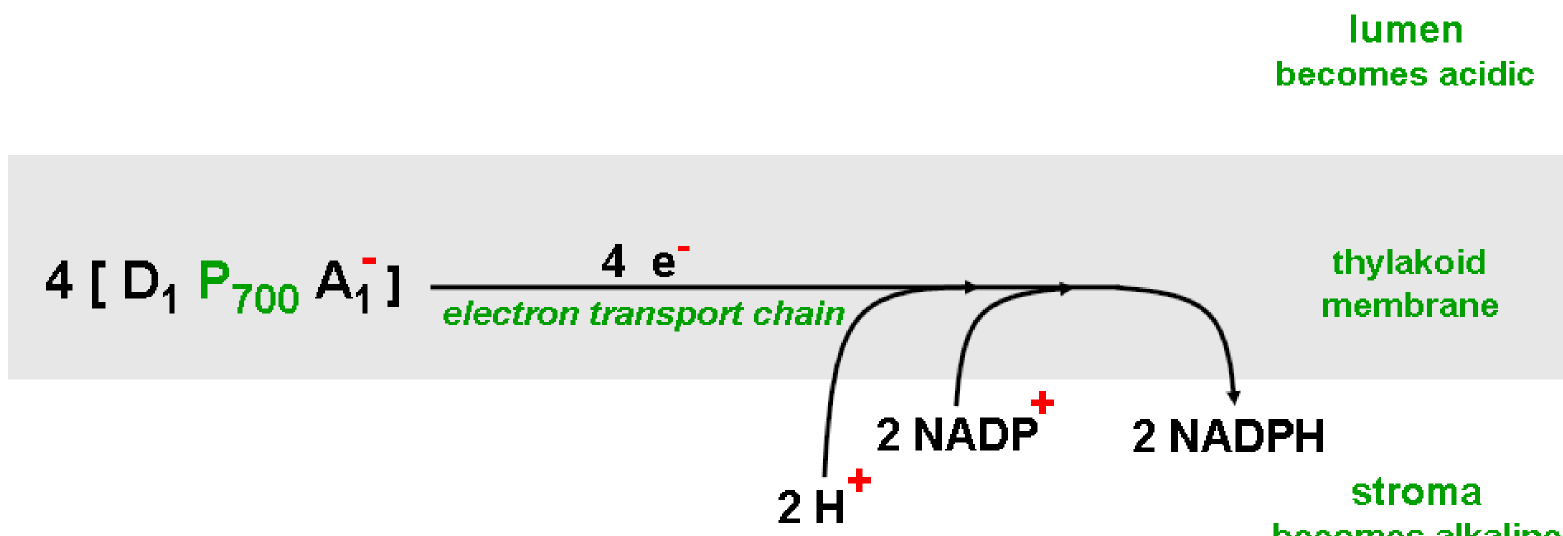
Electron Transport from RC 1 to NADP$^+$



net: $4\ A_1^- + 2\ NADP^+ + 2\ H^+ \longrightarrow 4\ A + 2\ NADPH$

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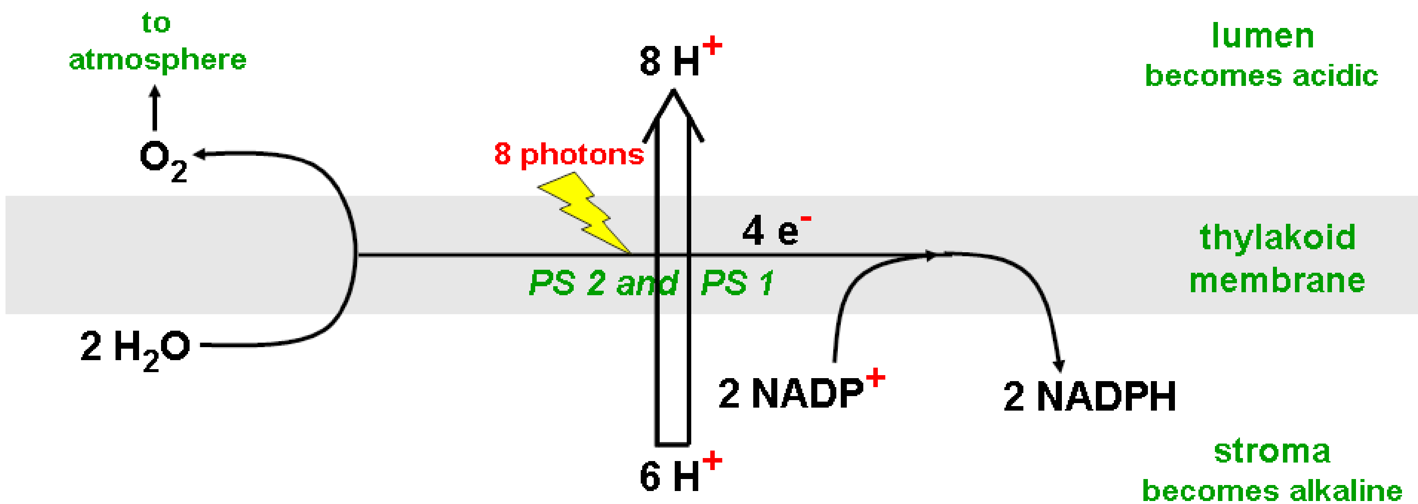
Reactants and Products of PS II and PS I Electron Transport



net:

$$2\ H_2O + 2\ NADP^+ \xrightarrow[4\ e^-]{8\ photons} O_2 + 2\ NADPH + 2\ H^+$$

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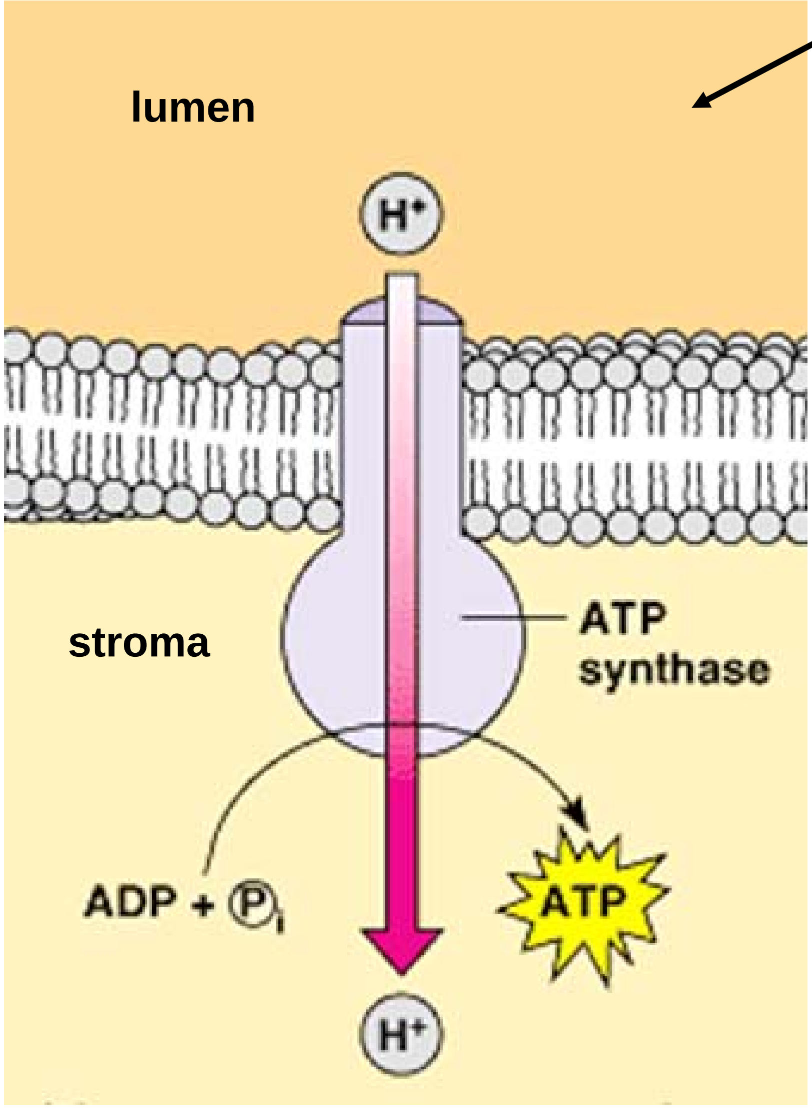
Function of ATP Synthase in the Thylakoid Membranes

See textbook Fig. 10.16, p. 192



Photosynthetic electron transport has created a much higher concentration of H^+ on this side of the membrane.

The resulting difference in pH and electrical charge across the membrane is a form of stored energy.

The only path available for protons to travel back across the membrane to equalize the pH and electrical charge on both sides is through ATP synthase, which captures some of the energy released during proton flow as ATP.

ATP synthase in the thylakoid membrane is structurally and functionally very similar to the ATP synthase in the mitochondrial inner membrane.

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The linear sequence of electron transfer from H_2O to $NADP^+$ in photosynthesis is called noncyclic electron transport.

Equation for Noncyclic Electron Transport and Accompanying ATP Synthesis of Photosynthesis:

$$2\ H_2O + 2\ NADP^+ + 2\ (ADP + P_i) \xrightarrow[\text{4 } e^- \text{ in noncyclic electron transport}]{\text{8 photons}} O_2 + 2\ (NADPH + H^+) + 2\ (ATP + H_2O)$$

ATP Synthesis that results from noncyclic electron electron flow in photosynthesis is called noncyclic photophosphorylation

Approximately 2 ATP are synthesized from the proton gradient that is produced from 4 electrons passing through the noncyclic electron transport pathway.

Thus, products of noncyclic electron transport are produced in the ratio of:
1 O_2 : 2 NADPH : 2 ATP

Both NADPH and ATP are required for operation of Calvin Cycle, the final metabolic pathway of photosynthesis. But the Calvin Cycle requires these compounds in the ratio of 2 NADPH : 3 ATP. Thus, either additional ATP must be made or some NADPH must be eliminated in order to obtain the correct ratio of NADPH to ATP.

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Cyclic Electron Flow in Photosynthesis

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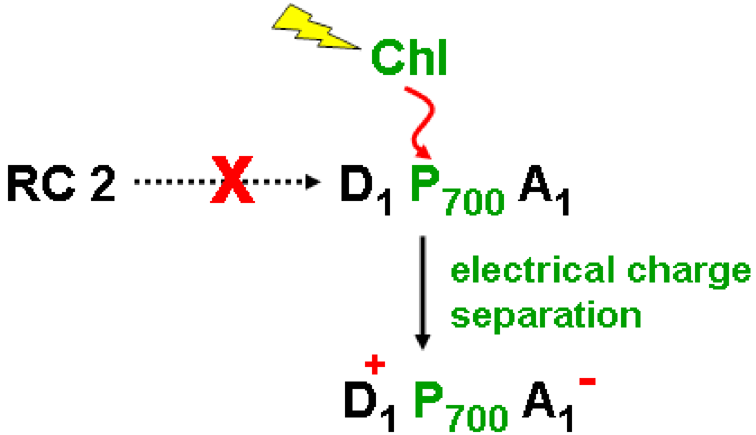
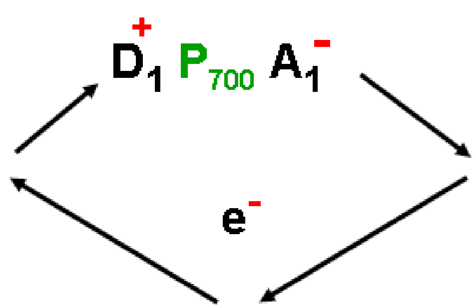
(1) Chloroplasts can temporarily inactivate PS 2 while PS 1 is still functional. Then the D_1^+ generated during the operation of PS 1 cannot be neutralized by electron transfer from A_2^- .



(2) The electron on A_1^- is used to neutralize D_1^+. However, the electron on A_1^- does not go back through P700, but instead must pass through an electron transport pathway in the thylakoid membrane in order to return to D_1^+.



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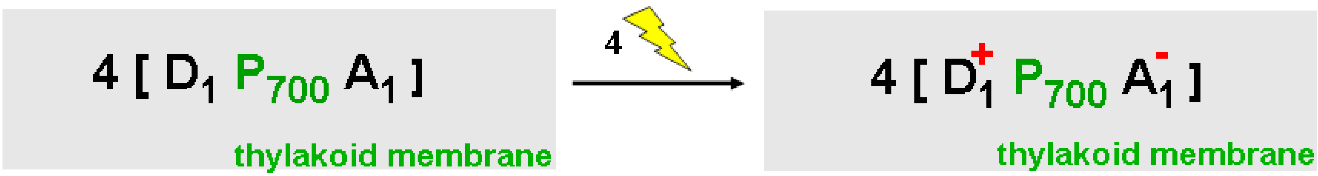
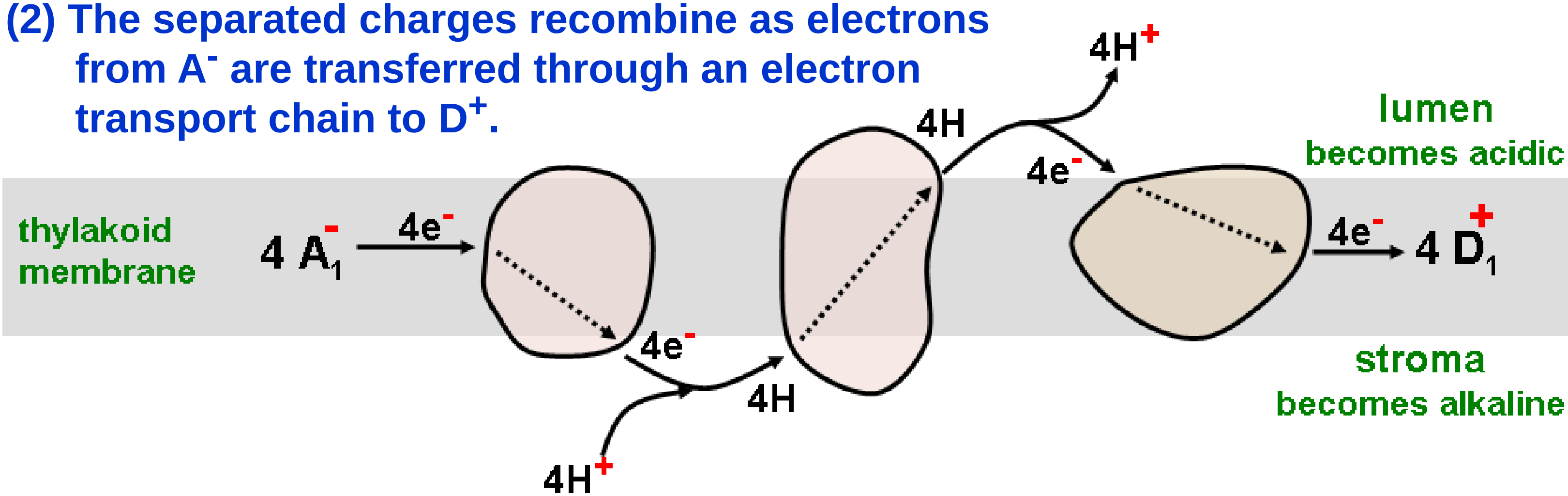
The Electron Transport Chain Around PS I; Cyclic Electron Transport

(1) Photochemical charge separation at RC I



(2) The separated charges recombine as electrons from A^- are transferred through an electron transport chain to D^+.



The net effect of the electron transport chain around PS 1 is to pump protons from the stroma to the lumen of thylakloids, creating a pH gradient across the thylakoid membrane. The transfer of four electrons is shown, which requires four quanta of light.

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Definitions and Descriptions

The difference in pH across the thylakoid membrane resulting from cyclic electron transport uses the same ATP synthase enzyme complex to synthesize ATP as is used in non-cyclic electron flow. Approximately 1 ATP is synthesized per four electrons transported around PS I during cyclic electron transport.

The light-driven synthesis of ATP by chloroplasts is called photophosphorylation*. The PHP resulting from electrons transferred from water to $NADP^+$ is called <u>noncyclic</u> <u>PHP</u>. The PHP resulting from electrons transferred around PS 1 is called <u>cyclic</u> <u>PHP</u>.

Light harvesting, electron transport and PHP (both cyclic and noncyclic) are collectively called the <u>light</u> <u>reactions</u> of photosynthesis.

***photophosphorylation is abbreviated as PHP.**

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