Ch. 10: Photosynthesis: Energy from the Sun

1. Identifying Photosynthetic Reactants and Products
2. The Two Pathways of Photosynthesis: An Overview
3. The Interactions of Light and Pigments
4. The Light Reactions: Electron Transport, Reductions, and Photophosphorylation
5. Making Carbohydrate from CO_2: The Calvin–Benson Cycle
6. Metabolic Pathways in Plants

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Ch.10 Objectives:

❖ **Students should be able to .....**

1. **Ch. 10:** Diagram and explain how light-harvesting pigments **capture light**, and how this is **converted to cellular energy** by ***noncyclic photosynthesis***.
2. *** Compare & contrast the **energy conversion mechanisms of cellular respiration** and the **light reactions** of photosynthesis. What energy inputs & outputs are used, and in what forms?
3. Describe and diagram the relationship between the **light reactions** and the **"dark" reactions** of photosynthesis.

❖ *Objectives and Study Guide Questions are your HOMEWORK between classes!! Due at the end of the week during Lecture!!*

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10.1) Identifying Photosynthetic Reactants and Products

- ***Photosynthesis*** = the biochemical process by which plants/algae/bacteria capture energy from sunlight and store it in carbohydrates.
  - = *the very basis of life on Earth!!*

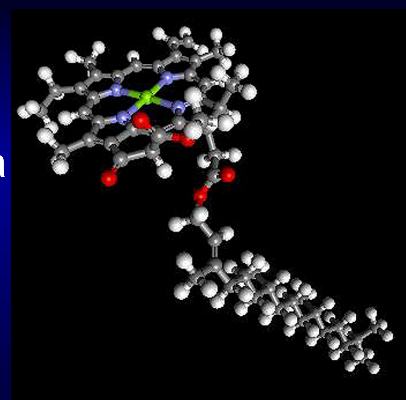

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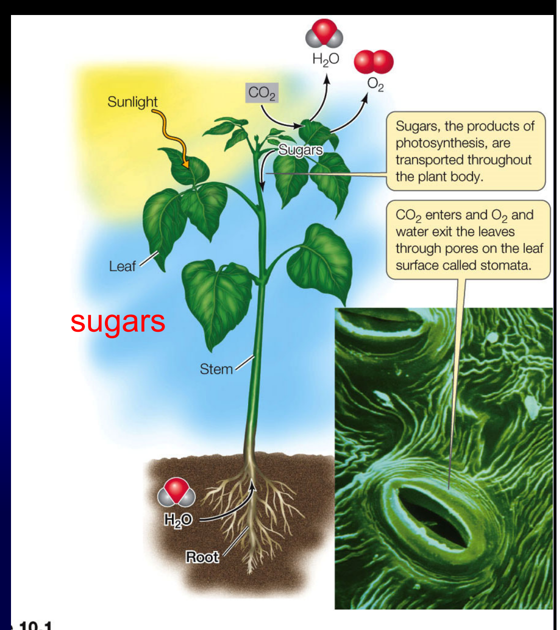
Figure 10.1 *The Ingredients for Photosynthesis*

- By the 1800s, scientists had learned:
  1. Three ingredients are needed for photosynthesis: **water, CO_2, & light.**
  2. There are two products: **carbohydrates & O_2.**
  3. The water, which comes primarily from the soil, is transported through the **roots** to the **leaves**.
  4. The CO_2 is taken in (and O_2 exits) from the air through ***stomata***, or pores, in the leaves.



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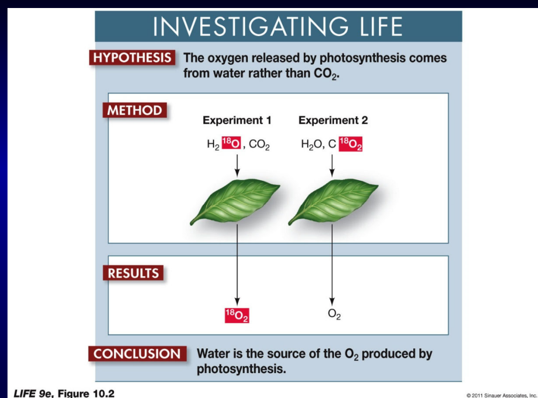
Photosynthetic Reactants & Products

- By 1804, scientists had summarized the overall chemical reaction of photosynthesis:
  - ❖ CO_2 + H_2O + light energy → sugar + O_2



LIFE 9e, Figure 10.2

- More recently, using H_2O and CO_2 labeled with radioactive isotopes, we know that the actual reaction is:
  - ❖ $6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$

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10.2) The Two Pathways of Photosynthesis: An Overview

A. **Photosynthesis** occurs in the ***chloroplasts***
   - green plant cells, algae (***photoautotrophs***)
   - photoautotrophic bacteria
   - consists of many reactions.

B. **Photosynthesis** can be divided into two pathways:
   1) The **light reaction** is driven by light energy captured by chlorophyll.
      - It produces ATP and NADPH + H^+.
   2) The **Calvin–Benson cycle** (***light-independent rxns/ dark rxns***) does not use light directly.
      - It uses ATP, NADPH + H^+, and CO_2 to produce sugars.

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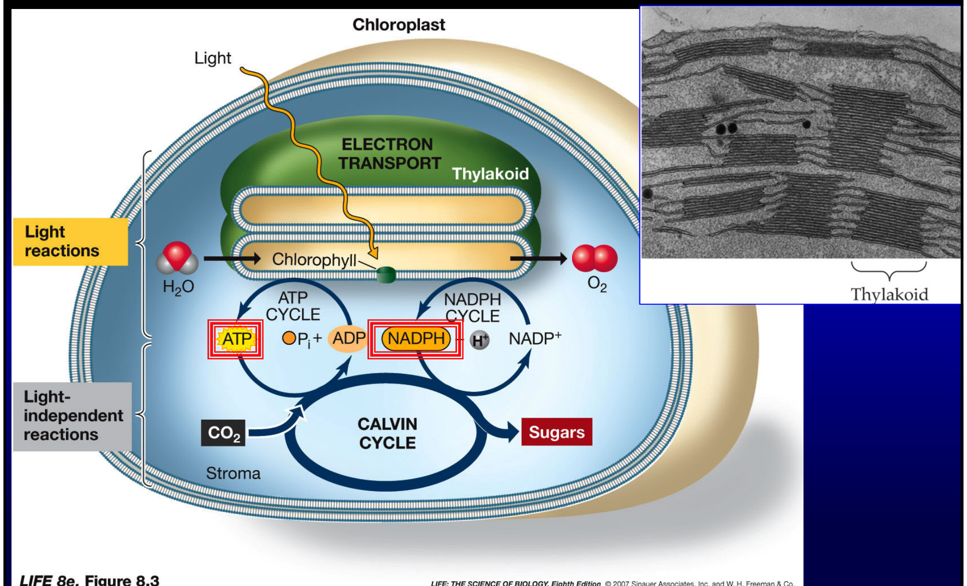
Figure 10.3 *An Overview of Photosynthesis*



http://www.compulink.co.uk/~argus/Dreambio/photosynthesis/photosynthsis%20animation.htm

http://instruct1.cit.cornell.edu/courses/biomi290/MOVIES/OXYGENIC.HTML

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10.3) The Interactions of Light & Pigments

- Visible light is part of the electromagnetic radiation spectrum.
  - comes in discrete packets called ***photons***.
  - also behaves as if it were a ***wave***.

- Two things are required for photons to be active in a biological process:
  1. Photons ***must be absorbed*** by receptive molecules.
  2. Photons must have ***sufficient energy*** to perform the chemical work required.

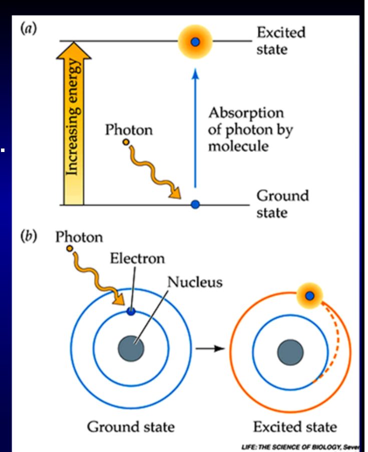

Figure 10.5 *Exciting a Molecule*

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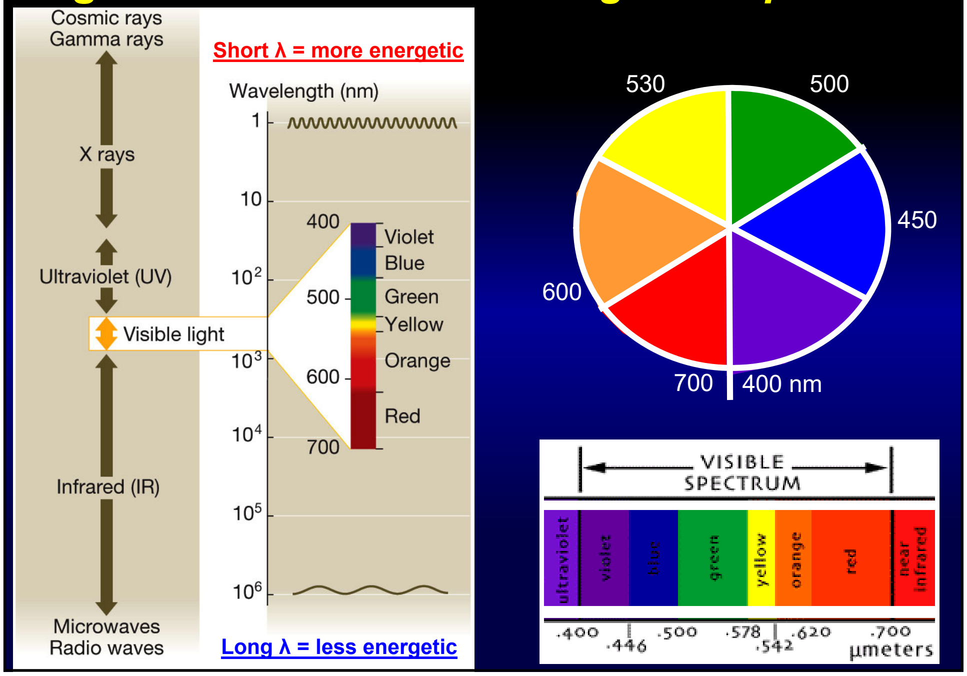
Figure 10.4 *The Electromagnetic Spectrum*



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A. Light Activation of a Molecule

- When a photon and a pigment molecule meet, one of three things happens:
  1. **The** photon may **bounce off**,
  2. **pass through**,or
  3. **be absorbed** by the molecule.
- If absorbed, the energy of the photon is acquired by the molecule.
- The molecule is ***raised from its ground state to an excited state of higher energy***.

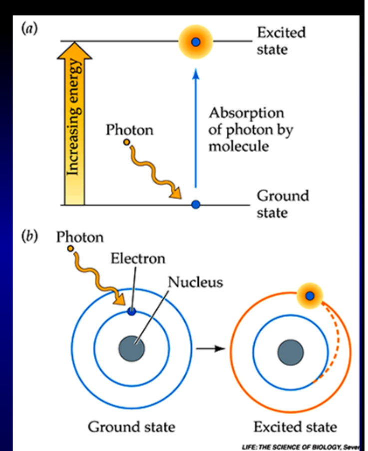

Figure 10.5 *Exciting a Molecule*

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B. Pigment Spectra

❖ *A molecule can absorb radiant energy of only certain wavelengths.*

1. If we plot the absorption by the compound as a function of wavelength, the result is an ***Absorption Spectrum***.

2. If absorption results in a biological activity:
   a) then a plot of the effectiveness of the light as a function of wavelength
   b) is called an ***Action Spectrum***.

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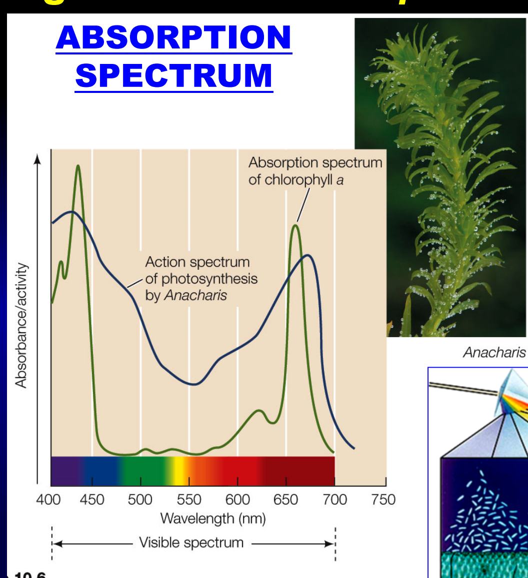
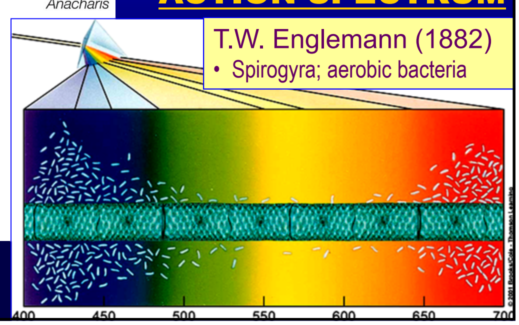
Figure 10.6 *Absorption and Action Spectra*

ABSORPTION SPECTRUM



ACTION SPECTRUM

T.W. Englemann (1882)
- Spirogyra; aerobic bacteria



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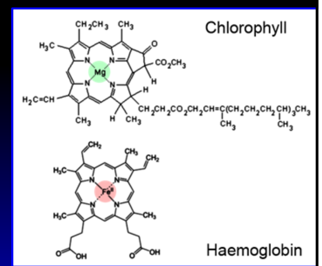
C. Photosynthetic Pigments

- Plants have two predominant chlorophylls: **chlorophyll *a*** and **chlorophyll *b***.
  - absorb Blue and Red wavelengths
    - Are near the ends of the visible spectrum.



- Other ***accessory pigments*** absorb photons between the red and blue wavelengths
  - transfer a portion of that energy to chlorophylls.
  - Eg: the ***carotenoids***, such as **β-carotene**.

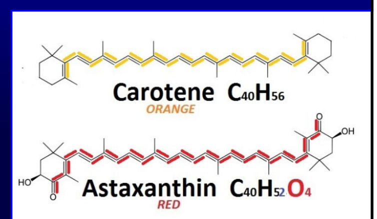


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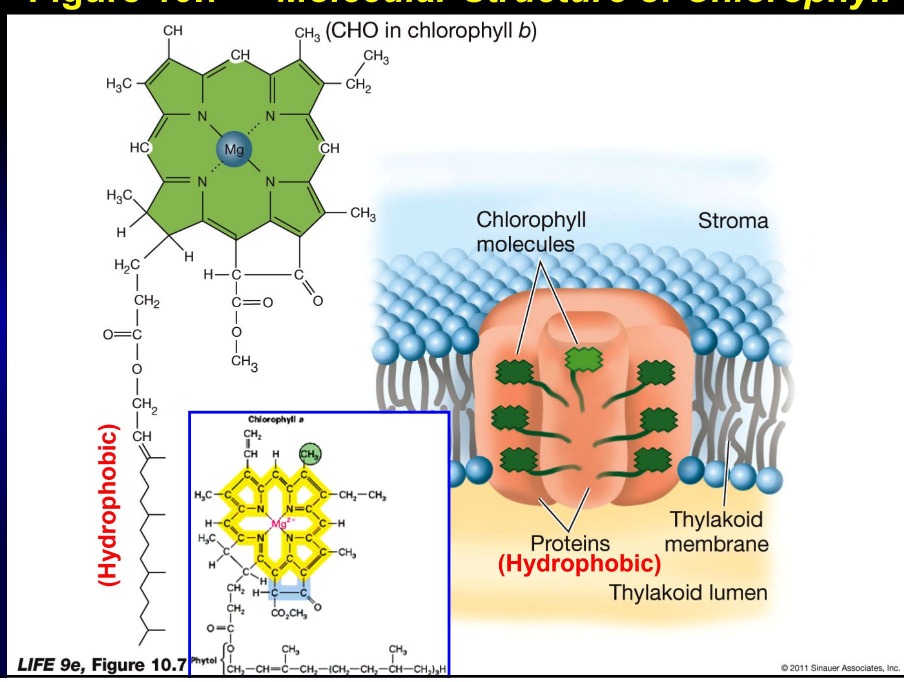
Figure 10.7 *Molecular Structure of Chlorophyll*



LIFE 9e, Figure 10.7

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D. Interactions of Light and Pigments

1. When it absorbs a photon, a pigment molecule enters an unstable ***excited state***.
   - molecule may return to the ***ground state***.
     a) If returns to ground: some of the absorbed energy is given off as **heat** .
     b) the rest is given off as **light** energy, or ***fluorescence***.
     c) If fluorescence does not occur:
     - pigment molecule may pass some absorbed energy to other pigment molecules.

2. Pigments in photosynthetic organisms are arranged into ***antenna systems ("light harvesting complexes")***.
   - pigments are **packed together** & **attached to thylakoid membrane proteins**
   - to enable the transfer of energy.

3. The excitation energy is passed to the ***Reaction Center*** of the antenna complex.
   - In plants, the pigment molecule in the center is always a molecule of ***chlorophyll a.***

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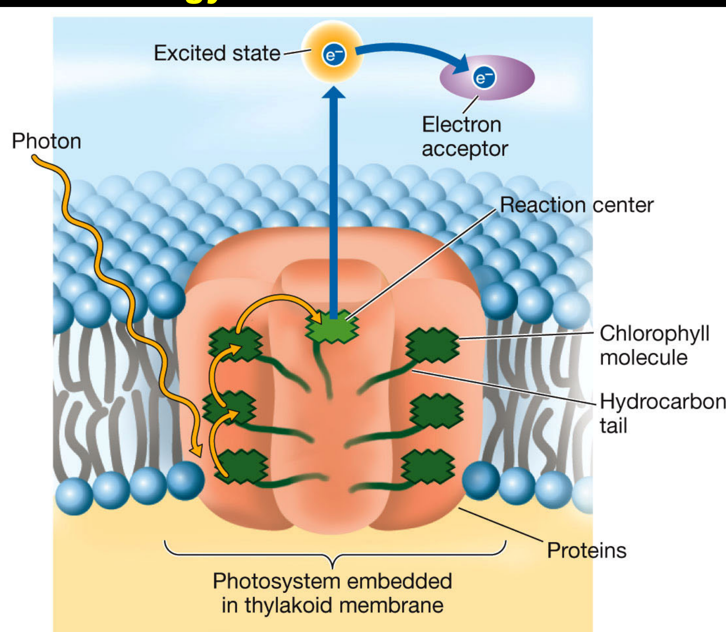
Fig. 10.8 *Energy Transfer and Electron Transport*



LIFE 9e, Figure 10.8

http://www.whyevolution.com/photosyn.html

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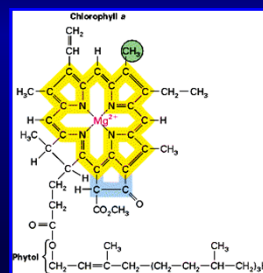
Light and Pigments

- ***Excited chlorophyll (Chl*)*** in the reaction center acts as a reducing agent.
  - electrons of an excited molecule are less tightly held by the nucleus (less stable!!),
  - and more likely to be passed on in a redox reaction to an oxidizing agent.



- Chl* can react with an oxidizing agent in a reaction such as:
  - **$Chl^* + A \rightarrow Chl^+ + A^-$**
- **Chlorophyll becomes a reducing agent** in a redox reaction.

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10.4) The Light Reactions: Electron Transport, Reductions, & Photophosphorylation

1. The energized electron that leaves the Chl* in the reaction center immediately participates in a series of redox reactions.
   - The electron flows through a series of carriers in the **thylakoid membrane**, = electron transport.
   - 2 energy rich products of the light reactions result:
     - NADPH + H^+ and ATP, are the result.
2. Chemiosmotic synthesis of ATP in the thylakoid membrane is called ***PhotoPhosphorylation***.
3. There are two different systems for transport of electrons in photosynthesis.
   a) **Noncyclic Electron Transport** produces **NADPH** + H^+ and **ATP** & **O_2**.
   b) **Cyclic Electron Transport** produces only **ATP**.

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A. Light Reactions: Noncyclic Electron Transport

- In ***NONCYCLIC Electron Transport***, two photosystems are needed.
- ***Photosystems*** = light-driven molecular units.
  - consist of ***many chlorophyll molecules and accessory pigments.***
  - ***bound to proteins*** in separate energy-absorbing antenna systems.

1. ***Photosystem I*** uses light energy to reduce $NADP^+ \rightarrow$ **NADPH + H^+.**
   - The reaction center contains a chlorophyll *a* molecule called **P_{700}**
     - it best absorbs light at a wavelength of 700 nm.
2. ***Photosystem II*** uses light energy to oxidize water.
   - producing electrons, protons, and O_2.
   - The reaction center contains a chlorophyll *a* molecule called **P_{680}**
     - best absorbs light at a wavelength of 680 nm.

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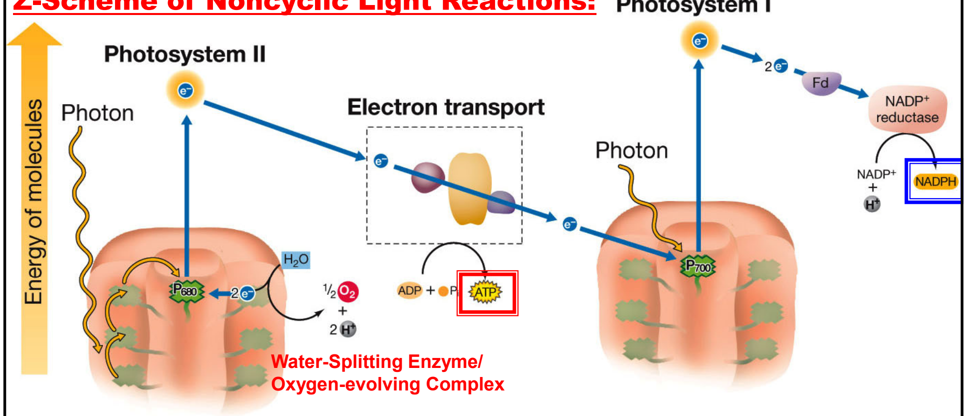
Figure 10.10 ***Noncyclic Electron Transport Uses Two Photosystems***

Z-Scheme of Noncyclic Light Reactions:



- ***To keep noncyclic electron transport going, both photosystems must constantly be absorbing light.***

http://vcell.ndsu.nodak.edu/animations/photosynthesis/movie.htm

***LIFE* 9e, Figure 10.10**

http://vcell.ndsu.nodak.edu/animations/photosystemII/movie.htm

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B. Light Reactions: Cyclic Electron Transport

1. **Cyclic** electron transport produces only ATP.
   a) called cyclic, because:
   b) the electron passed from an excited P_{700} molecule cycles back to the same P_{700} molecule.

2. ***Water** does not enter into the cyclic electron flow reactions, and no O_2 is released.*
3. In cyclic electron flow, **Photosystem-I acts on its own**.

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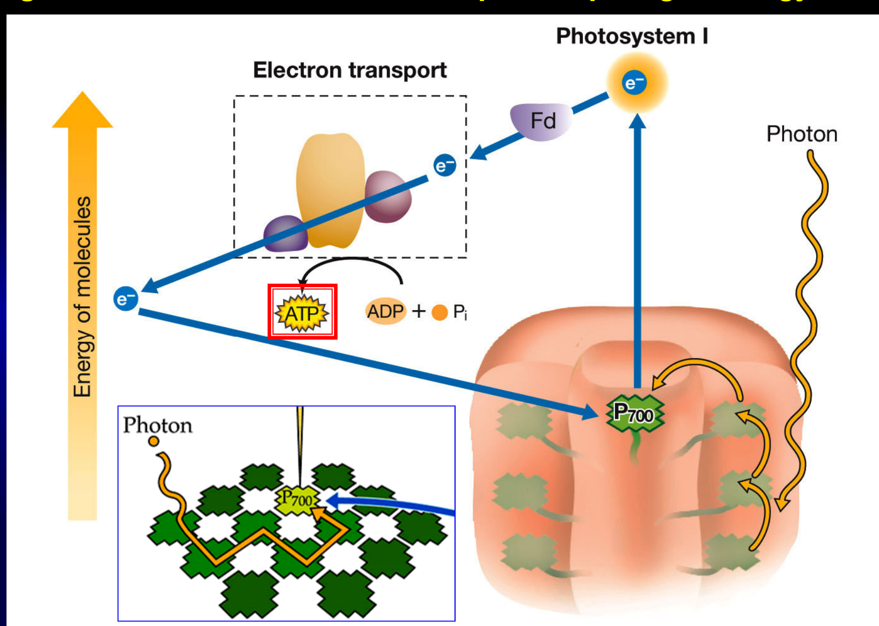
Fig. 10.11 ***CYCLIC Electron Transport Traps Light Energy as ATP***



***LIFE 9e*, Figure 10.11**

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C. Light Reactions: Photophosphorylation

1. ATP is produced by a ***Chemiosmotic Mechanism*** similar to that of mitochondria, called ***PhotoPhosphorylation***.
   a) High-energy electrons move through a series of redox reactions
   b) release energy used to transport protons across the membrane.

2. Active proton transport results in the ***Proton-Motive Force***: a difference in pH and electric charge across the membrane.

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Light Reactions: Photophosphorylation & Chemiosmosis

1. **The electron carriers in the thylakoids *move protons into the interior of the thylakoid (lumen!)***
   – the ***inside*** becomes ***acidic*** with respect to the outside.

- This difference in pH:
  – leads to the diffusion of H+ out of the thylakoid
  – through specific protein channels, ***ATP Synthases***.

2. ***The ATP Synthases couple*** *the formation of ATP to proton diffusion back across the thylakoid membrane.*
   – **** JUST LIKE Ox. Phos'n in Mitochondria!!!! ****

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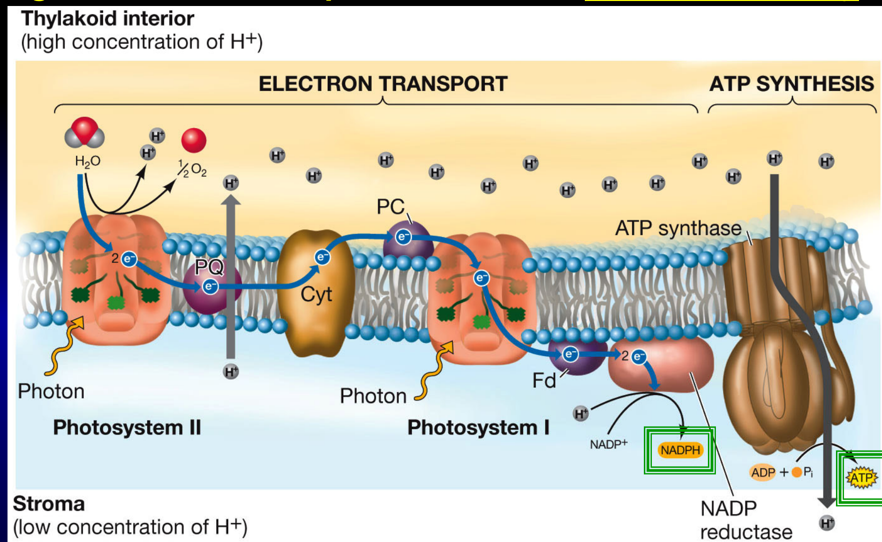
Figure 10.12 *Chloroplasts Form ATP Chemiosmotically*



http://vcell.ndsu.nodak.edu/animations/photosystemII/movie.htm

LIFE 9e, Figure 10.12 (Part 2)

http://www.science.smith.edu/departments/Biology/Bio231/ltrxn.html

http://www.sumanasinc.com/webcontent/anisamples/majorsbiology/harvestinglight.swf

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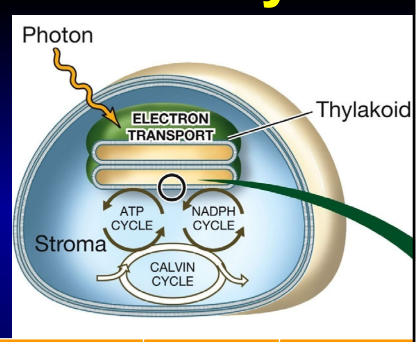
10.5) Making Carbohydrate from CO_2: The Calvin–Benson Cycle

- Calvin-Benson cycle reactions = in stroma.
  - does not use sunlight directly;
  - but *it requires the ATP and NADPH + H^+ produced in the light reactions*
  - these cannot be "stockpiled".



- ***Calvin-Benson reactions require light indirectly & take place only in the presence of light!***
  (not really "Dark" rxns!)

Energy Transfer Molecule Type:	Mostly for Catabolism	Mostly for Anabolism
Triphosphate Nucleotides	**ATP**	**GTP**
High-Energy Electron Carriers	**NADH** (and **$FADH_2$**)	**NADPH**

http://www.science.smith.edu/departments/Biology/Bio231/ltrxn.html

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A. The Calvin–Benson Cycle: Experimental Discovery

1. Experiments showed:
   – steps of the Calvin–Benson cycle required radioactively labeled carbon in *CO_2.
2. Exposure of ***Chlorella*** (unicellular algae) cells to $^{14}CO_2$ for 3 seconds:
   – one compound was labeled with ^{14}C.
   – a 3-C sugar called **3-phosphoglycerate (3PG).**
3. Other products of the cycle:
   – found by stepwise increases in time of exposure
   – until the whole pathway was revealed.

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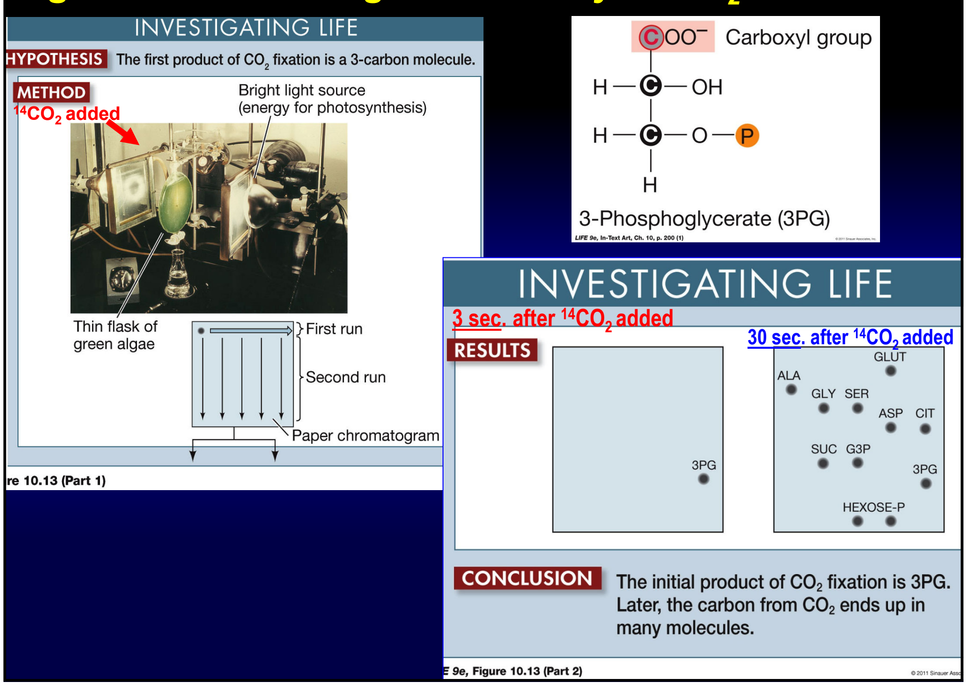
Figure 10.13 *Tracing the Pathway of CO_2*



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B. Fixation of CO_2: The Calvin–Benson Cycle

1. The initial reaction of the Calvin–Benson cycle **fixes one CO_2 into a 5-carbon compound, ribulose 1,5-bisphosphate (RuBP).**
2. An unstable **intermediate 6-carbon compound** forms → breaks down into **two 3-C molecules of 3PG**.
3. The enzyme that catalyzes the fixation of CO_2 is ***ribulose bisphosphate carboxylase/oxygenase***, called ***RUBISCO***. ***(Carbon-Fixation!!)***
4. *Rubisco is the most abundant protein in the world!!*

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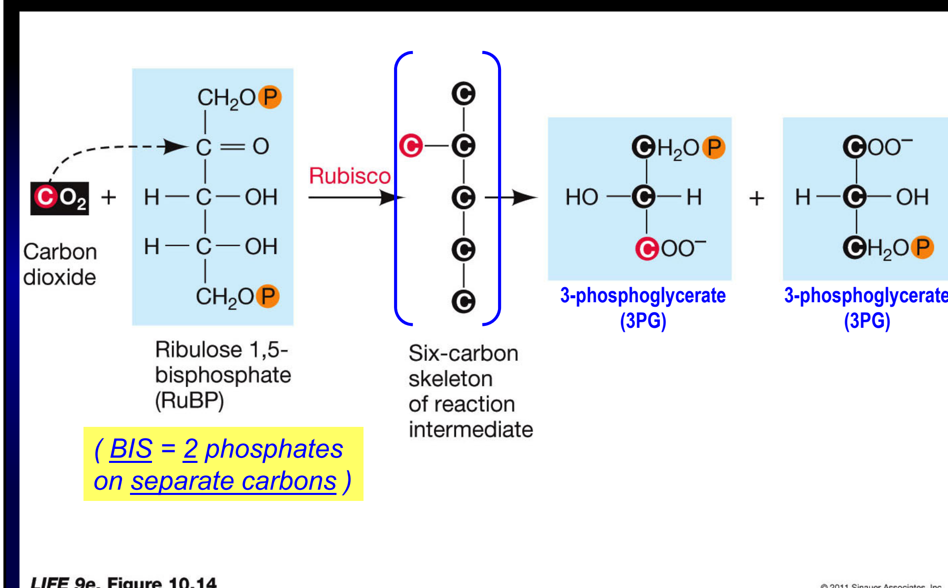
Figure 10.14 *RuBP Is the Carbon Dioxide Acceptor*



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Fixation of CO_2: The Calvin–Benson Cycle

- **The Calvin–Benson cycle consists of three processes:**
  1. **Fixation of CO_2**, by combination with **RuBP** (catalyzed by ***RUBISCO***).
  2. Conversion of fixed CO_2 into carbohydrate (3PG) ***(this step uses ATP and NADPH).***
  3. Regeneration of the CO_2 acceptor RuBP (5/6 of the carbon fixed!!!) by ATP.

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C. The Calvin–Benson Cycle: Products

- The end product of the cycle is **glyceraldehyde 3-phosphate, G3P**.
- **There are two fates for the stored G3P:**
  - **1/3** ends up as ***starch***, which is stored in the chloroplast and serves as a source of glucose.
  - **2/3** is converted to the disaccharide ***sucrose***, which is transported to other organs.

http://www.science.smith.edu/departments/Biology/Bio231/calvin.html

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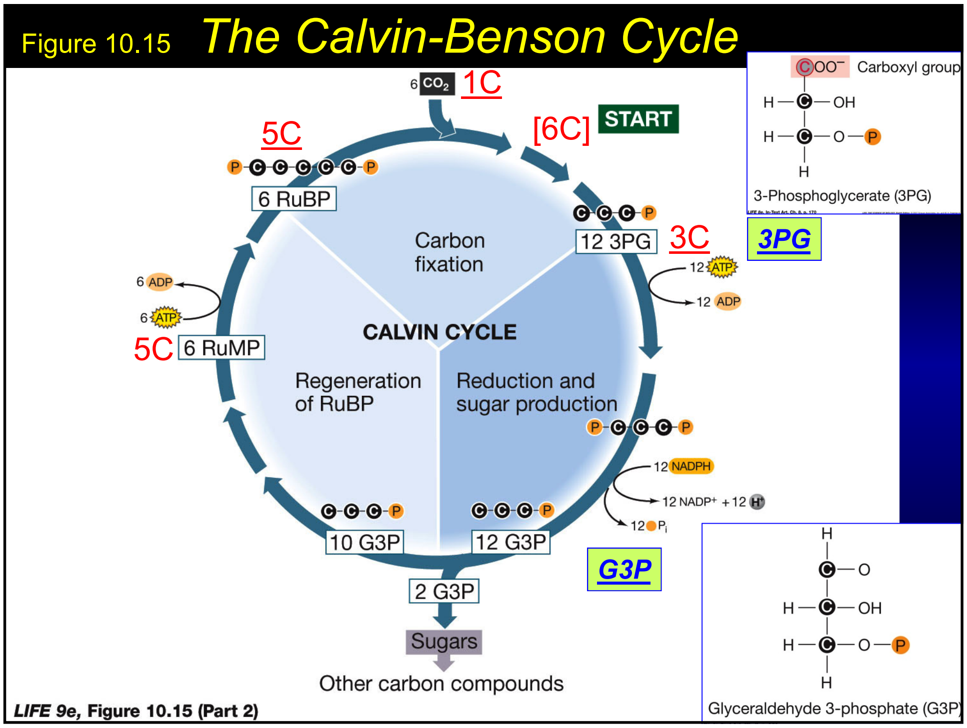

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Making Carbohydrate from CO_2: The Calvin–Benson Cycle

- Products of the Calvin–Benson cycle:
  - are vitally important to the ***biosphere***:
  - they are the total energy yield from sunlight conversion by green plants.

❖ ***Most of the stored energy is released by the <u>plant's own Glycolysis & Cellular Respiration</u>.***
  - Some of the carbon of glucose becomes **part of amino acids, lipids, & nucleic acids**.
  - Some of the stored energy is **<u>consumed by heterotrophs</u>**, where glycolysis and respiration release the stored energy.

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10.6) Metabolic Pathways in Plants

1. Green plants are ***autotrophs*** = "Producers"!!
   - synthesize all their molecules from 3 simple starting materials: **CO_2, H_2O, & NH_4.**
2. To satisfy their need for ATP, plants, like all other organisms, carry out **cellular respiration**.
   - Both aerobic respiration and fermentation can occur in plants
   - respiration is more common.
3. Cellular respiration takes place **both in dark and in light**.
4. Photosynthesis and respiration = closely linked by the Calvin–Benson cycle.
   - Some **G3P** from Calvin–Benson → pyruvate, the end product of glycolysis.
5. Some G3P → **hexose phosphates**, which can enter glycolysis.
   - Once carbon skeletons from the Calvin–Benson cycle enter glycolysis and the TCA cycle, they can be ***used to make lipids, proteins, and other carbohydrates***.

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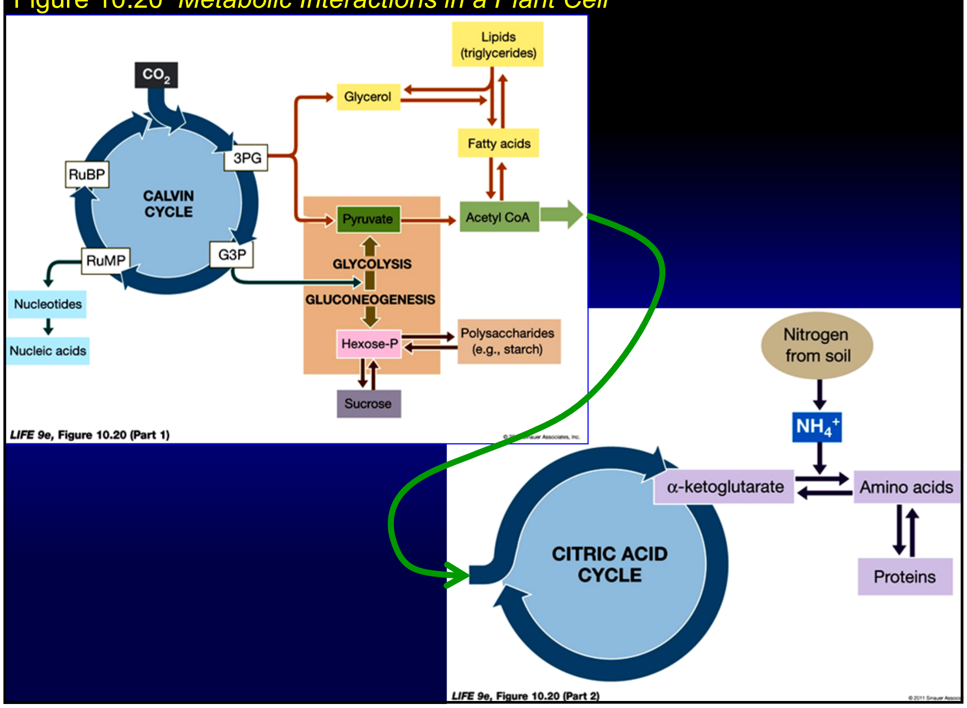
Figure 10.20 *Metabolic Interactions in a Plant Cell*



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Metabolic Pathways in Plants

1. Energy flows from ***sunlight*** to ***reduced carbon*** in photosynthesis to ***ATP*** in respiration.
2. Energy can be stored in ***macromolecules*** such as polysaccharides, lipids, and proteins.
3. For plants *to grow,*
   a) ***energy storage must exceed energy released*** or
   b) overall **carbon fixation** by photosynthesis must exceed respiration.
4. The capture and movement of sun energy becomes the **basis for ecological food chains**.