

LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 10

Photosynthesis



Lectures by
Erin Barley
Kathleen Fitzpatrick

© 2011 Pearson Education, Inc.

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

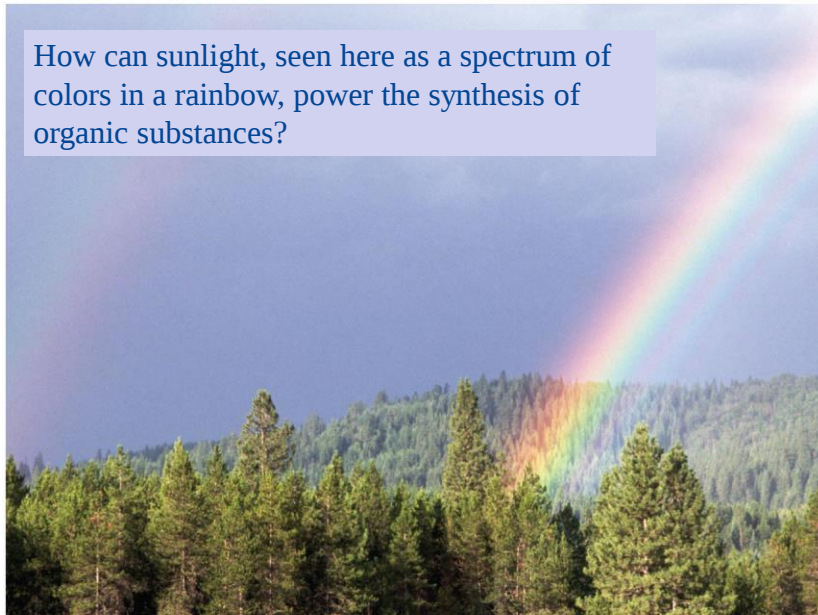
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

- **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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-1

How can sunlight, seen here as a spectrum of colors in a rainbow, power the synthesis of organic substances?



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.

- **Photosynthesis** occurs in **plants, algae, certain other protists**, and some **prokaryotes**
- These organisms feed not only themselves but also most of the living world

PLAY

BioFlix: Photosynthesis

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.2



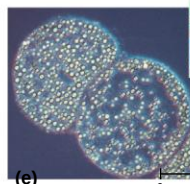
(a) Plants



(b) Multicellular alga



(c) Unicellular protists

10 μm 

(e) Purple sulfur bacteria

1 μm (d) Cyanobacteria 40 μm

Photoautotrophs

-
- **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 O₂

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

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
- CO₂ enters and O₂ exits the leaf through microscopic pores called **stomata**

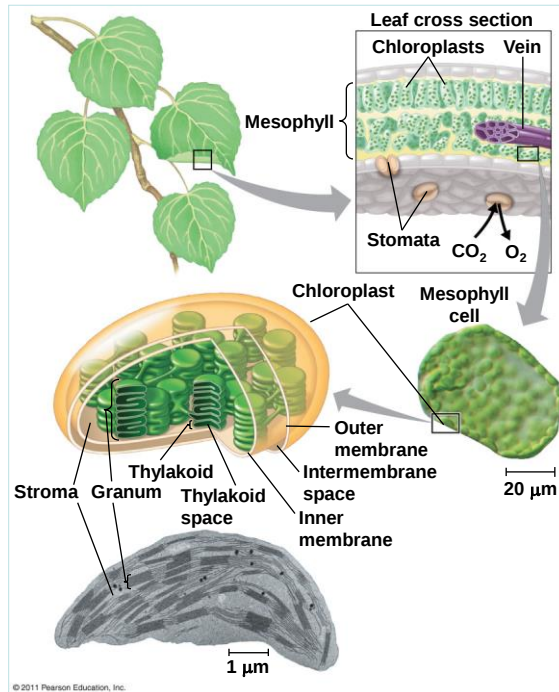
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

-
- **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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.4

Zooming in on the location of photosynthesis in a plant.



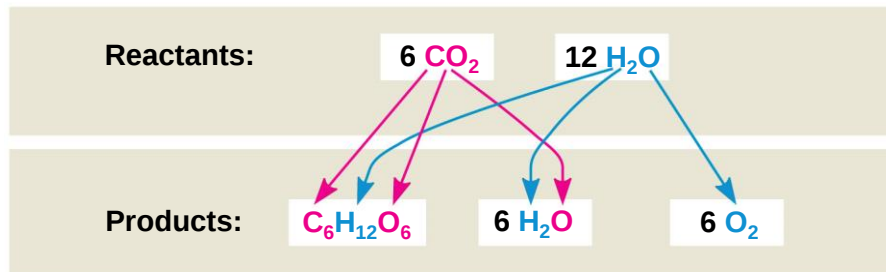
Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:



Figure 10.5

Tracking atoms through photosynthesis.



The Splitting of Water

- **Chloroplasts split H₂O** into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules
 - Plants: $\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{O}_2$
 - Sulfur bacteria: $\text{CO}_2 + \text{H}_2\text{S} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{S}_2$
- CO₂ is not split into C and O₂!! This hypothesis was cancelled by van Neil in 1930s

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Class activity!

- How you can prove the hypothesis of van Neil, that splitting of water rather than CO₂ is the source of O₂??



Class activity!

- It was proved using Oxygen-18 (¹⁸O), a heavy isotope incorporated into water, as a tracer to follow the fate of O₂ during photosynthesis?
- **Experiment 1:** (¹⁸O) incorporated
 - $\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{O}_2$
- **Experiment 2:** (¹⁸O) incorporated in CO₂
 - $\text{C}^{18}\text{O}_2 + 2\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{O}_2$

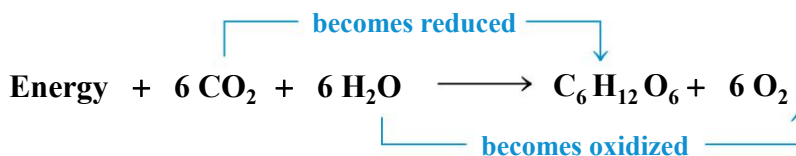


Photosynthesis as a Redox Process

- Photosynthesis is a **redox process** in which **H₂O is oxidized** and **CO₂ is reduced**

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.UN01



© 2011 Pearson Education, Inc.

- **Summary:**
- **H₂O** is split, & electrons are transferred along with H ions from **H₂O** to **CO₂** reducing it to **sugars!**
- Endergonic reaction.

How this reaction relates to cellular respiration??



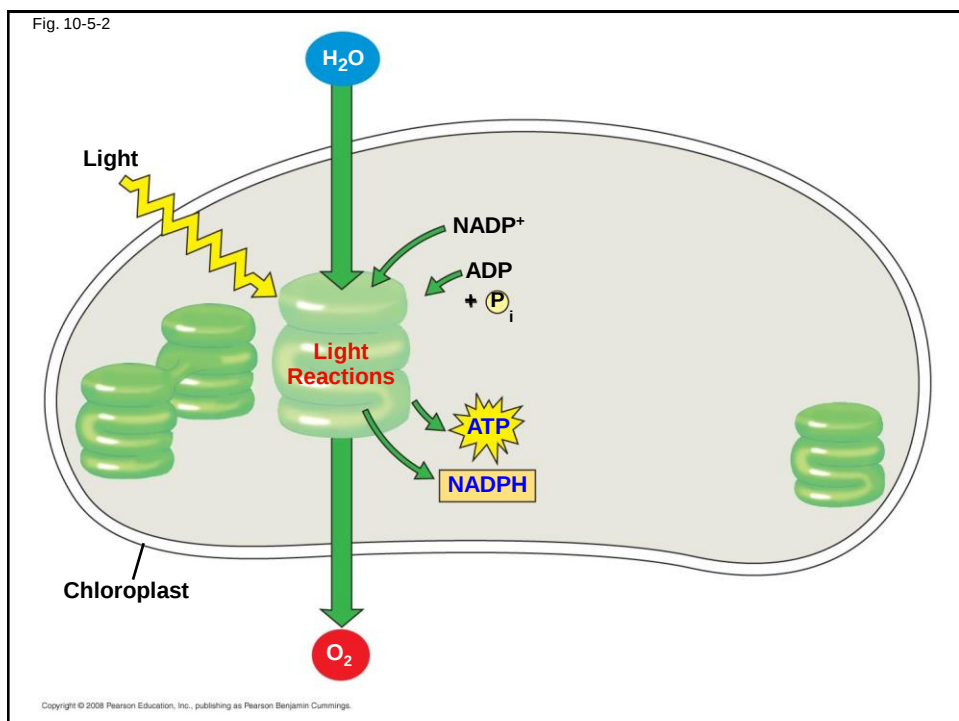
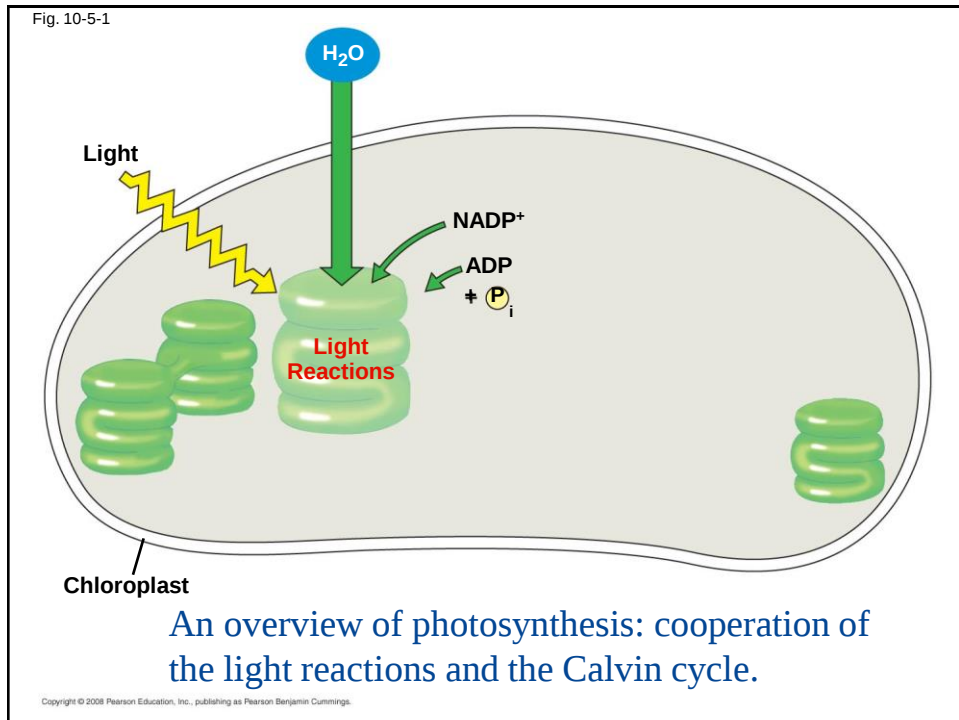
The Two Stages of Photosynthesis: A Preview

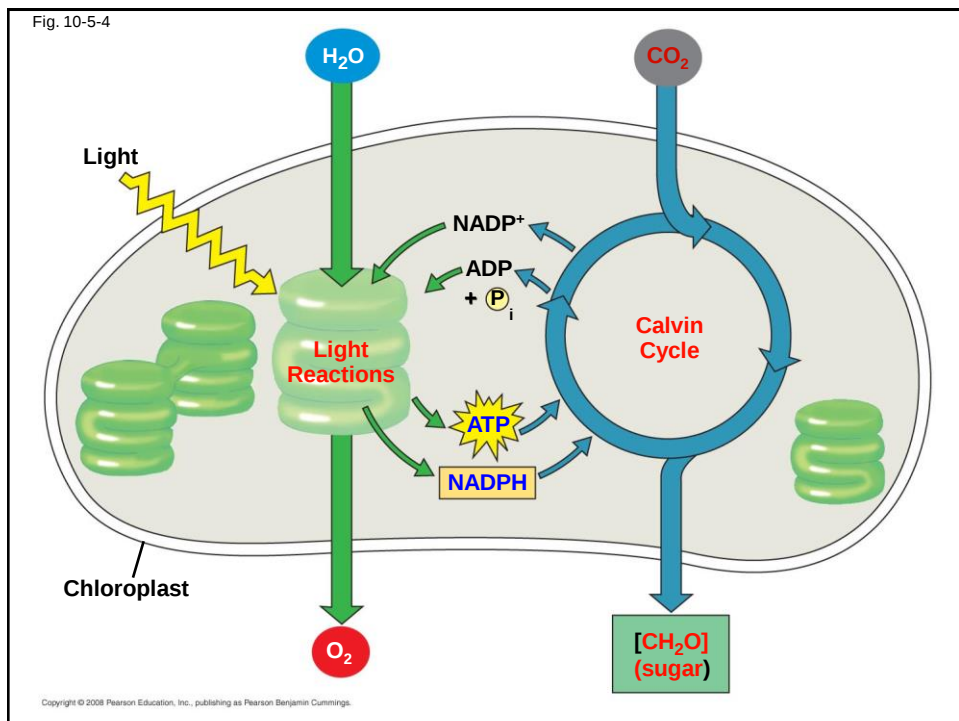
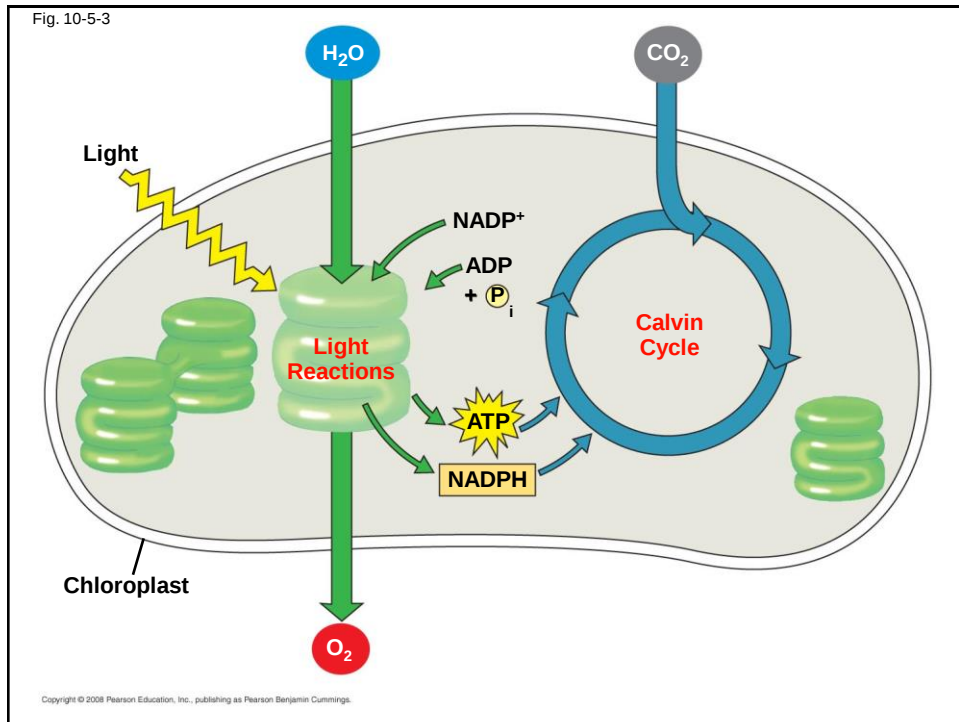
- **Photosynthesis** consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
 - **The light reactions** (*in the thylakoids*):
 - Split H_2O
 - Release O_2
 - Reduce **NADP⁺** to **NADPH**
 - Generate **ATP** from ADP by **photophosphorylation**
-

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

-
- **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
-

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings





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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

The Nature of Sunlight

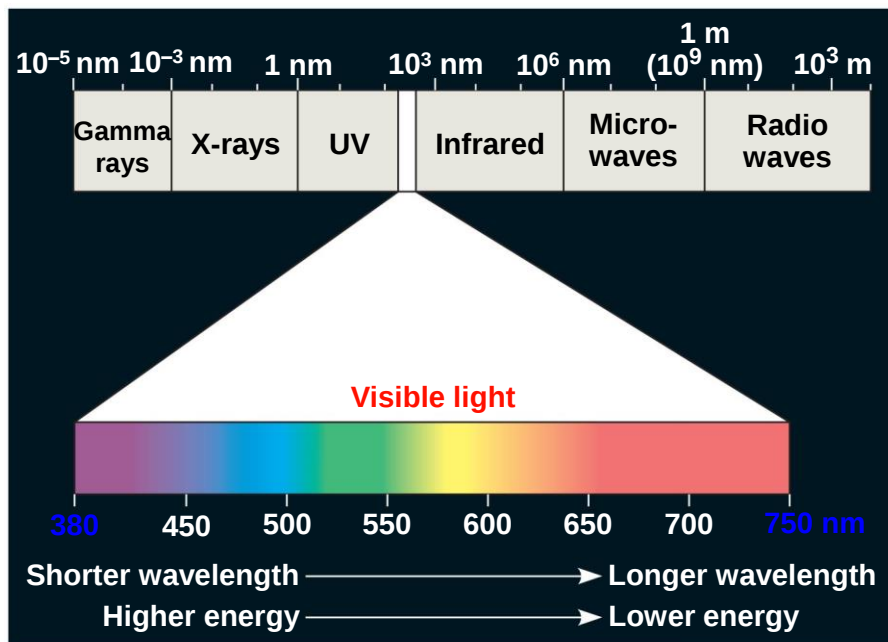
- **Light** is a form of **electromagnetic energy**, also called **electromagnetic radiation**
- Like other electromagnetic energy, **light travels** in **rhythmic waves**
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

- 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**

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-6



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.

Photosynthetic Pigments: The Light Receptors

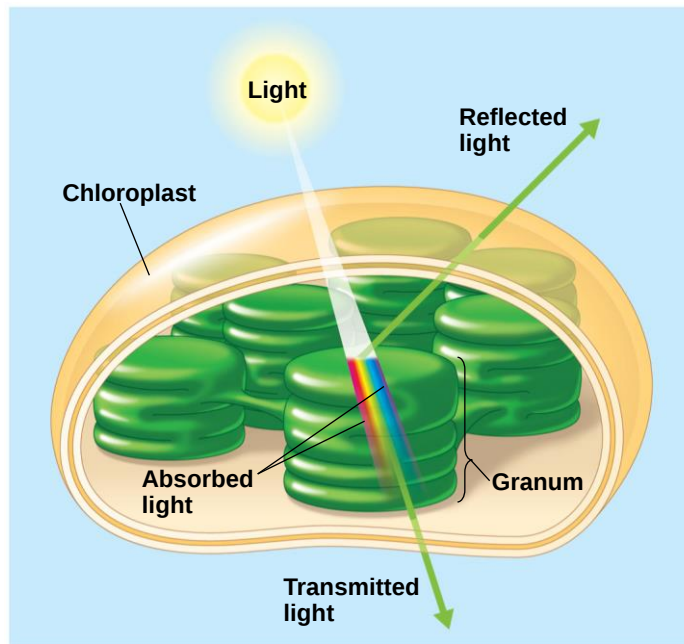
- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll reflects and transmits green light

PLAY

Animation: Light and Pigments

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.8



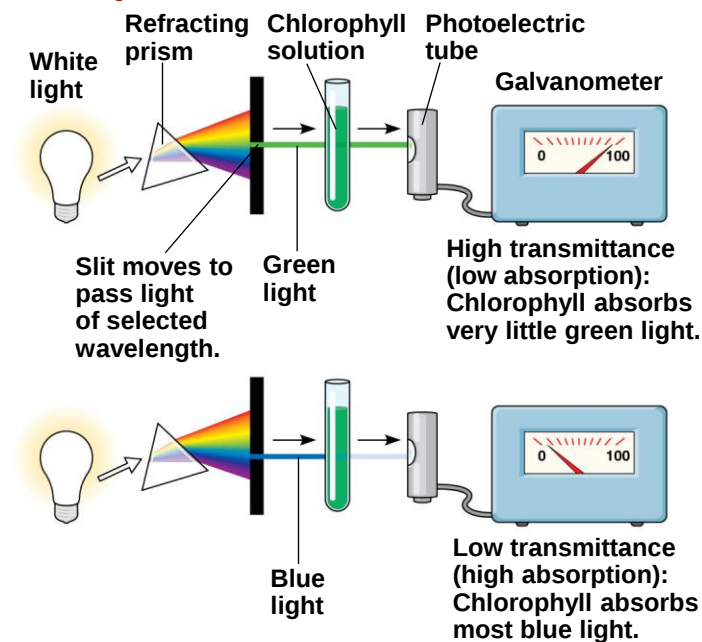
© 2011 Pearson Education, Inc.

- 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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.9

TECHNIQUE



© 2011 Pearson Education, Inc.

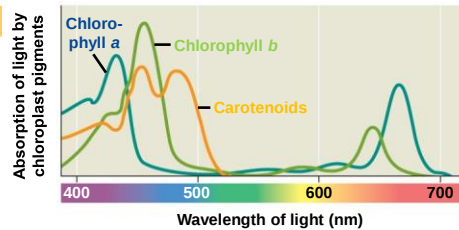
- An **absorption spectrum** is a graph plotting a pigment's **light absorption versus wavelength**
- The absorption spectrum of **chlorophyll a** suggests that violet-blue and **red light** work best for photosynthesis

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-9

RESULTS

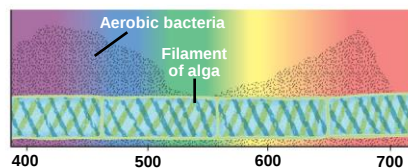
(a) Absorption spectra



(b) Action spectrum



(c) Engelmann's experiment

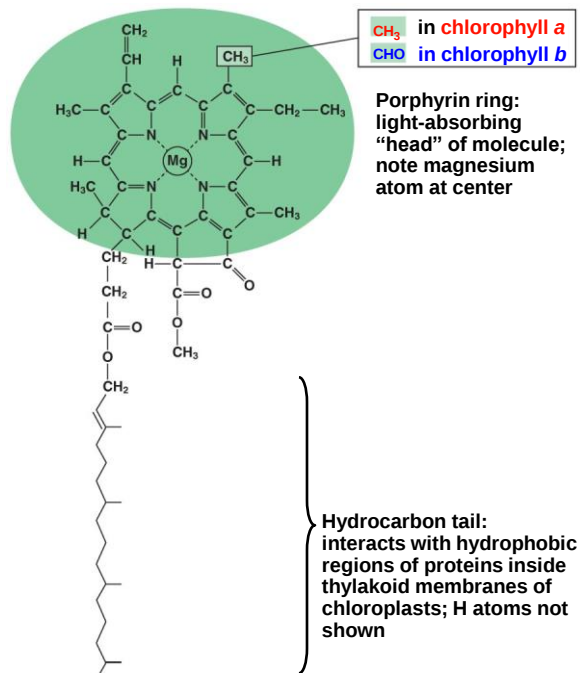


Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

- **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**

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-10



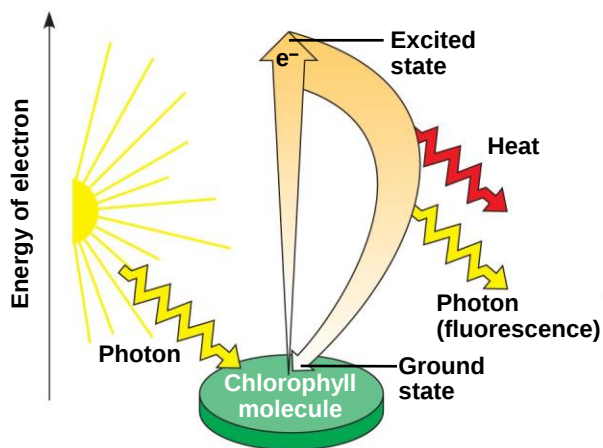
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

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

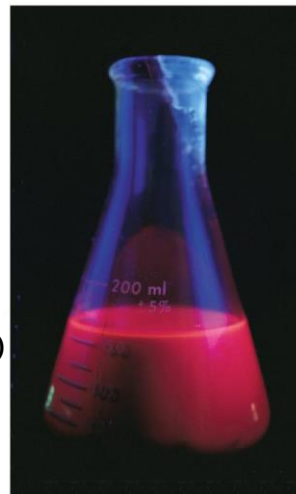
Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-11



(a) Excitation of isolated chlorophyll molecule

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.



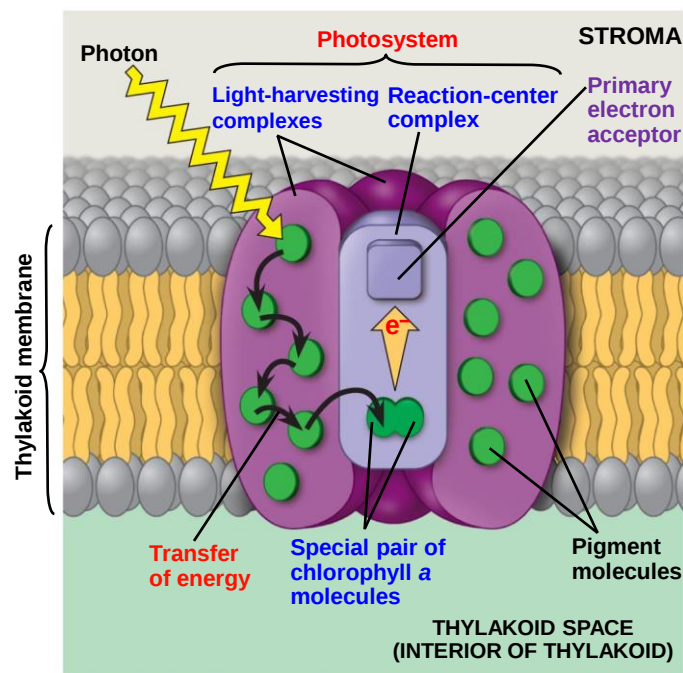
(b) Fluorescence

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*

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Fig. 10-12



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.

- 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**

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.13

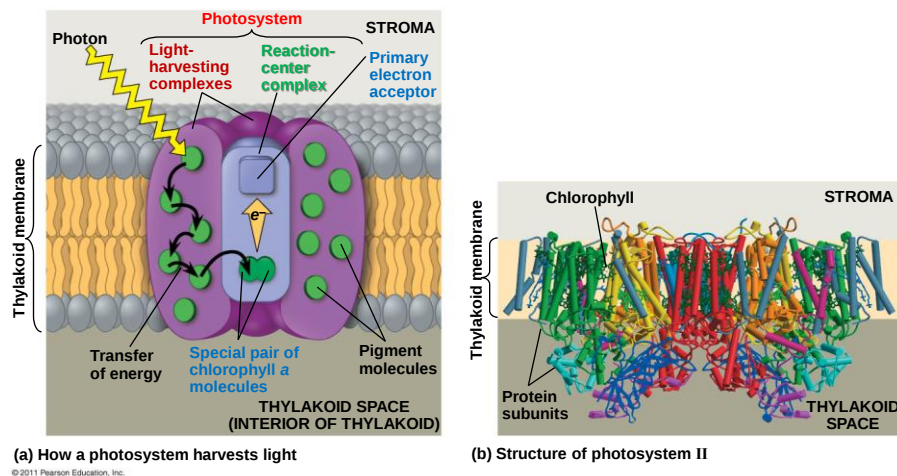
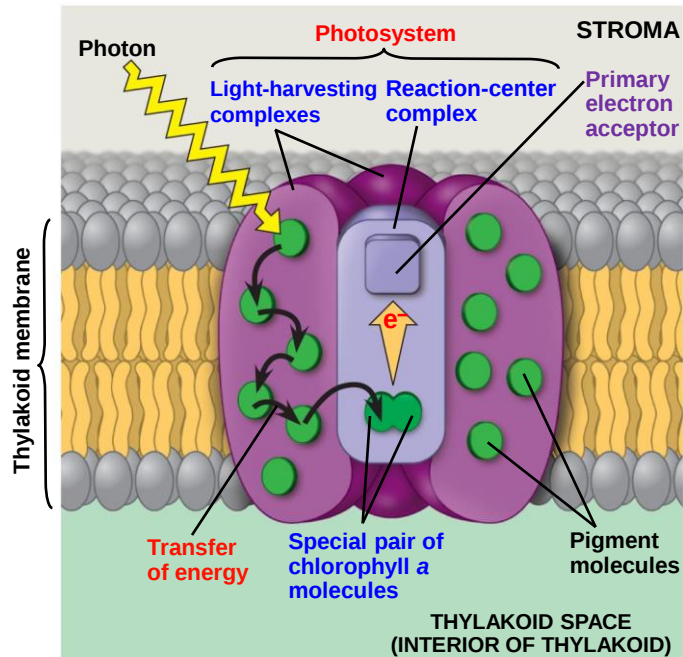


Fig. 10-12



Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings.

- 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**

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Linear Electron Flow

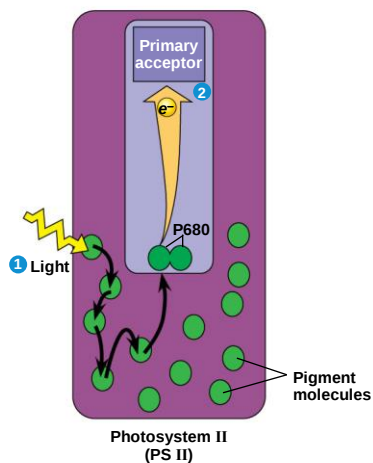
- During the light reactions, there are **two possible routes for electron flow**: **cyclic** and **linear**
- **Linear electron flow**, the **primary pathway**, involves **both photosystems** and **produces ATP and NADPH** using light energy

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

- 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

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.14-1

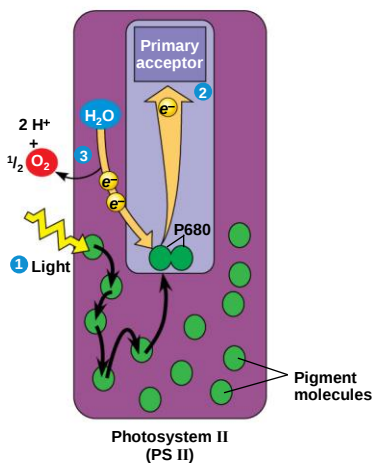


© 2011 Pearson Education, Inc.

- P680⁺ is a very **strong oxidizing agent**
- **H₂O is split by enzymes**, and the electrons are transferred **from the hydrogen atoms to P680⁺, thus reducing it to P680**
- **O₂ is released** as a by-product of this reaction

© 2011 Pearson Education, Inc.

Figure 10.14-2

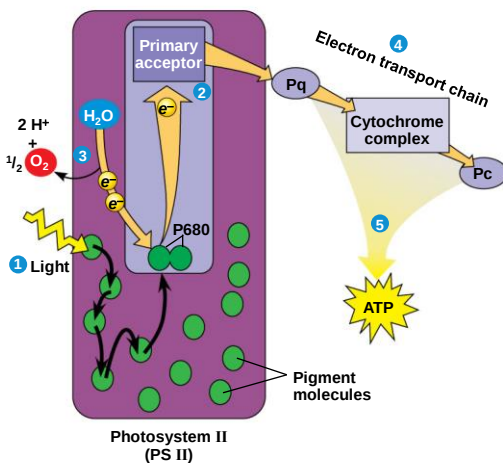


© 2011 Pearson Education, Inc.

- 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**

© 2011 Pearson Education, Inc.

Figure 10.14-3

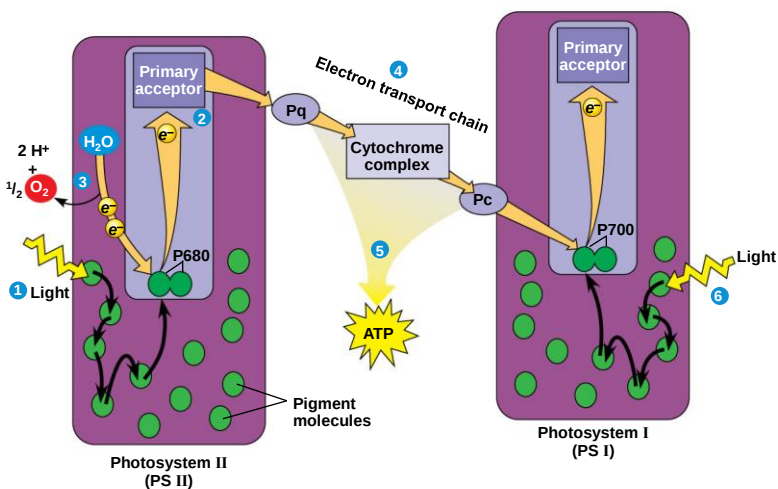


© 2011 Pearson Education, Inc.

- 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**

© 2011 Pearson Education, Inc.

Figure 10.14-4



© 2011 Pearson Education, Inc.

- 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
- **This process also removes an H⁺ from the stroma**

© 2011 Pearson Education, Inc.

Figure 10.14-5

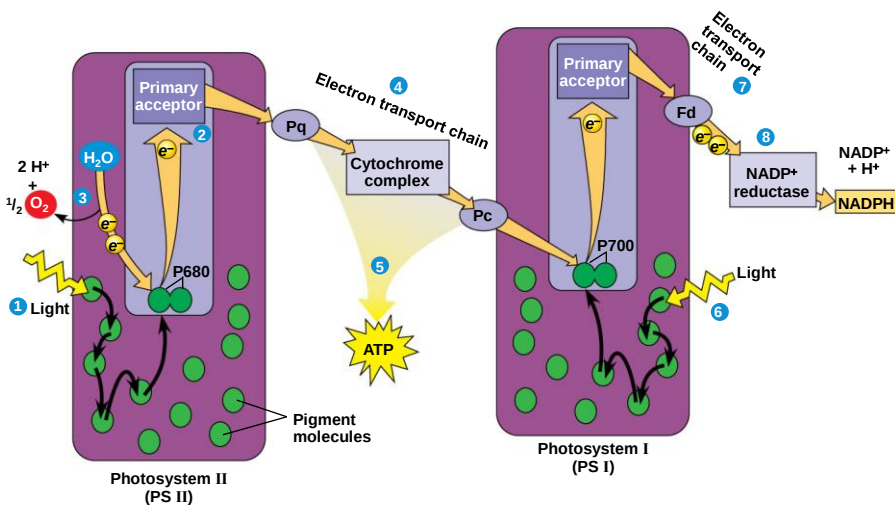
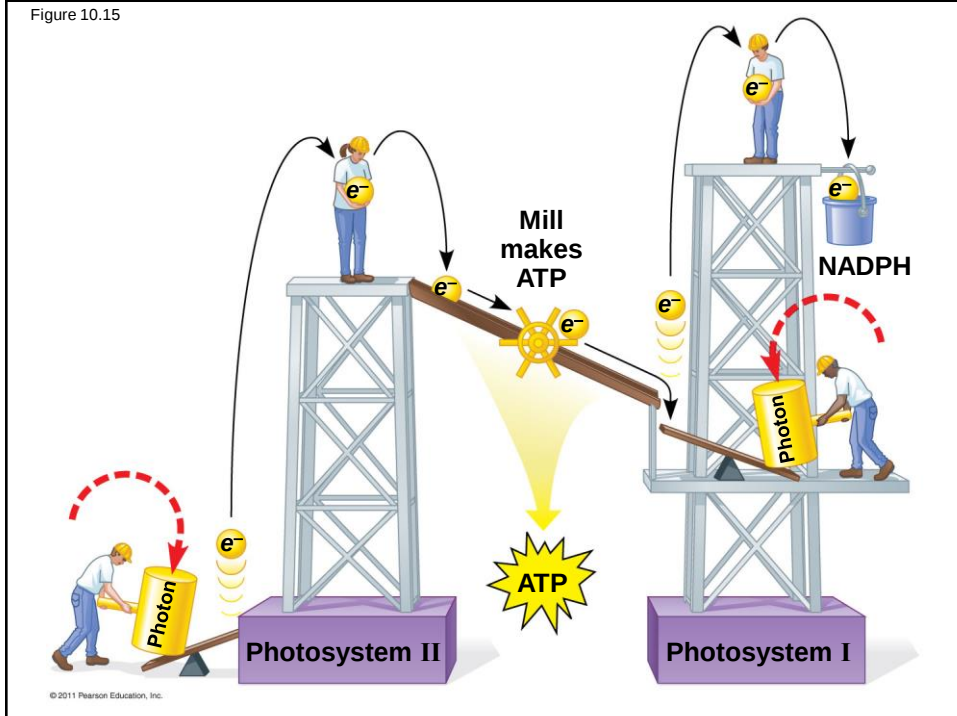


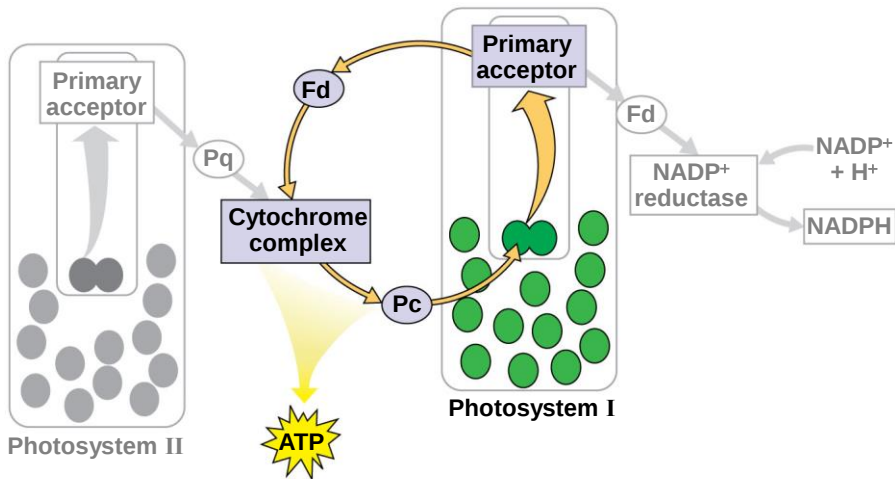
Figure 10.15



Cyclic Electron Flow

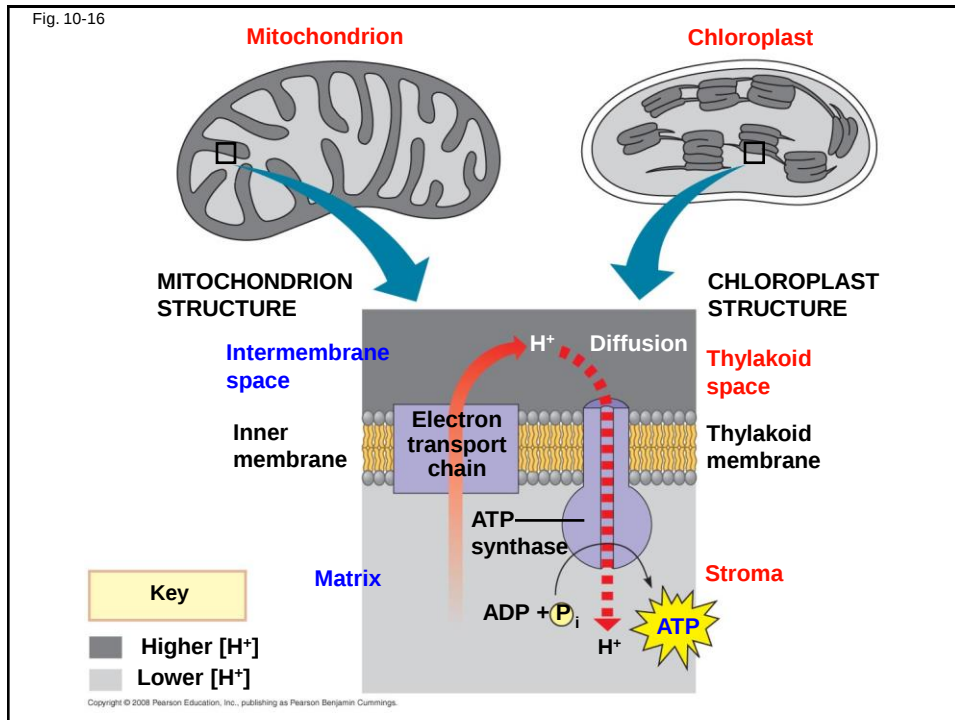
- Cyclic electron flow uses only photosystem I and produces ATP, but not NADPH
- Cyclic electron flow generates **surplus ATP**, *satisfying the higher demand in the Calvin cycle*

Figure 10.16



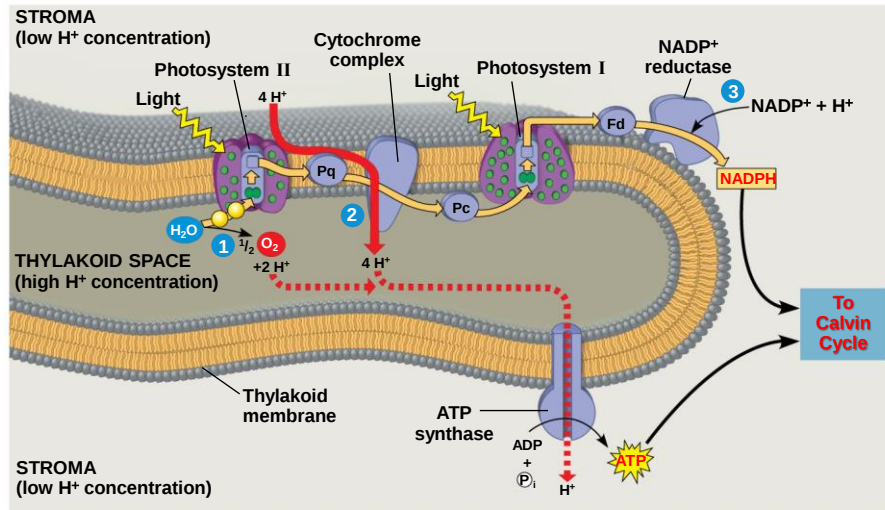
A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- 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



- **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 10.18



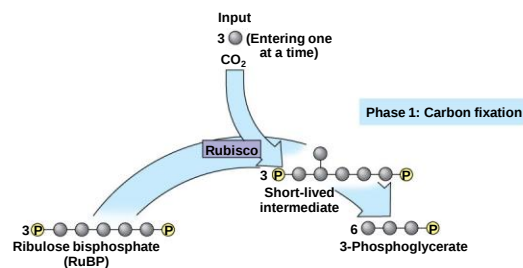
Concept 10.3: **The Calvin cycle uses ATP and NADPH to convert CO_2 to sugar**

- 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**

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde-3-phosphate (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)

Copyright © 2008 Pearson Education, Inc., publishing as Pearson Benjamin Cummings

Figure 10.19-1



© 2011 Pearson Education, Inc.

Figure 10.19-2

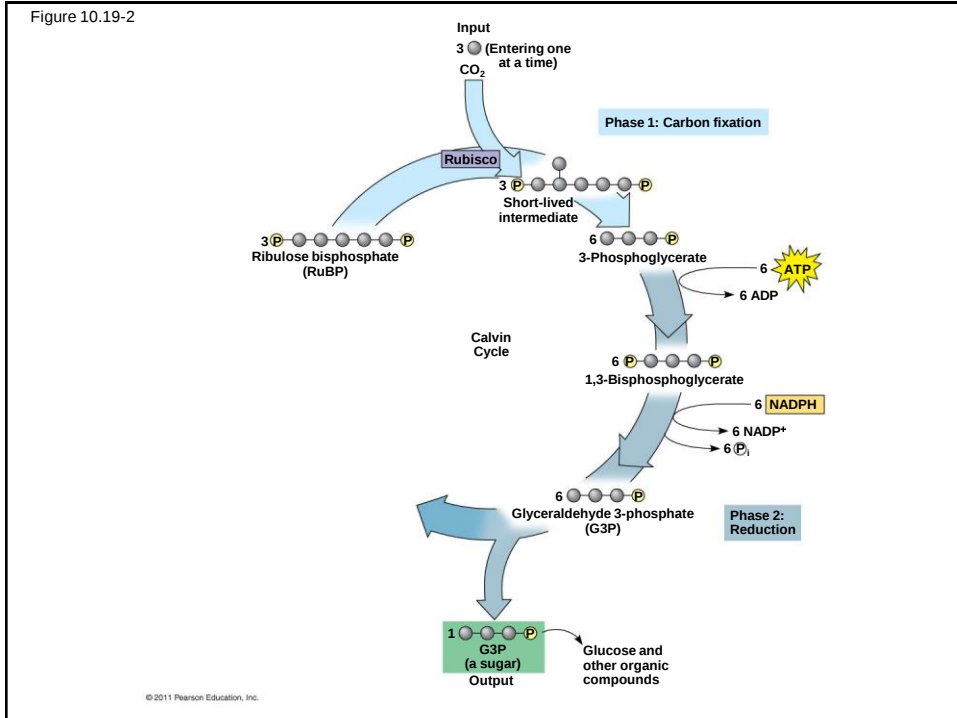
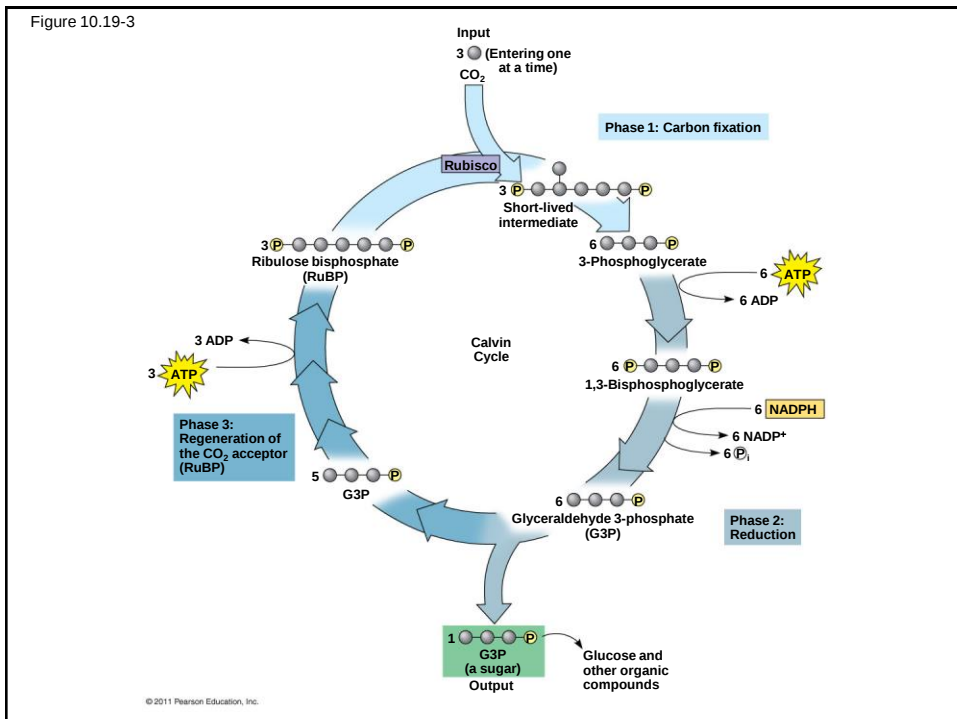
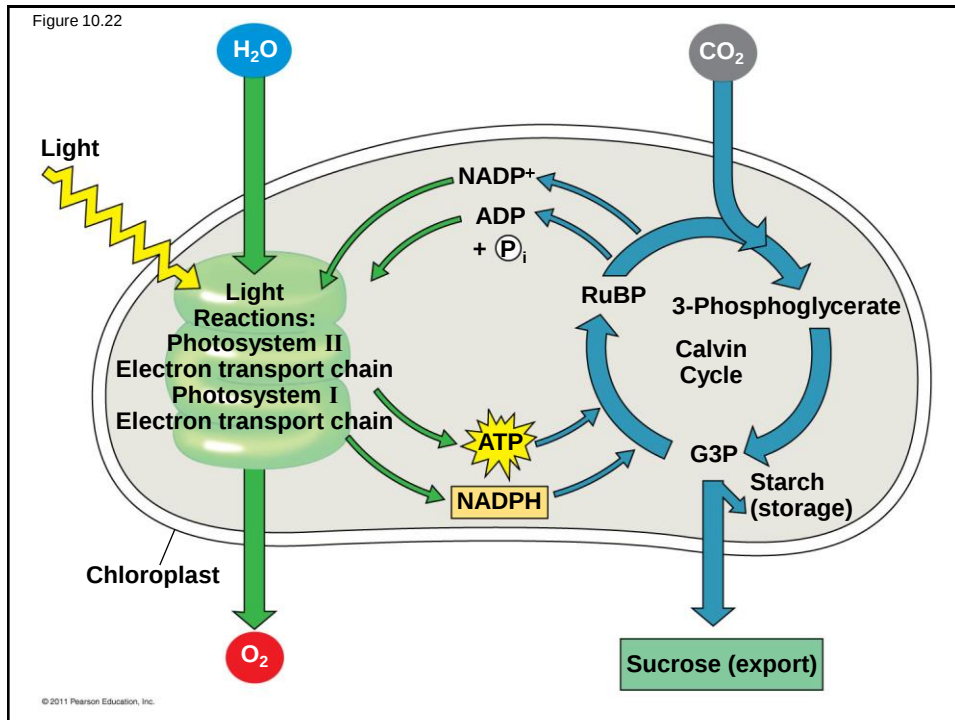


Figure 10.19-3





Class activity!

- To synthesize one molecule of GLUCOSE, the Calvin cycle uses ----- molecules of CO_2 , ----- molecules of ATP, and ----- molecules of NADPH?
- Answer: 6, 18, 12

Class activity!

- How are the large numbers of ATP and NADPH molecules used during Calvin cycle consistent with the high value of glucose as an energy source?
- Glucose is a valuable energy source, because it is highly reduced, storing lots of potential energy in its electrons

Class activity!

- Explain why a poison that inhibits an enzyme in the Calvin cycle, also inhibits the light reaction??
- Light reaction requires ADP & NADP⁺ in sufficient quantities via the Calvin cycle