Chapter 10

Photosynthesis

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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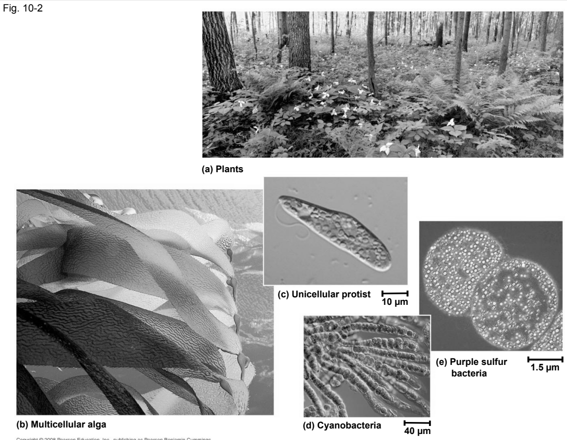
Lectures by Chris Romero, updated by Erin Barley with contributions from Joan Sharp

Fig. 10-2



Overview: The Process That Feeds the Biosphere

- **Photosynthesis** is the process that converts solar energy into chemical energy
- Directly or indirectly, photosynthesis nourishes almost the entire living world

- **Heterotrophs** obtain their organic material from other organisms
- Heterotrophs are the *consumers* of the biosphere
- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O_2

- **Autotrophs** sustain themselves without eating anything derived from other organisms
- Autotrophs are the *producers* of the biosphere, producing organic molecules from CO_2 and other inorganic molecules
- Almost all plants are *photo*autotrophs, using the energy of sunlight to make organic molecules from H_2O and CO_2

Concept 10.1: Photosynthesis converts light energy to the chemical energy of food

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria
- The structural organization of these cells allows for the chemical reactions of photosynthesis

Chloroplasts: The Sites of Photosynthesis in Plants

- Leaves are the major locations of photosynthesis
- Their green color is from **chlorophyll**, the green pigment within chloroplasts
- Light energy absorbed by chlorophyll drives the synthesis of organic molecules in the chloroplast
- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**

Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

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

- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- A typical mesophyll cell has 30–40 chloroplasts
- The chlorophyll is in the membranes of **thylakoids** (connected sacs in the chloroplast); thylakoids may be stacked in columns called *grana*
- Chloroplasts also contain **stroma**, a dense fluid

The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules

Fig. 10-3

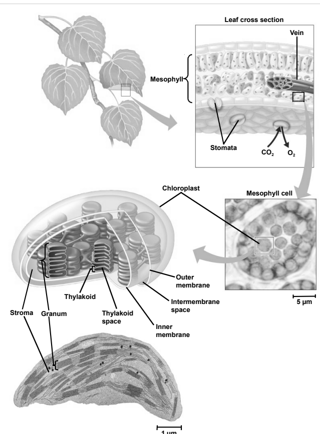
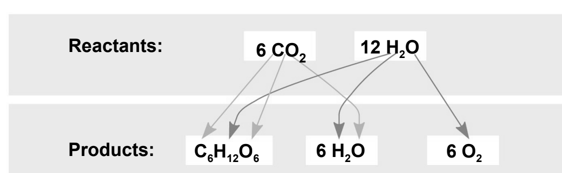


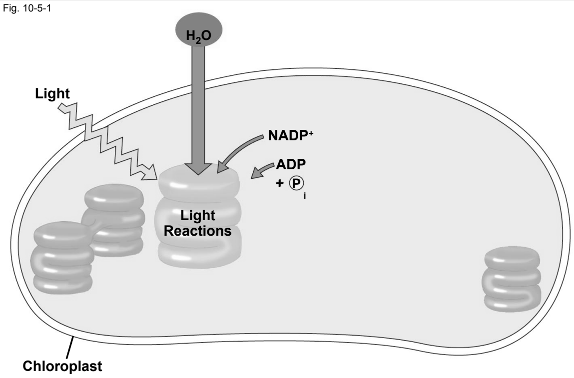
Fig. 10-4



Photosynthesis as a Redox Process

- Photosynthesis is a redox process in which H_2O is oxidized and CO_2 is reduced

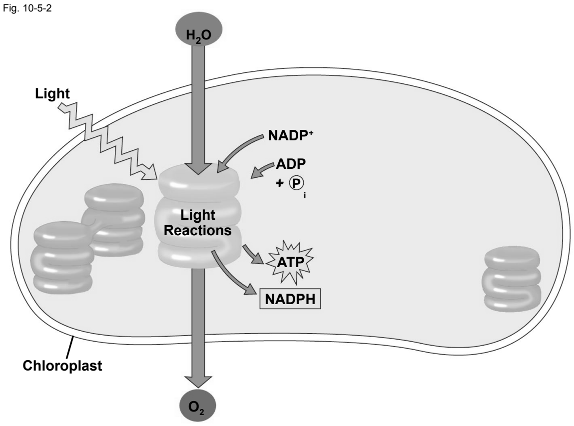
Fig. 10-5-1



The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
- The light reactions (in the thylakoids):
  - Split H_2O
  - Release O_2
  - Reduce **NADP$^+$** to NADPH
  - Generate ATP from ADP by **photophosphorylation**

Fig. 10-5-2



- The Calvin cycle (in the stroma) forms sugar from CO_2, using ATP and NADPH
- The Calvin cycle begins with **carbon fixation**, incorporating CO_2 into organic molecules

Fig. 10-5-3

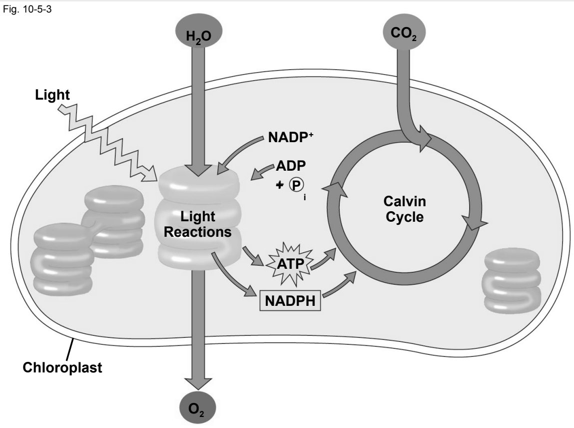
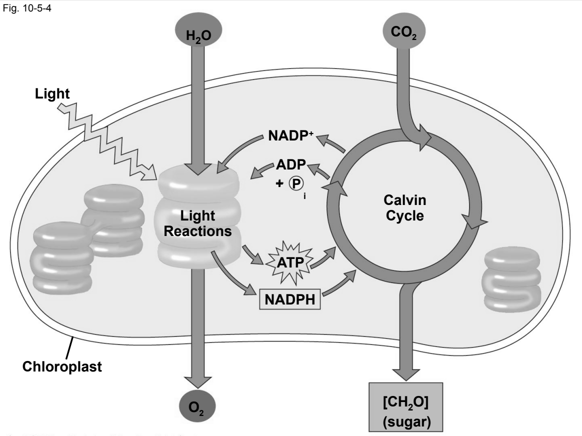


Fig. 10-5-4

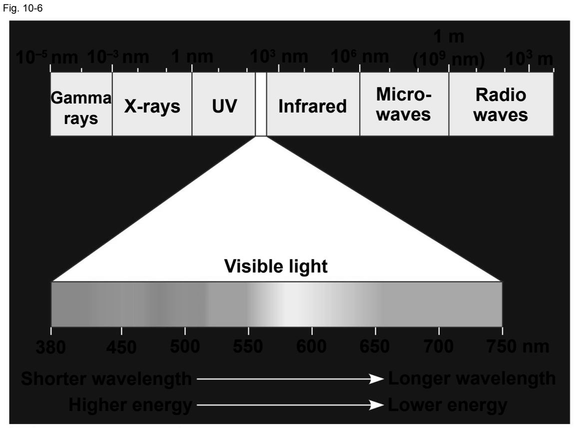


- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (including those that drive photosynthesis) that produce colors we can see
- Light also behaves as though it consists of discrete particles, called **photons**

Concept 10.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

Fig. 10-6



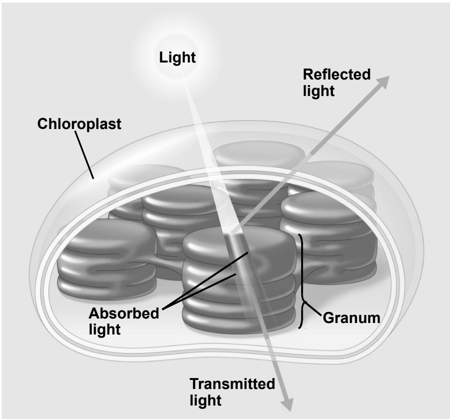
The Nature of Sunlight

- Light is a form of electromagnetic energy, also called electromagnetic radiation
- Like other electromagnetic energy, light travels in rhythmic waves
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

Photosynthetic Pigments: The Light Receptors

- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll reflects and transmits green light

Fig. 10-7



- Chlorophyll *a* is the main photosynthetic pigment
- Accessory pigments, such as **chlorophyll *b***, broaden the spectrum used for photosynthesis
- Accessory pigments called **carotenoids** absorb excessive light that would damage chlorophyll

- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of radiation in driving a process

Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state, which is unstable
- When excited electrons fall back to the ground state, photons are given off, an afterglow called fluorescence
- If illuminated, an isolated solution of chlorophyll will fluoresce, giving off light and heat

Fig. 10-9

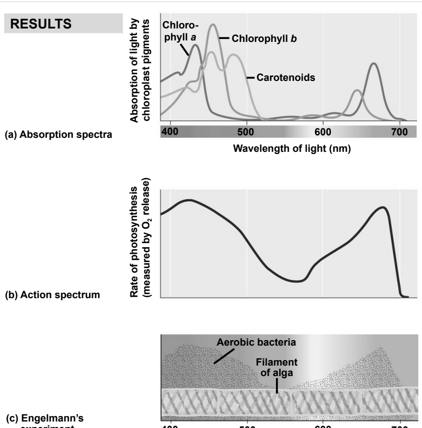
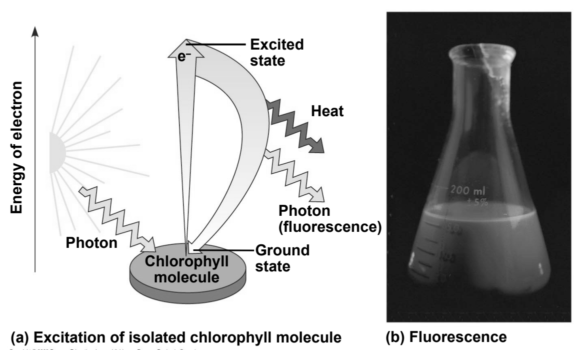


Fig. 10-11



A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

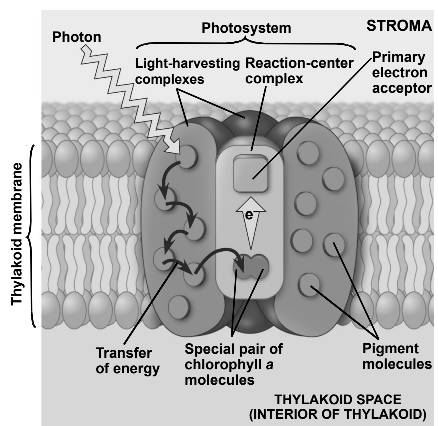
- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) funnel the energy of photons to the reaction center

- There are two types of photosystems in the thylakoid membrane
- **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of 680 nm
- The reaction-center chlorophyll *a* of PS II is called P680

- A **primary electron acceptor** in the reaction center accepts an excited electron from chlorophyll *a*
- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions

- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

Fig. 10-12



Linear Electron Flow

- During the light reactions, there are two possible routes for electron flow: cyclic and linear
- **Linear electron flow**, the primary pathway, involves both photosystems and produces ATP and NADPH using light energy

- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680
- An excited electron from P680 is transferred to the primary electron acceptor

Fig. 10-13-2

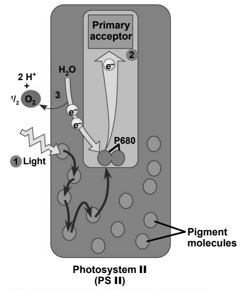
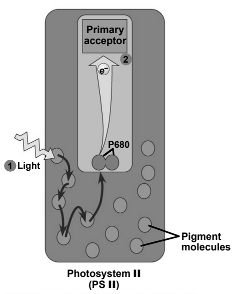


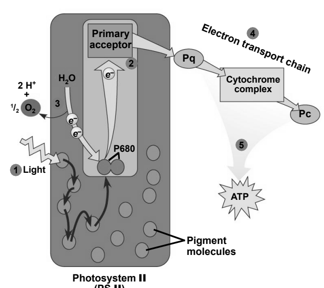
Fig. 10-13-1



- Each electron "falls" down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of H^+ (protons) across the membrane drives ATP synthesis

- $P680^+$ (P680 that is missing an electron) is a very strong oxidizing agent
- H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680
- O_2 is released as a by-product of this reaction

Fig. 10-13-3



- In PS I (like PS II), transferred light energy excites P700, which loses an electron to an electron acceptor
- P700+ (P700 that is missing an electron) accepts an electron passed down from PS II via the electron transport chain

Fig. 10-13-5

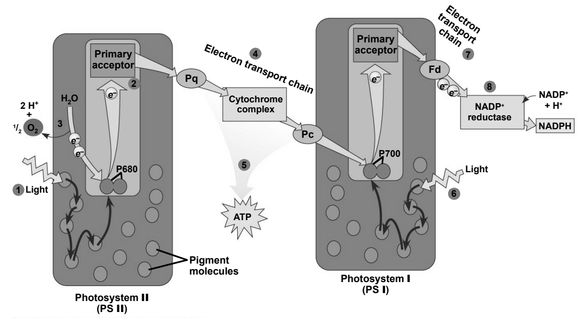
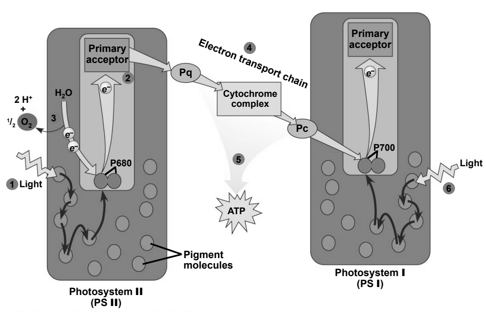


Fig. 10-13-4

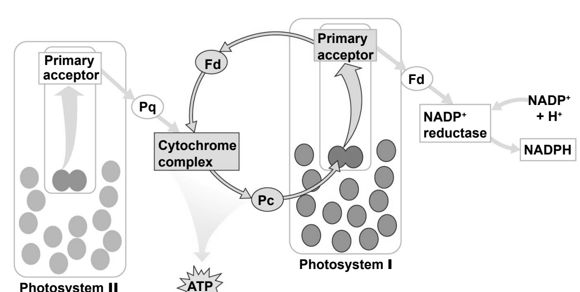


Cyclic Electron Flow

- **Cyclic electron flow** uses only photosystem I and produces ATP, but not NADPH
- Cyclic electron flow generates surplus ATP, satisfying the higher demand in the Calvin cycle

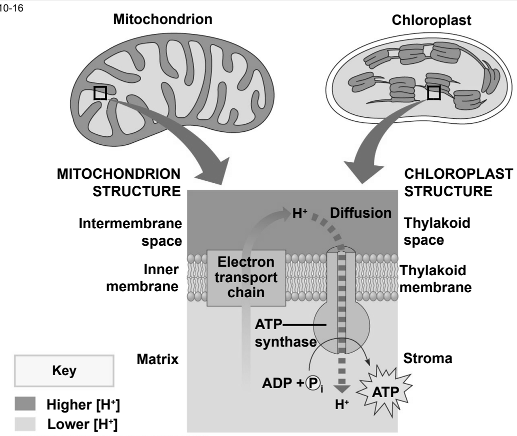
- Each electron "falls" down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
- The electrons are then transferred to NADP+ and reduce it to NADPH
- The electrons of NADPH are available for the reactions of the Calvin cycle

Fig. 10-15



- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

Fig. 10-16



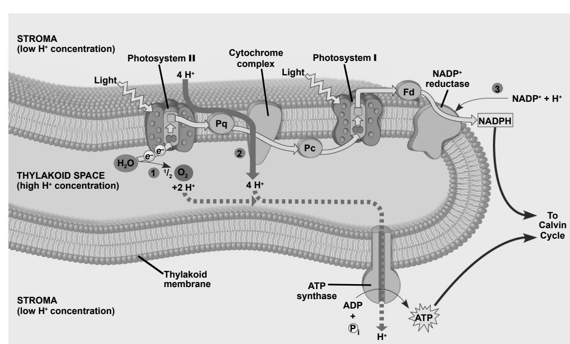
A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria generate ATP by chemiosmosis, but use different sources of energy
- Mitochondria transfer chemical energy from food to ATP; chloroplasts transform light energy into the chemical energy of ATP
- Spatial organization of chemiosmosis differs between chloroplasts and mitochondria but also shows similarities

- ATP and NADPH are produced on the side facing the stroma, where the Calvin cycle takes place
- In summary, light reactions generate ATP and increase the potential energy of electrons by moving them from H_2O to NADPH

- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma

Fig. 10-17



Concept 10.3: The Calvin cycle uses ATP and NADPH to convert CO_2 to sugar

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle
- The cycle builds sugar from smaller molecules by using ATP and the reducing power of electrons carried by NADPH

Concept 10.4: Alternative mechanisms of carbon fixation have evolved in hot, arid climates

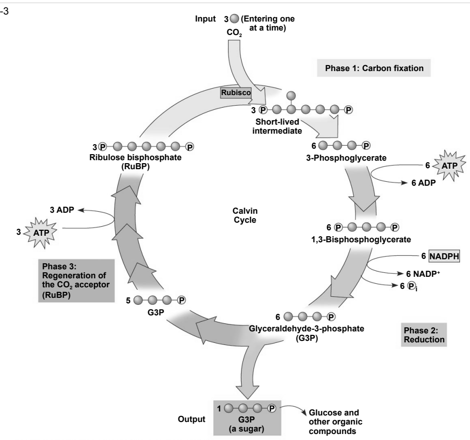
- Dehydration is a problem for plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis
- On hot, dry days, plants close stomata, which conserves H_2O but also limits photosynthesis
- The closing of stomata reduces access to CO_2 and causes O_2 to build up
- These conditions favor a seemingly wasteful process called photorespiration

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde-3-phospate (G3P)**
- For net synthesis of 1 G3P, the cycle must take place three times, fixing 3 molecules of CO_2
- The Calvin cycle has three phases:
  - **Carbon fixation** (catalyzed by **rubisco**)
  - **Reduction**
  - **Regeneration of the CO_2 acceptor (RuBP)**

Photorespiration: An Evolutionary Relic?

- In most plants (**C_3 plants**), initial fixation of CO_2, via rubisco, forms a three-carbon compound
- In **photorespiration**, rubisco adds O_2 instead of CO_2 in the Calvin cycle
- Photorespiration consumes O_2 and organic fuel and releases CO_2 without producing ATP or sugar

Fig. 10-18-3



- Photorespiration may be an evolutionary relic because rubisco first evolved at a time when the atmosphere had far less O_2 and more CO_2
- Photorespiration limits damaging products of light reactions that build up in the absence of the Calvin cycle
- In many plants, photorespiration is a problem because on a hot, dry day it can drain as much as 50% of the carbon fixed by the Calvin cycle