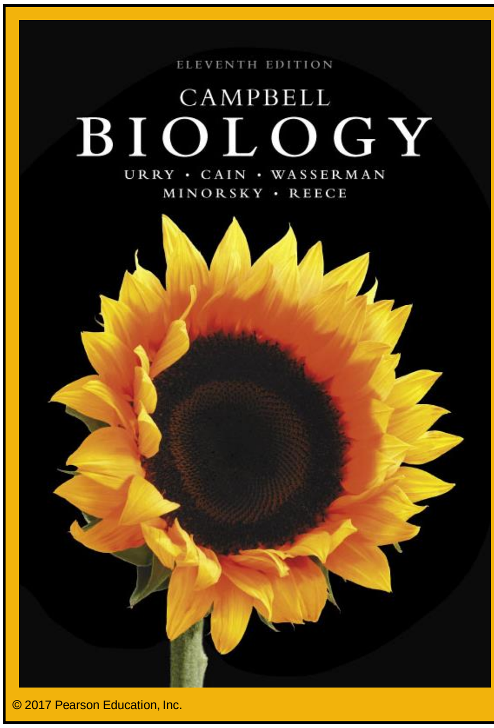


Chapter 10

Photosynthesis

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

The Process That Feeds the Biosphere

- Plants and other photosynthetic organisms contain organelles called **chloroplasts**
- **Photosynthesis** is the process that converts solar energy into chemical energy within chloroplasts
- Directly or indirectly, photosynthesis nourishes almost the entire living world
- Photosynthesis occurs in *plants*, *algae*, certain other *unicellular eukaryotes*, and some *prokaryotes*

- **Autotrophs** are “self-feeders” that 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 **photoautotrophs**, using the energy of sunlight to make organic molecules

Figure 10.1

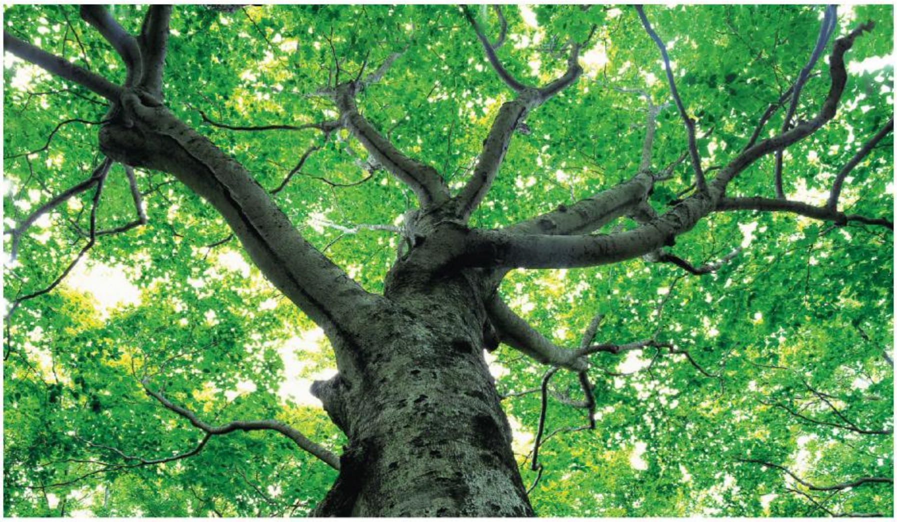
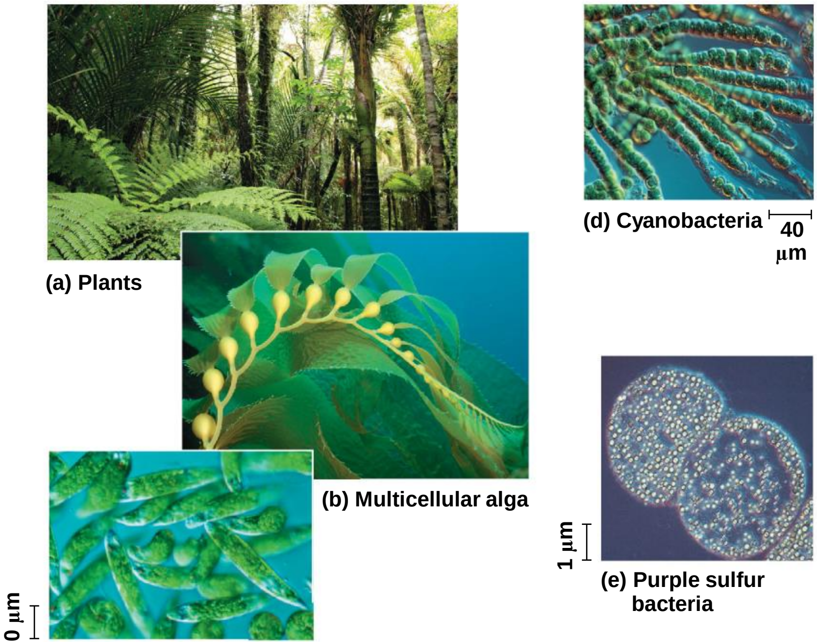


Figure 10.1a

Other organisms also benefit from photosynthesis.

Figure 10.2

Examples of photoautotrophs



- **Heterotrophs** obtain organic material from *other organisms*
- Heterotrophs are the **consumers** of the biosphere
- Some eat other living organisms; others, called **decomposers**, consume *dead organic material or feces*
- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O_2

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

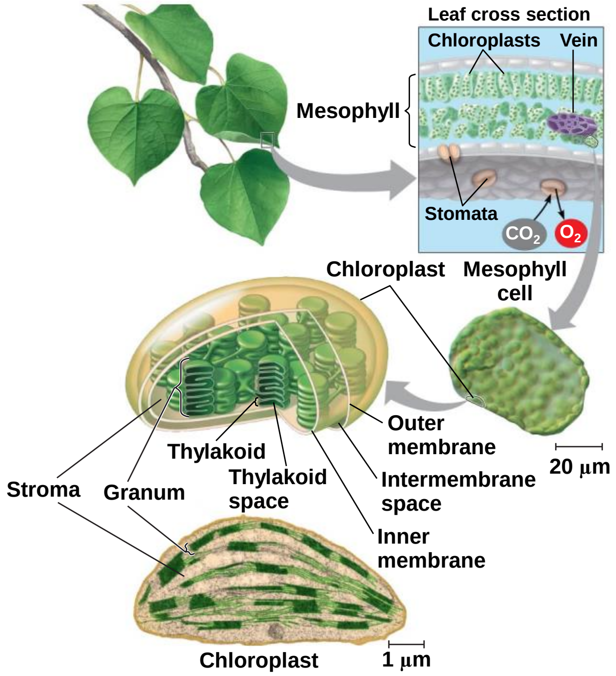
- Chloroplasts are *structurally similar* to, and likely evolved from, *photosynthetic bacteria*
- The structural organization of these organelles allows for the chemical reactions of photosynthesis

Chloroplasts: The Sites of Photosynthesis in Plants

- *Leaves* are the major locations of photosynthesis in plants
- Chloroplasts are found mainly in cells of the **mesophyll**, *the interior tissue of the leaf*
- Each mesophyll cell contains *30–40 chloroplasts*
- CO_2 enters and O_2 exits the leaf through *microscopic pores* called **stomata**

- A chloroplast has an envelope of two membranes surrounding a dense fluid called the **stroma**
- **Thylakoids** are connected sacs in the chloroplast that compose a third membrane system
- Thylakoids may be stacked in columns called **grana**
- **Chlorophyll**, the pigment that gives leaves their green color, resides in the thylakoid membranes

Figure 10.4



Photosynthesis: *Splitting of Water*

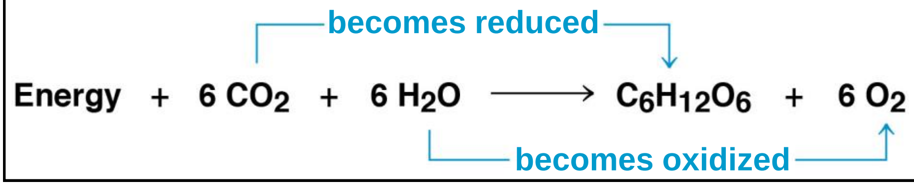
- Photosynthesis is a complex series of reactions that can be summarized as the following equation:

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

- The overall chemical change during photosynthesis is the *reverse* of the one that occurs during *cellular respiration*
- Chloroplasts split H_2O into **hydrogen** and **oxygen**, incorporating *the electrons of hydrogen into sugar molecules* and *releasing oxygen gas as a by-product*

Photosynthesis as a Redox Process

- Photosynthesis *reverses the direction of electron flow compared to respiration*
- **Photosynthesis is a redox process in which H_2O is oxidized and CO_2 is reduced**
- ***Remember***: *In respiration, O_2 is reduced to H_2O and sugar molecules are oxidized to CO_2*
- Photosynthesis is an ***endergonic process***; the energy is provided by *light*



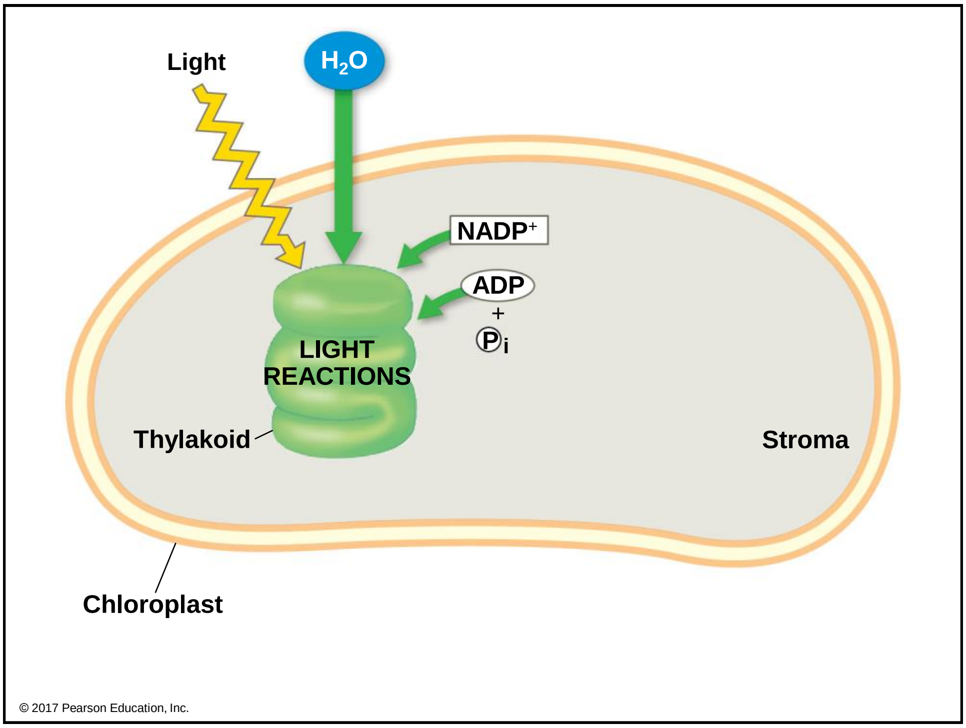
becomes reduced

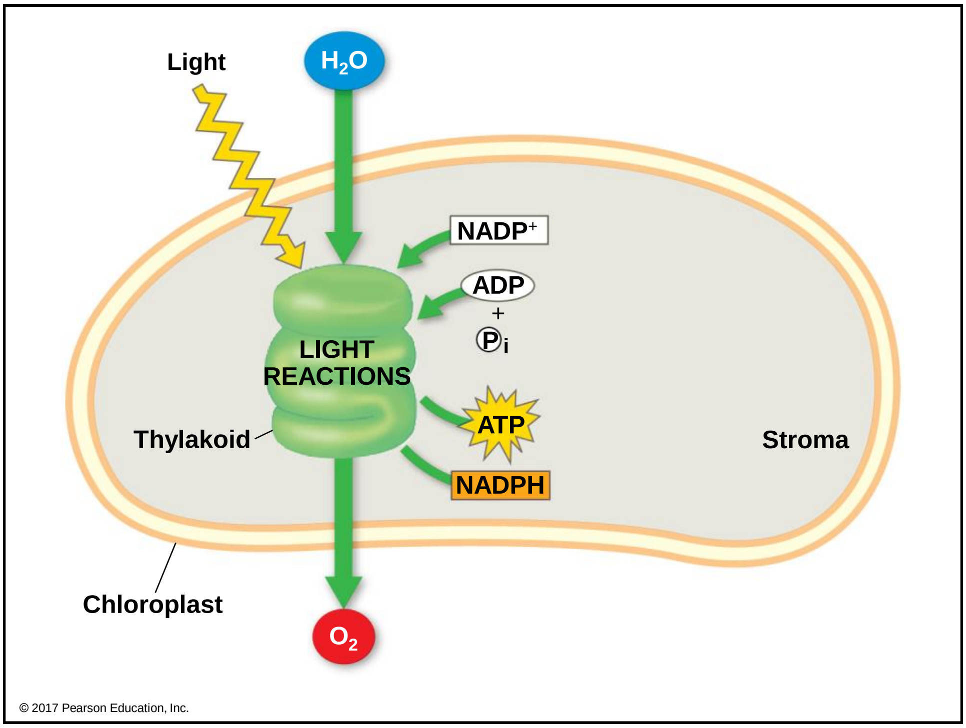
$$\text{Energy} + 6\,CO_2 + 6\,H_2O \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

becomes oxidized

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 the electron acceptor **$NADP^+$** to **NADPH**
  - Generate ATP from ADP by **photophosphorylation**


Light
H_2O
$NADP^+$
ADP
+
Ⓟi
LIGHT REACTIONS
Thylakoid
Stroma
Chloroplast


Light
H_2O
$NADP^+$
ADP
+
Ⓟi
LIGHT REACTIONS
ATP
NADPH
Thylakoid
Stroma
Chloroplast
O_2

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

Figure 10.6_3

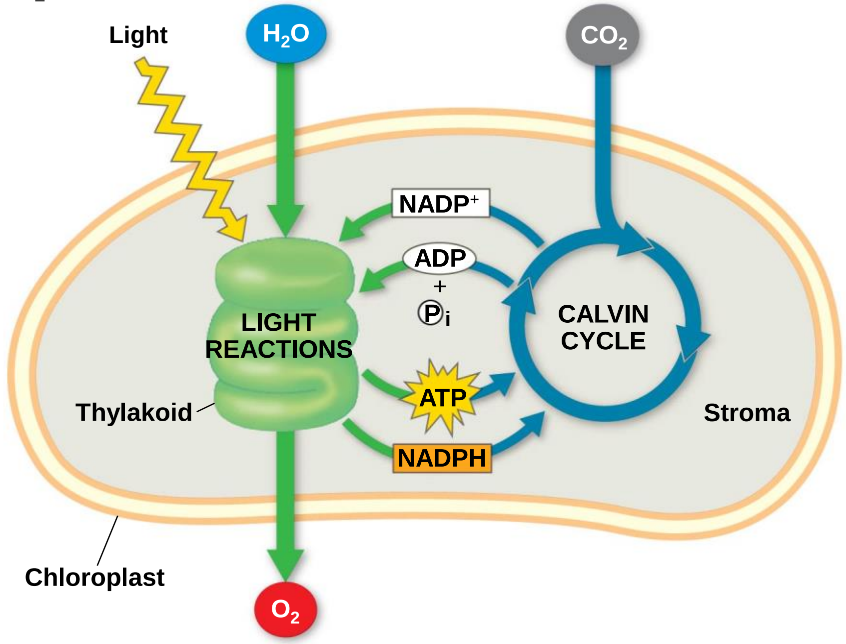
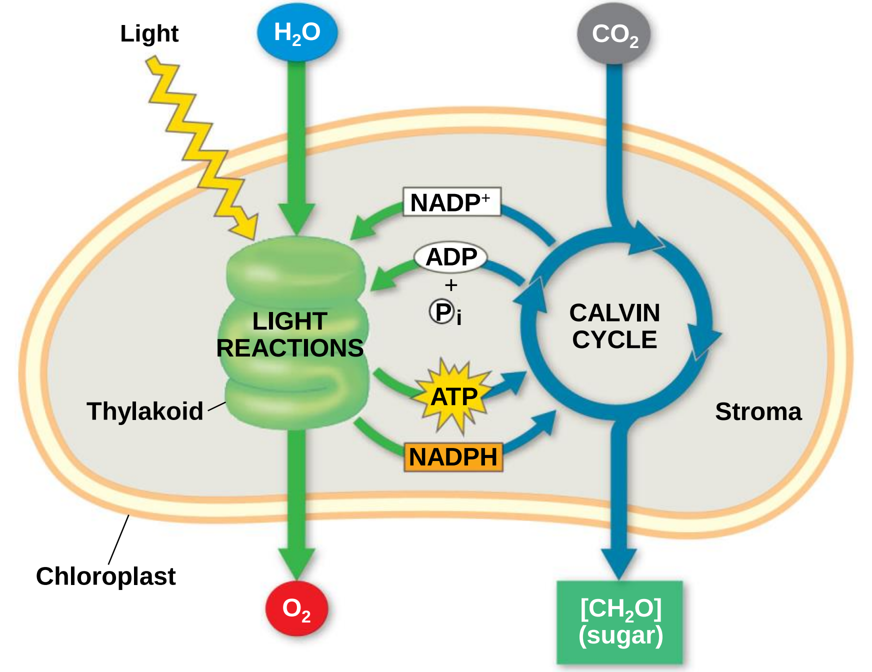


Figure 10.6_4

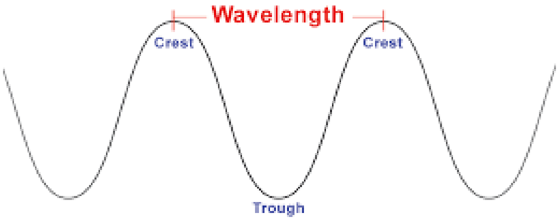


Concept 10.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

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

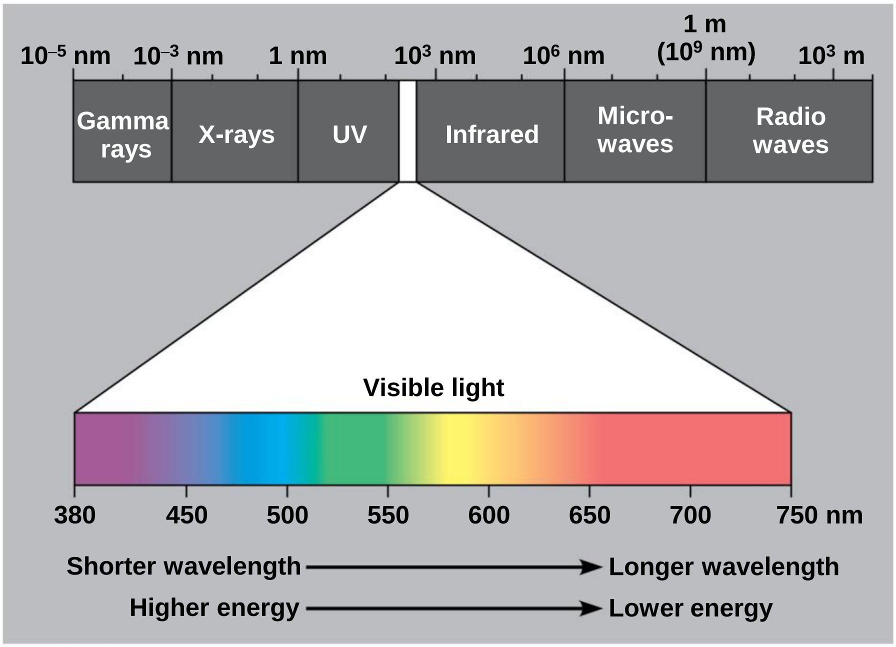
The Nature of Sunlight

- Light is *electromagnetic energy*, also called electromagnetic radiation
- Electromagnetic energy travels in rhythmic waves
- Light also behaves as if it consists of discrete particles, called photons
- **Wavelength** is the distance between crests of electromagnetic waves



- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (380 nm to 750 nm) that produce colors we can see
- Visible light also includes the wavelengths that drive photosynthesis

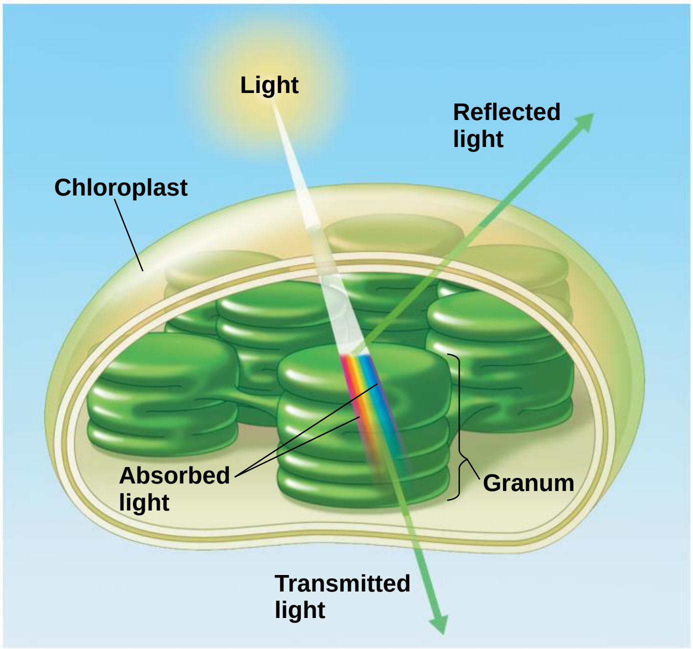
Figure 10.7



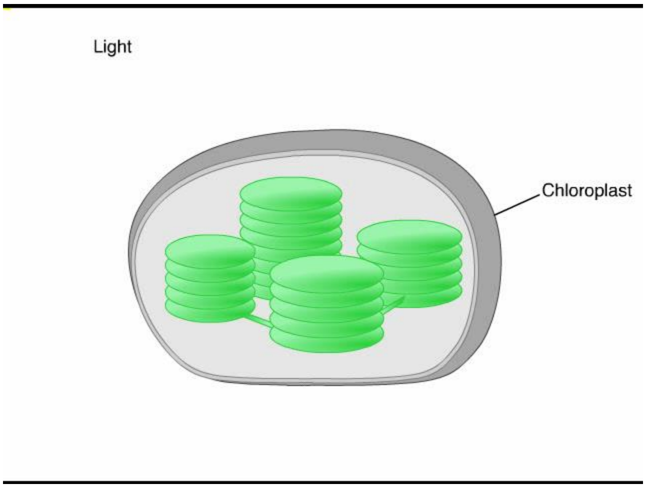
Photosynthetic Pigments: The Light Receptors

- **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*

Figure 10.8



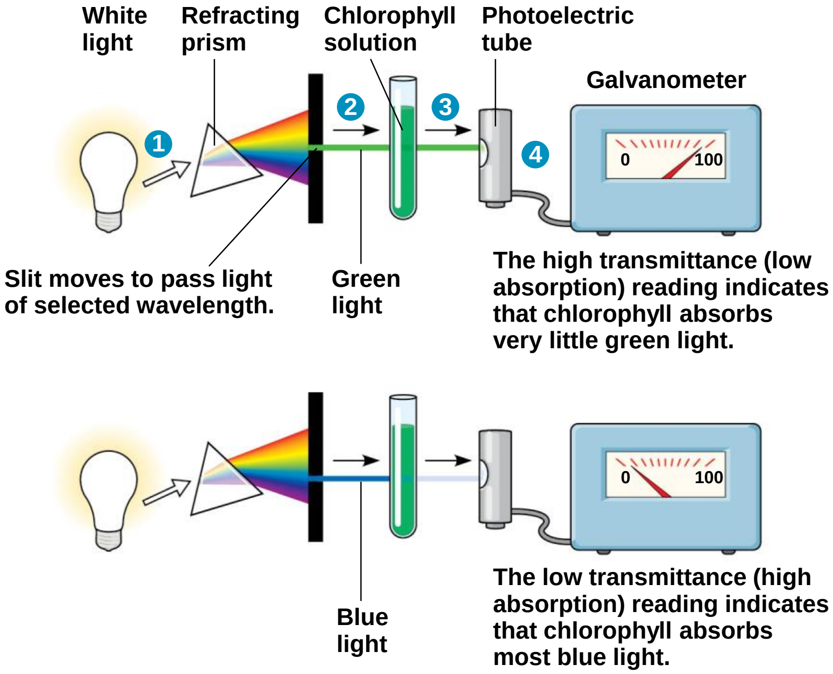
Animation: Light Energy and Pigments



- There are three types of pigments in chloroplasts:
  - **Chlorophyll *a***, the key light-capturing pigment
  - **Chlorophyll *b***, an accessory pigment
  - **Carotenoids**, a separate group of accessory pigments

- A **spectrophotometer** measures a pigment’s ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

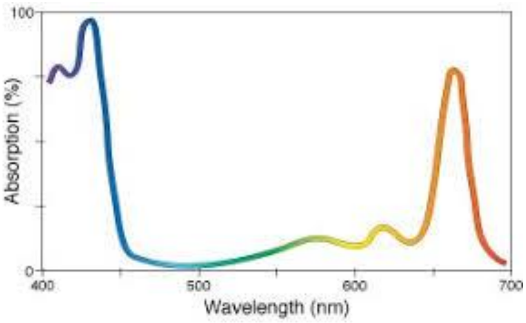
Figure 10.9



The high transmittance (low absorption) reading indicates that chlorophyll absorbs very little green light.

The low transmittance (high absorption) reading indicates that chlorophyll absorbs most blue light.

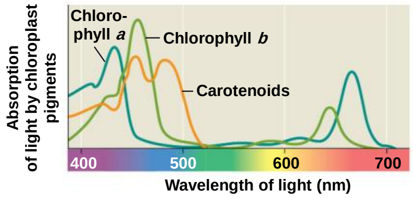
- An **absorption spectrum** is a graph plotting a pigment’s light absorption versus wavelength



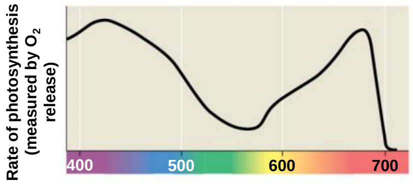
- The absorption spectrum of chlorophyll *a* suggests that violet-blue and red light work best for photosynthesis

Figure 10.10

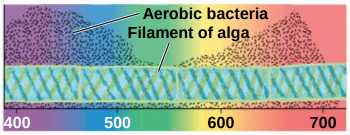
- An **action spectrum** profiles the relative effectiveness of different wavelengths of radiation in driving a process (e.g. photosynthesis)



(a) Absorption spectra



(b) Action spectrum



(c) Engelmann's experiment

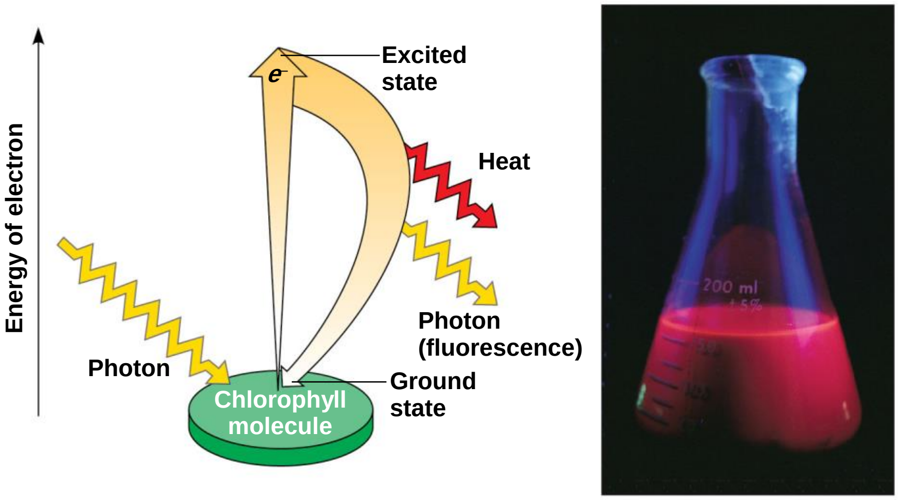
Data from T. W. Engelmann, *Bacterium photometricum*. Ein Beitrag zur vergleichenden Physiologie des Licht-und Farbensinnes, *Archiv. für Physiologie* 30:95–124 (1883).

- The action spectrum for photosynthesis is **broader** than the absorption spectrum of chlorophyll
- *Accessory pigments, such as chlorophyll b, broaden the spectrum used for photosynthesis*
- Other accessory pigments (**carotenoids**) may also broaden the spectrum of colors that drive photosynthesis
- Some carotenoids function in ***photoprotection***; they absorb excessive light that would damage chlorophyll or react with oxygen

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, excess energy is released as **heat**
- In isolation, some pigments also emit light, an afterglow called **fluorescence**

Figure 10.12



(a) Excitation of isolated chlorophyll molecule

(b) Fluorescence

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

- A **photosystem** consists of a reaction-center complex surrounded by light-harvesting complexes
- The **reaction-center complex** is an association of proteins holding *a special pair of chlorophyll a* molecules and *a primary electron acceptor*
- The **light-harvesting complex** consists of pigment molecules bound to proteins

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- Light-harvesting complexes transfer the energy of photons to the chlorophyll *a* molecules in the reaction-center complex
- *These chlorophyll a molecules are special because they can transfer an excited electron to a different molecule*

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

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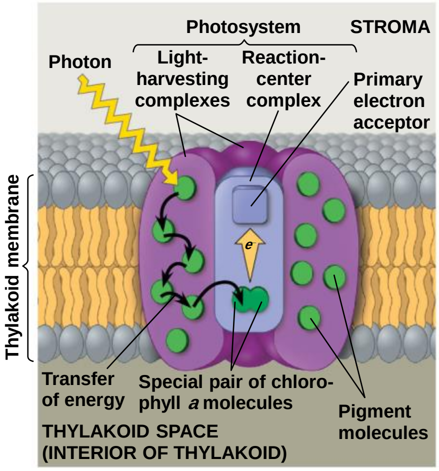
Figure 10.13



(a) How a photosystem harvests light

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

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

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

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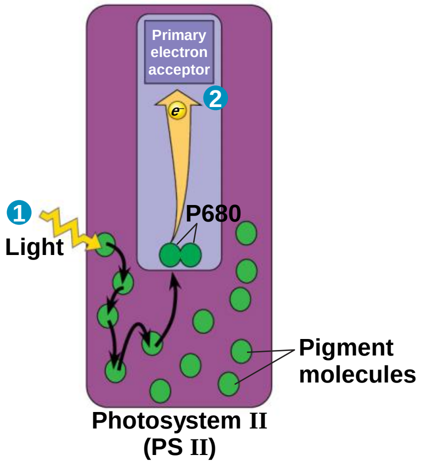
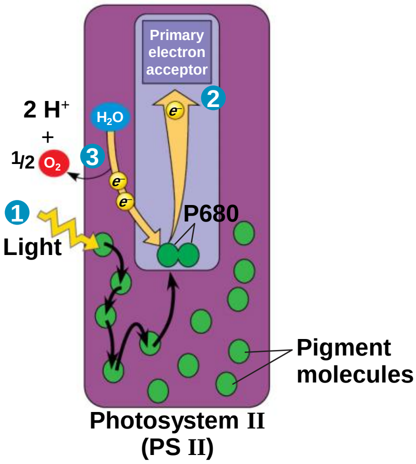
- There are eight steps in linear electron flow:
  1. A photon hits a pigment in a light-harvesting complex of PS II, and its energy is passed among pigment molecules until it excites P680
  2. An excited electron from P680 is transferred to the primary electron acceptor (we now call it $P680^+$)

Figure 10.14_1



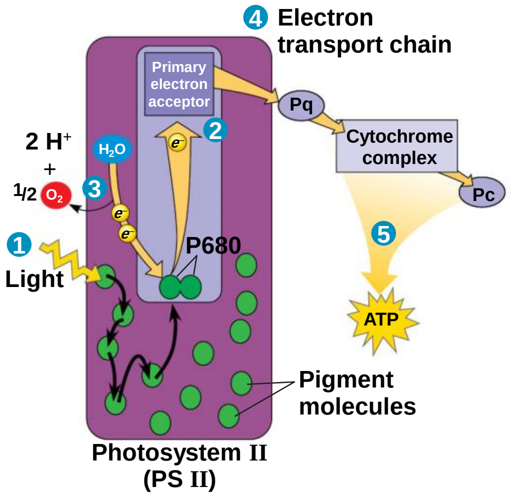
3. H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680
   - $P680^+$ is the strongest known biological oxidizing agent
   - The H^+ are released into the thylakoid space
   - O_2 is released as a by-product of this reaction

Figure 10.14_2



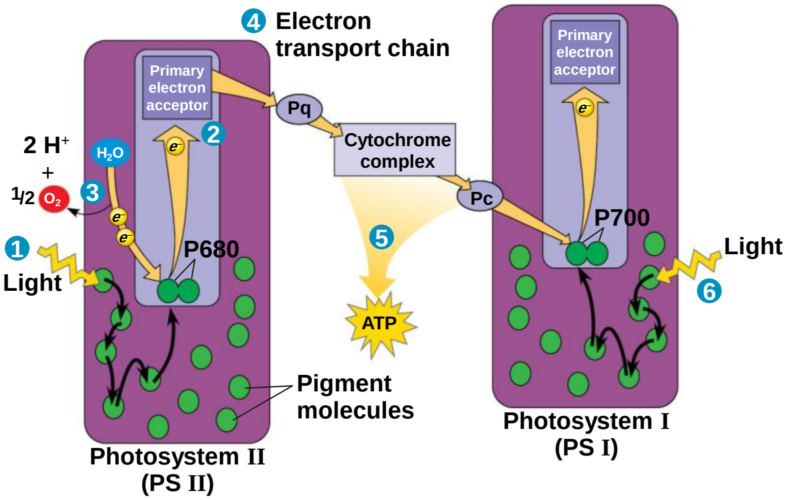
4. Each electron "falls" down an electron transport chain from the primary electron acceptor of PS II to PS I. Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
5. Potential energy stored in the proton gradient drives production of ATP by chemiosmosis

Figure 10.14_3



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

Figure 10.14_4



7. Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
8. $NADP^+$ reductase catalyzes the transfer of electrons to $NADP^+$, reducing it to NADPH
    - The electrons of NADPH are available for the reactions of the Calvin cycle
    - This process also removes an H^+ from the stroma

Figure 10.14_5

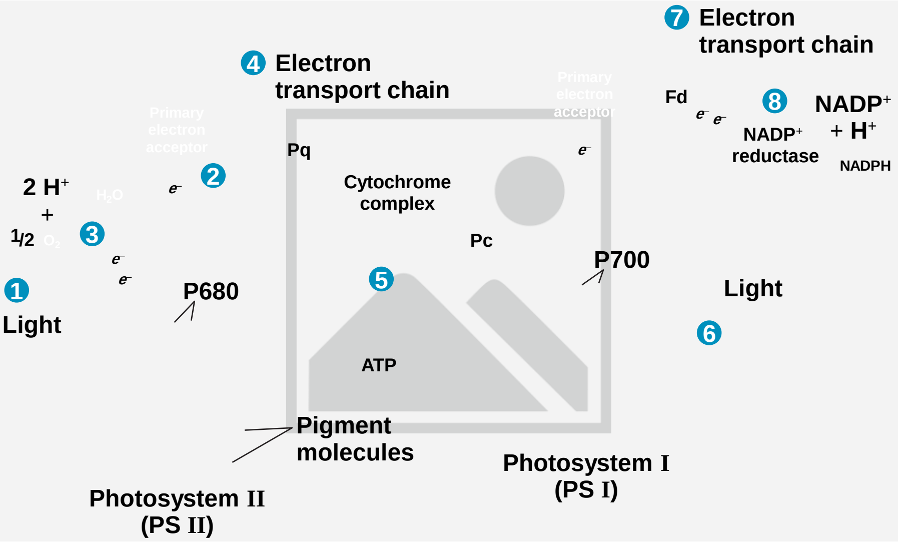
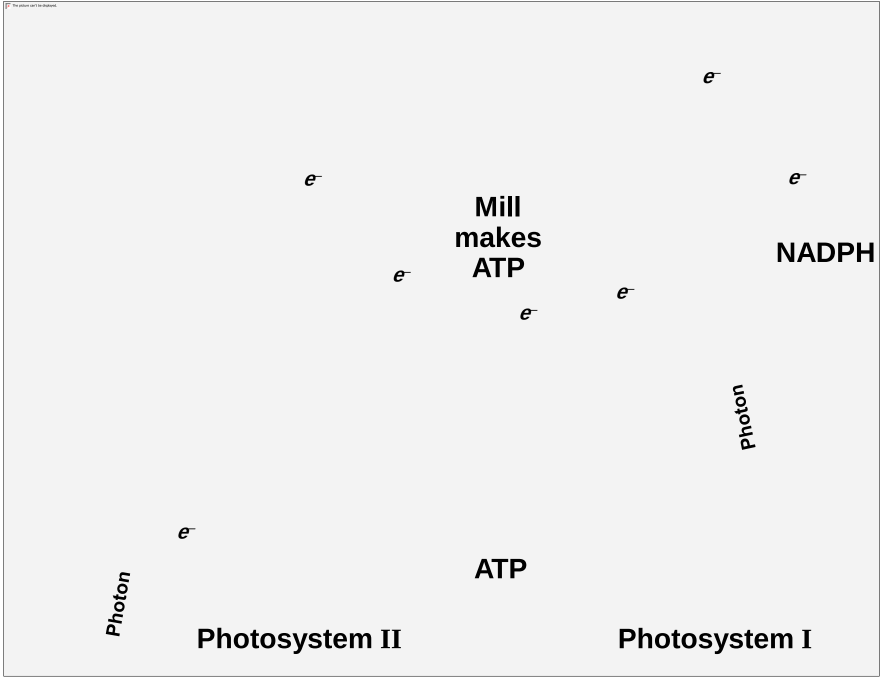


Figure 10.15



Cyclic Electron Flow

- In **cyclic electron flow**, electrons cycle back from Fd to the PS I reaction center via a plastocyanin molecule (Pc)
- Cyclic electron flow uses only photosystem I and produces ATP, but not NADPH
- No oxygen is released

Figure 10.16

Primary acceptor

Fd

Primary acceptor

Fd

Pq

NADP$^+$ reductase

NADP$^+$ + H$^+$

Cytochrome complex

NADPH

Pc

Photosystem I

Photosystem II

ATP

- 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

Figure 10.UN03

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H_2O

CO_2

Light

$NADP^+$

ADP

LIGHT REACTIONS

CALVIN CYCLE

ATP

NADPH

O_2

$[CH_2O]$ (sugar)

Figure 10.18

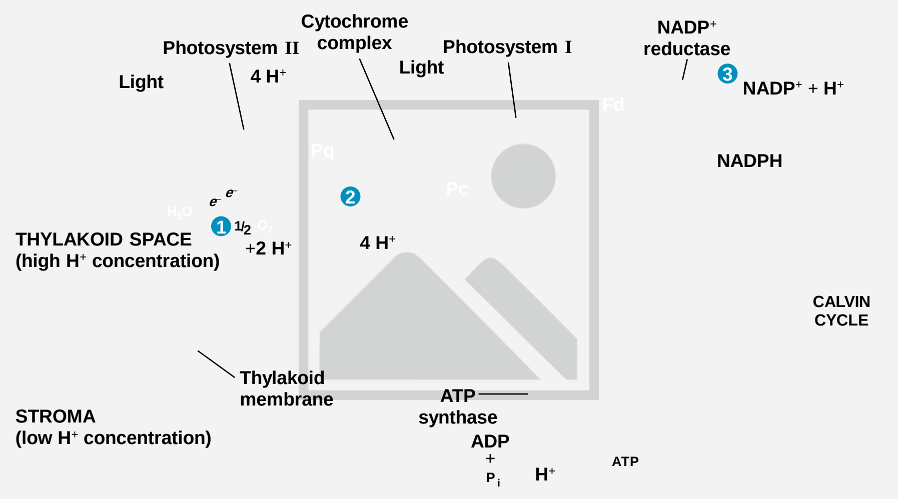

Figure 10.22c

LIGHT REACTIONS	CALVIN CYCLE REACTIONS
• Are carried out by molecules in the thylakoid membranes • Convert light energy to the chemical energy of ATP and NADPH • Split H_2O and release O_2 to the atmosphere	• Take place in the stroma • Use ATP and NADPH to convert CO_2 to the sugar G3P • Return ADP, inorganic phosphate, and $NADP^+$ to the light reactions