LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
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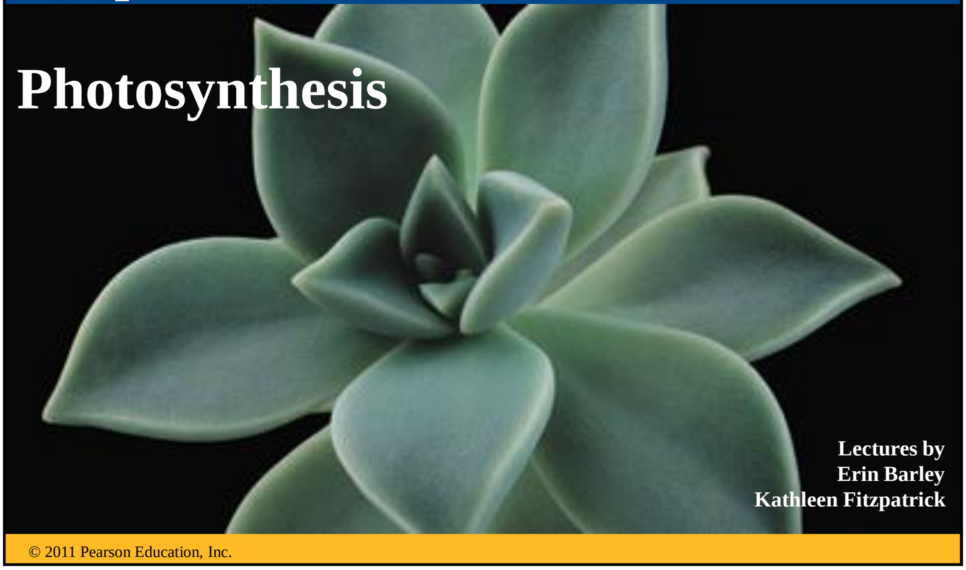
Chapter 10



Photosynthesis

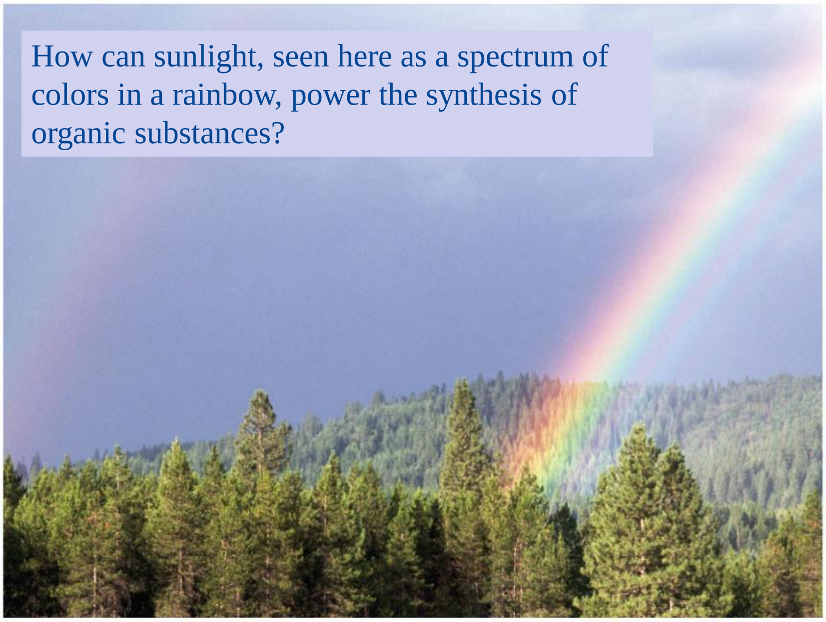
Lectures by
Erin Barley
Kathleen Fitzpatrick

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

- **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

Fig. 10-1



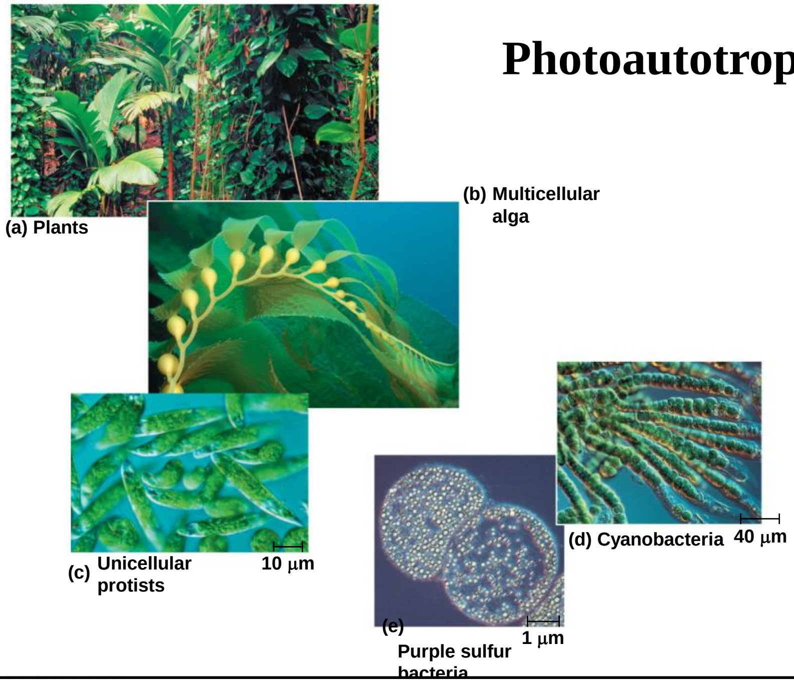
How can sunlight, seen here as a spectrum of colors in a rainbow, power the synthesis of organic substances?

- 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

Figure 10.2

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 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 cells allows for the chemical reactions of photosynthesis

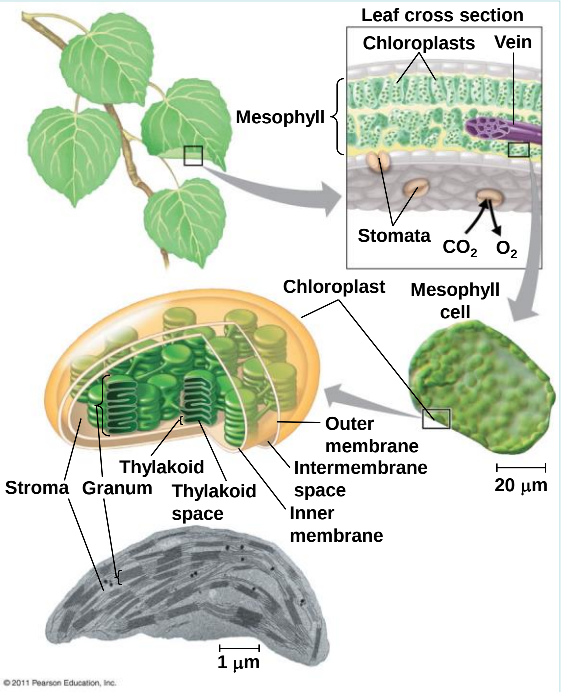
Chloroplasts: The Sites of Photosynthesis in Plants

- 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**

- 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

Figure 10.4

Zooming in on the location of photosynthesis in a plant.



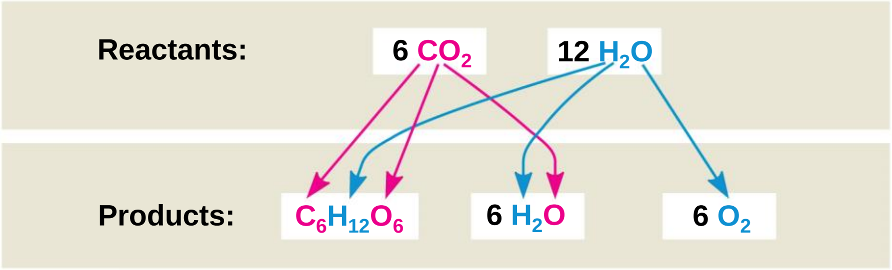
Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

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

Figure 10.5

Tracking atoms through photosynthesis.



The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules
  - – Plants: CO2 + 2H2O →[CH2O] + H2O + O2
  - – Sulfur bacteria: CO2 + H2S → [CH2O] + H2O + S2
- CO2 is not split into C and O2!! This hypothesis was cancelled by van Neil in 1930s

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 (^{18}O), a heavy isotope incorporated into water, as a tracer to follow the fate of O2 during photosynthesis?
- Experiment 1: (^{18}O) incorporated i
  - CO2 + 2H2O →[CH2O] + H2O + O2

- Experiment 2: (^{18}O) incorporated in CO2
  - CO2 + 2H2O →[CH2O] + H2O + O2

Photosynthesis as a Redox Process

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

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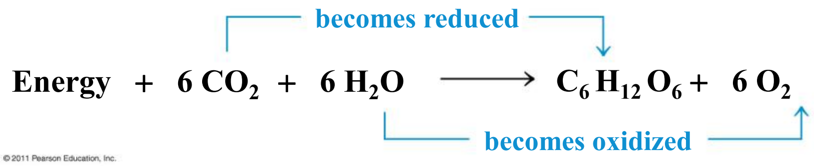
Figure 10.UN01



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

- 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**

- **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

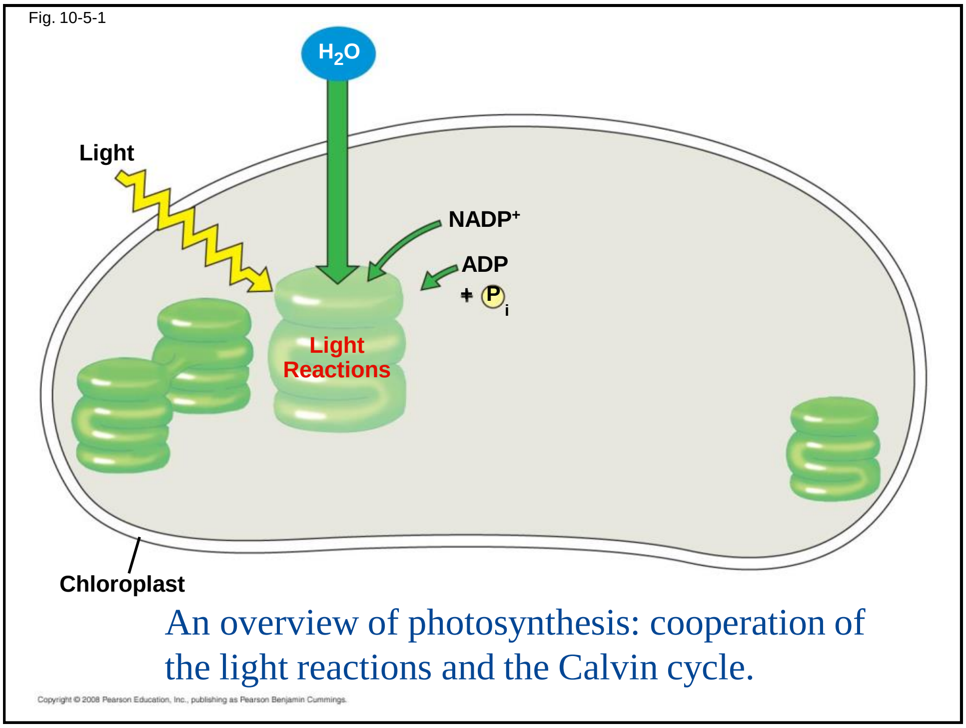


Fig. 10-5-1

An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle.

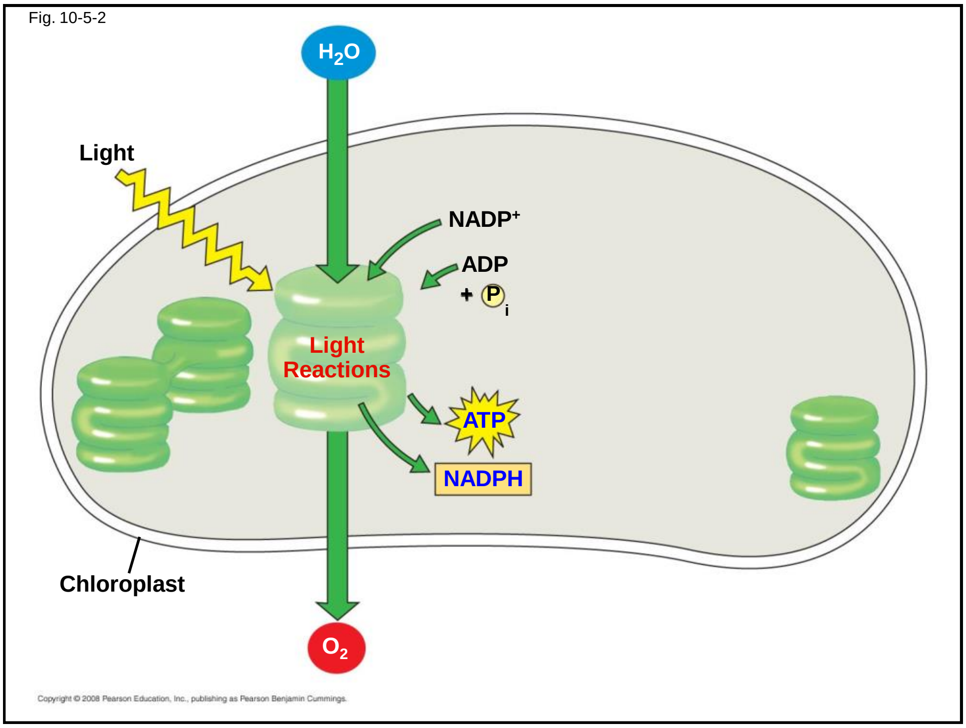


Fig. 10-5-2

Fig. 10-5-3

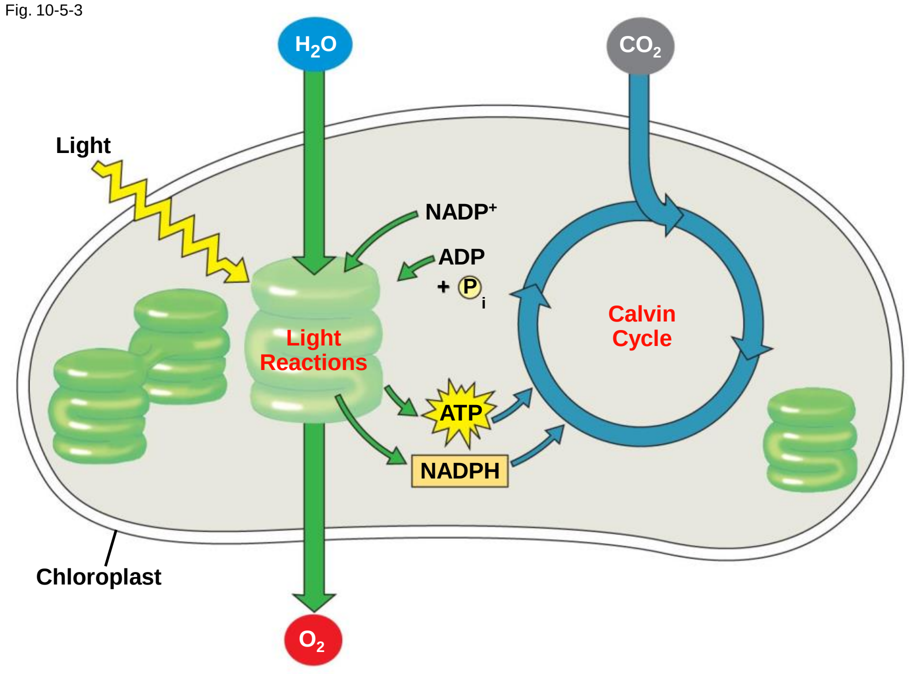
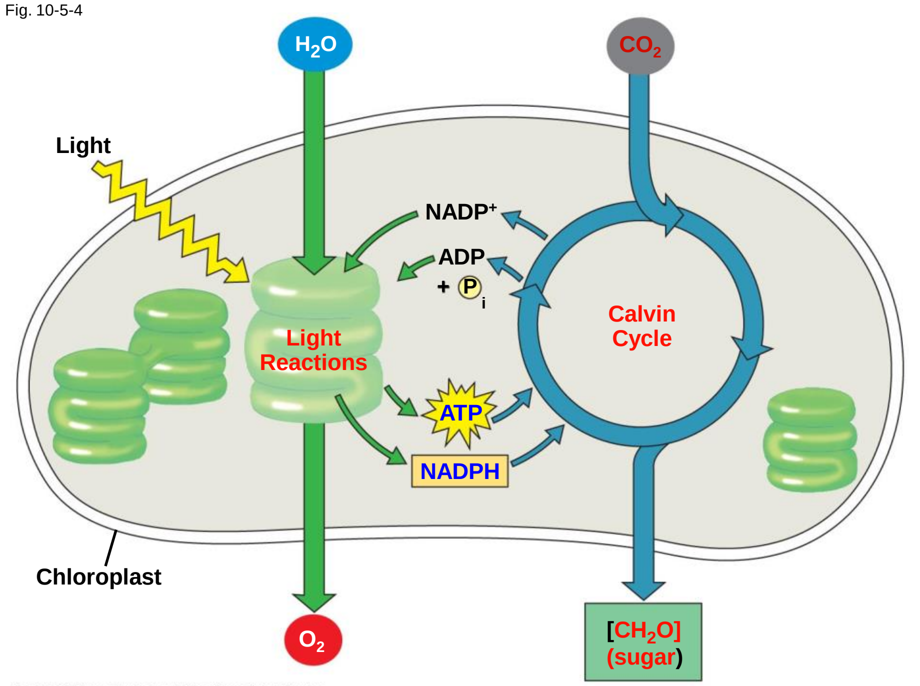


Fig. 10-5-4



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

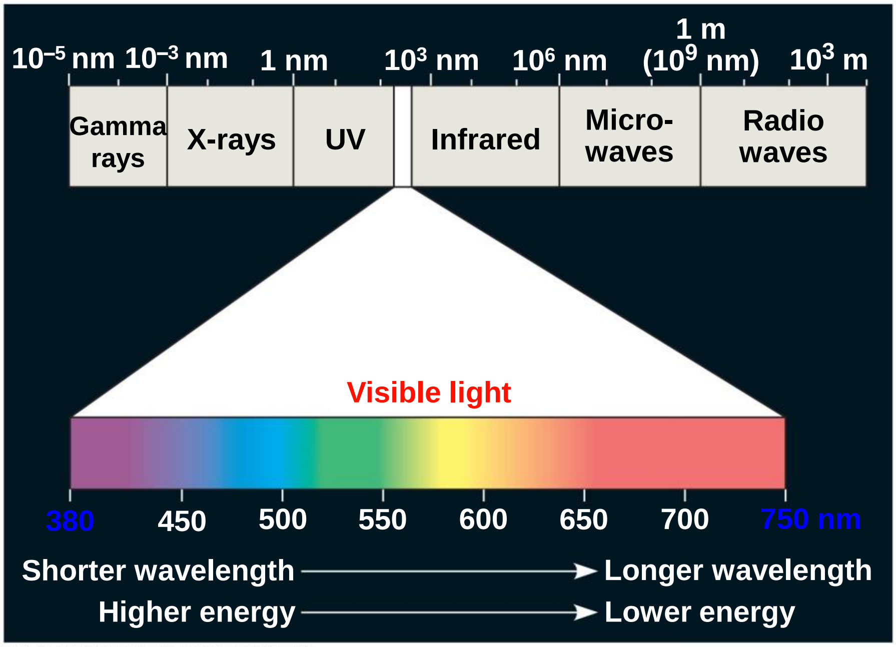
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is 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

- 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**

Fig. 10-6

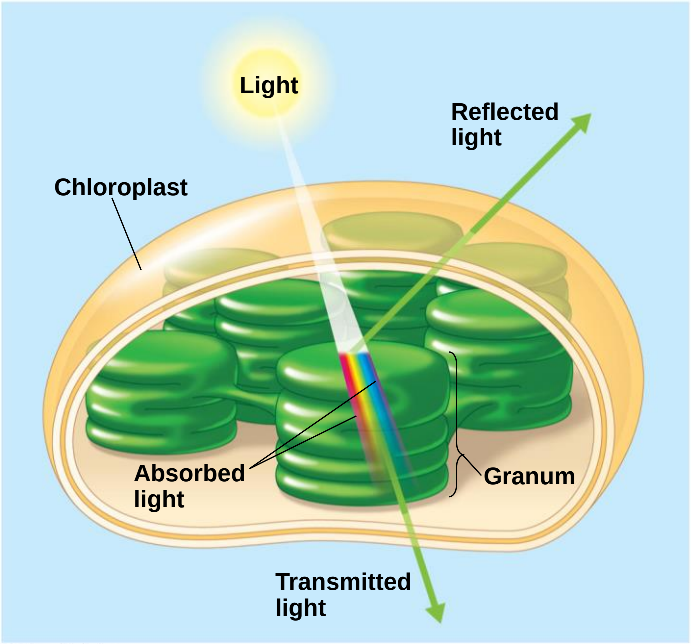


Photosynthetic Pigments: The Light Receptors

- 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

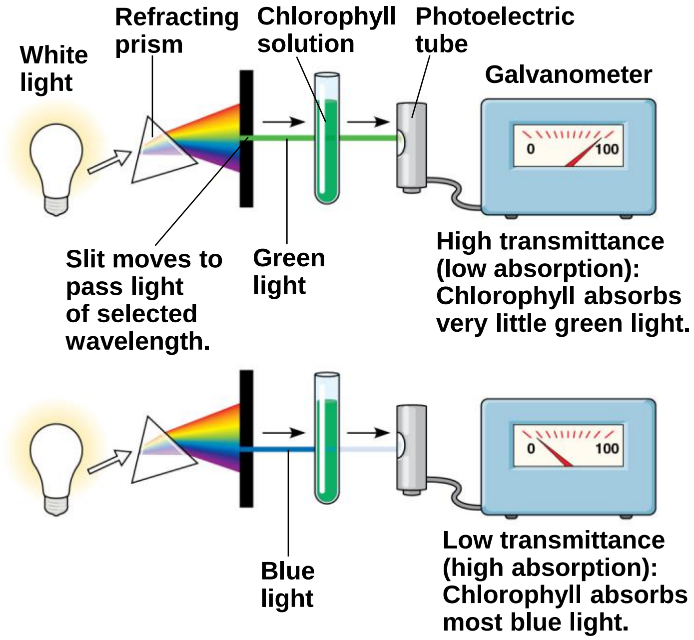
Figure 10.8



- 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

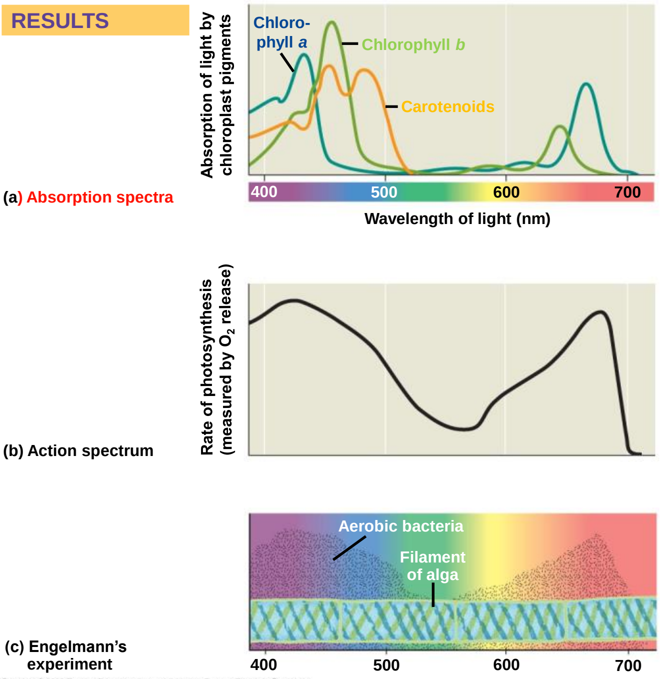
Figure 10.9

TECHNIQUE



- 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

Fig. 10-9



(a) Absorption spectra

(b) Action spectrum

(c) Engelmann’s experiment

- **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

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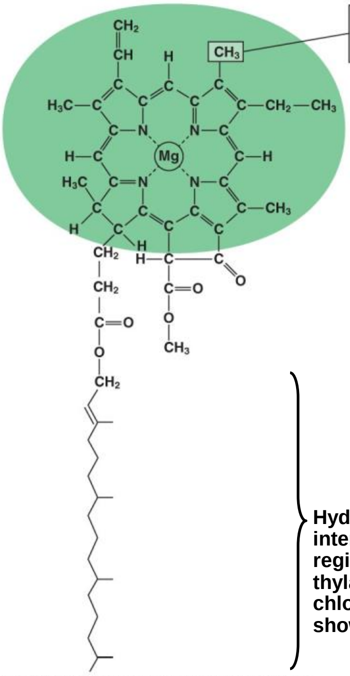
Fig. 10-10



CH_3	in **chlorophyll *a***
CHO	in **chlorophyll *b***

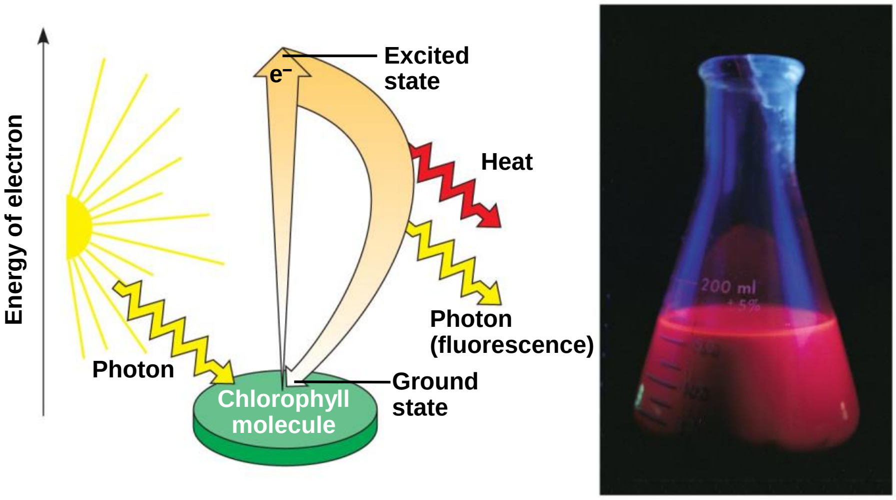
Porphyrin ring: light-absorbing "head" of molecule; note magnesium atom at center

Hydrocarbon tail: interacts with hydrophobic regions of proteins inside thylakoid membranes of chloroplasts; H atoms not shown

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. 10-11



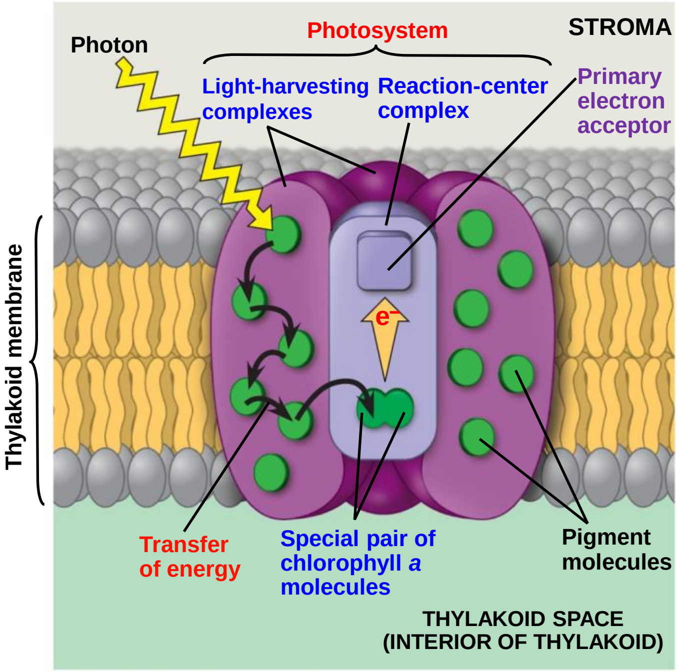
(a) Excitation of isolated chlorophyll molecule

(b) Fluorescence

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

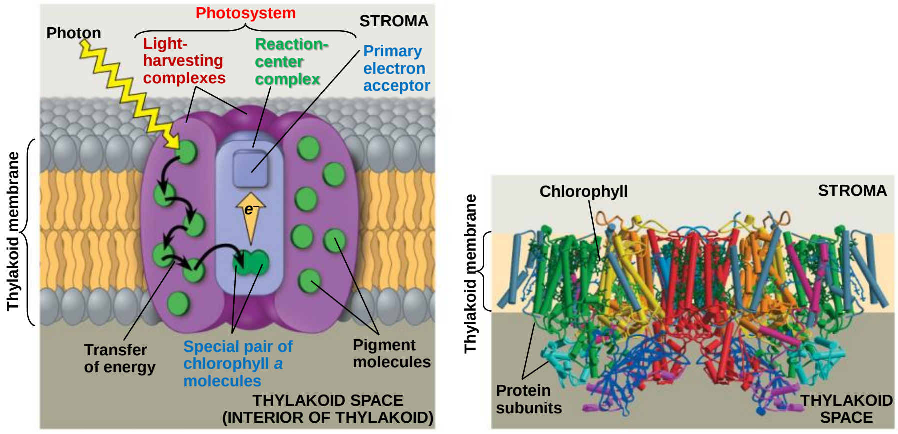
- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) *funnel the energy of photons to the reaction center*

Fig. 10-12



- 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**

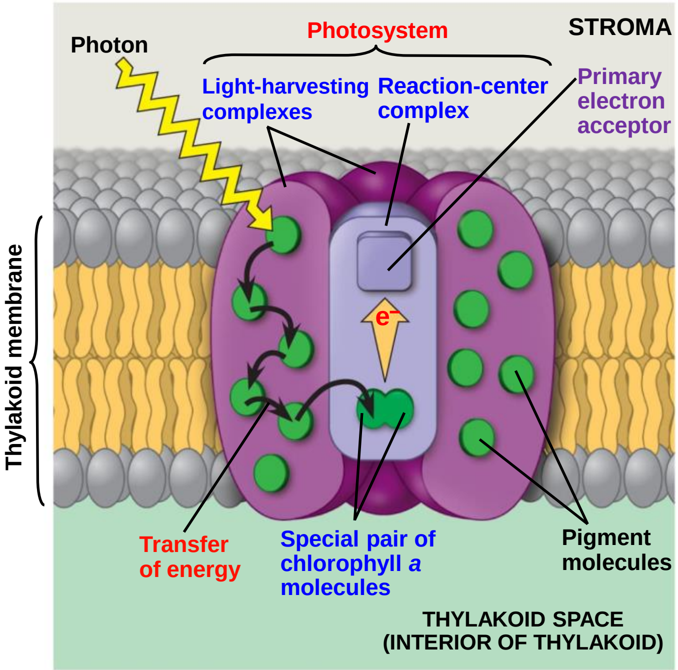
Figure 10.13



(a) How a photosystem harvests light

(b) Structure of photosystem II

Fig. 10-12



- 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

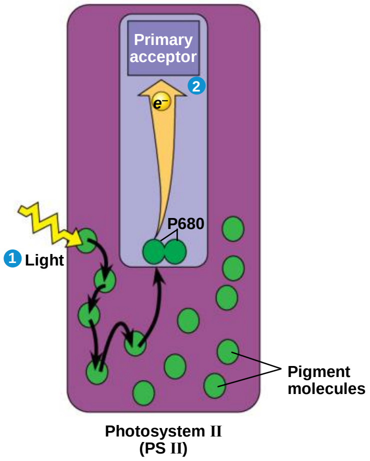
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

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

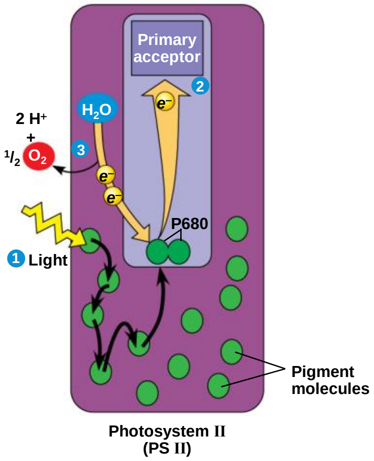
- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680
- An excited electron from P680 is transferred to the primary electron acceptor

Figure 10.14-1



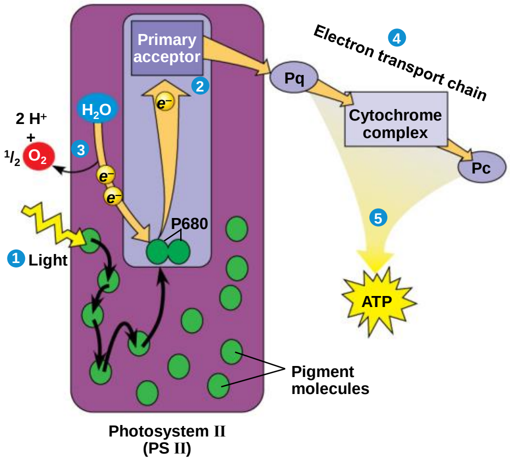
- P680$^+$ is a very strong oxidizing agent
- **H_2O is split by enzymes**, and the electrons are transferred from the hydrogen atoms to P680$^+$, **thus reducing it to P680**
- **O_2 is released** as a by-product of this reaction

Figure 10.14-2



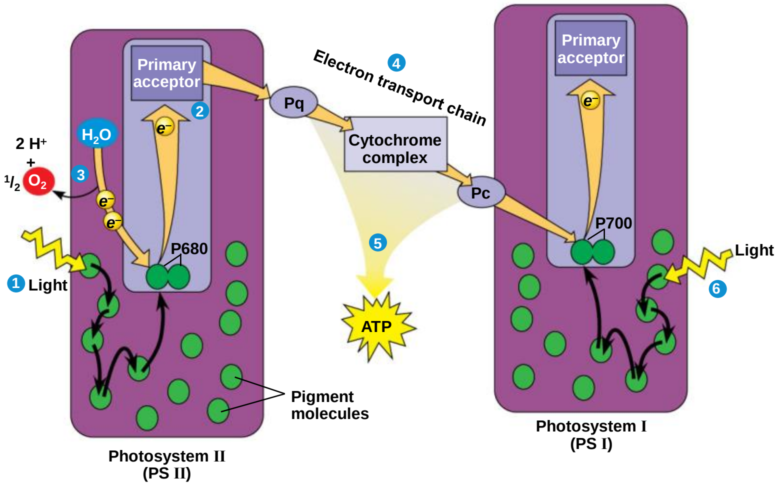
- Each electron “**falls” down an electron transport chain** from the primary electron acceptor of PS II to PS I
- Energy **released by the fall** drives the **creation of a proton gradient** across the thylakoid membrane
- Diffusion of H^+ (protons) across the membrane **drives ATP synthesis**

Figure 10.14-3



- 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**

Figure 10.14-4



- 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**

Figure 10.14-5

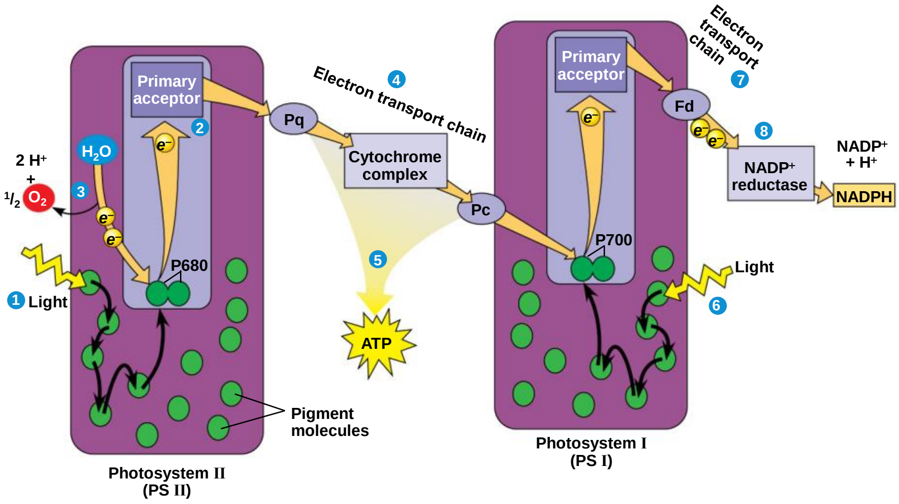
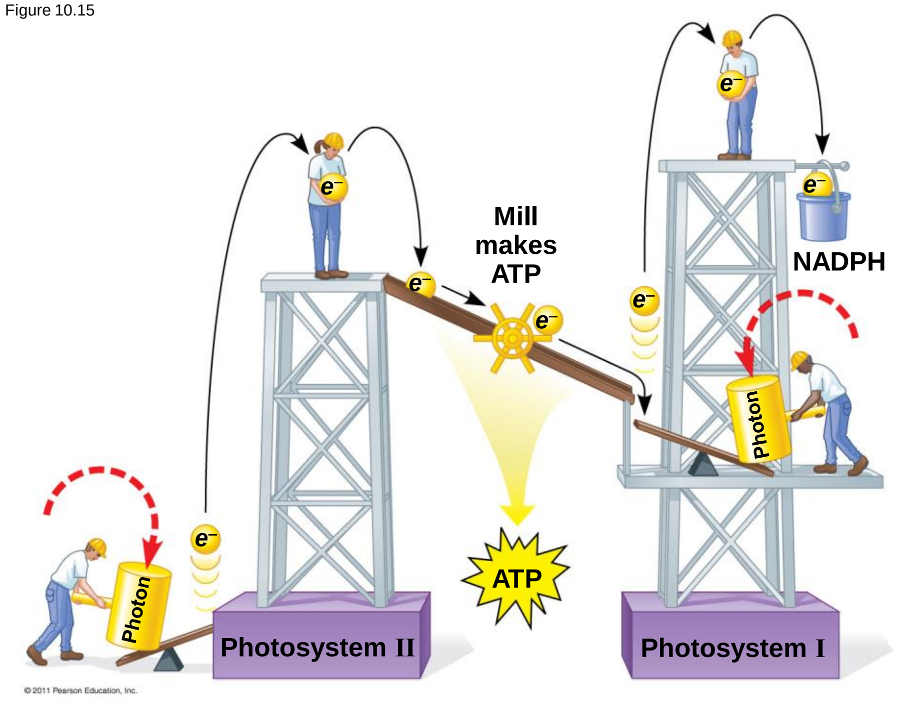


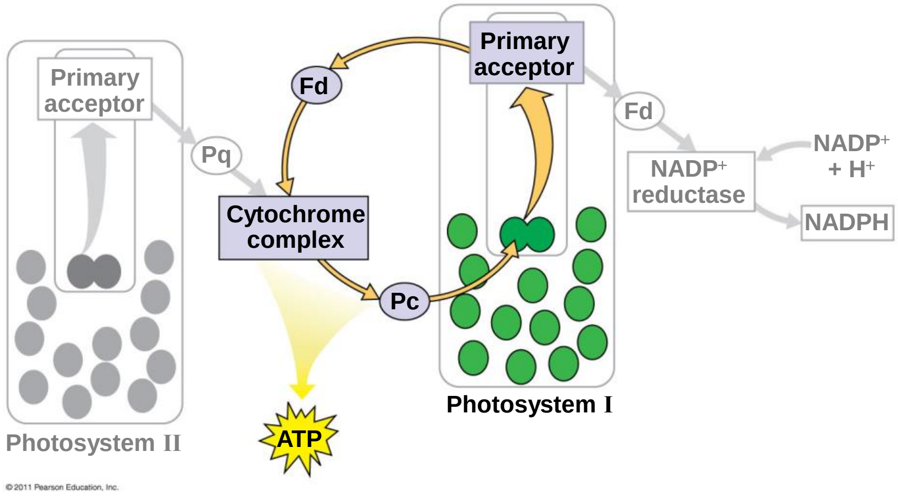
Figure 10.15



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*

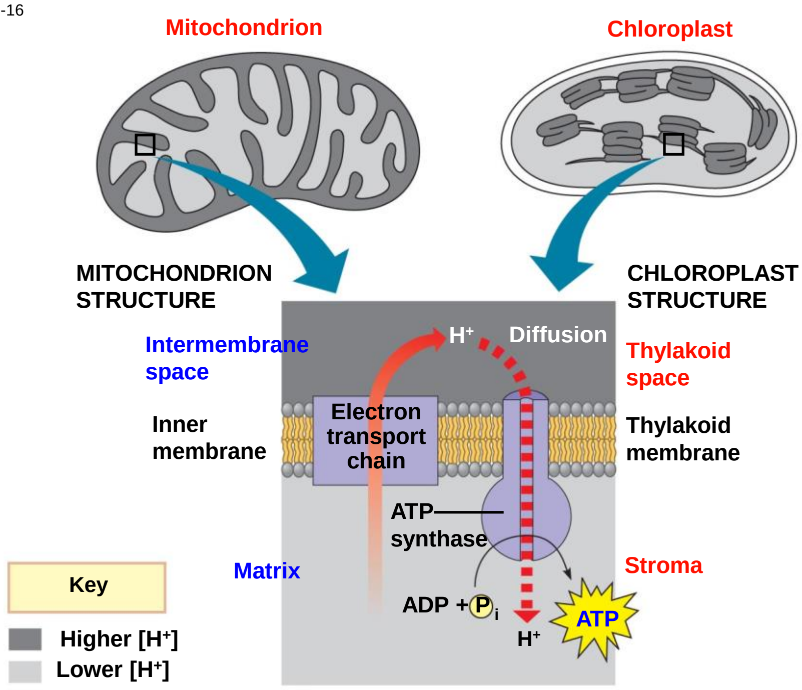
Figure 10.16



A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

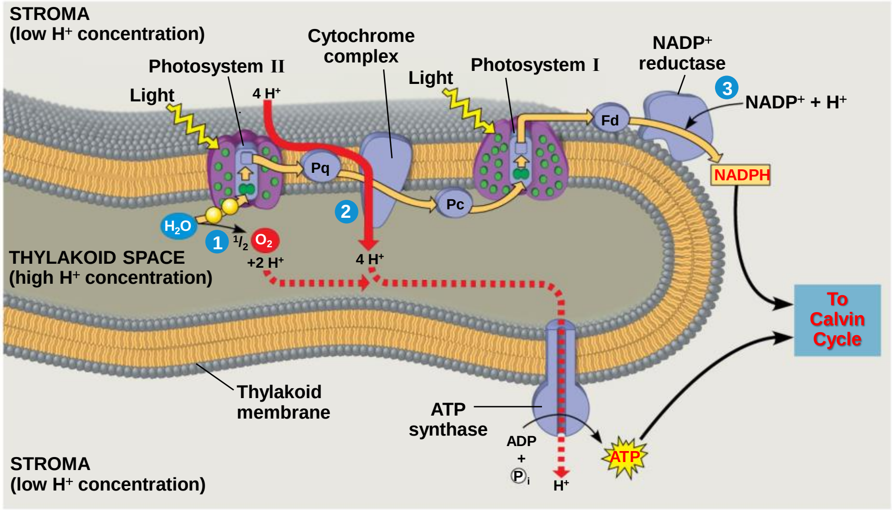
- Chloroplasts and mitochondria generate ATP by chemiosmosis, but use different sources of energy
- Mitochondria transfer **chemical** energy from **food to ATP**; chloroplasts transform light energy into the chemical energy of ATP

Fig. 10-16



- **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-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)**

Figure 10.19-1

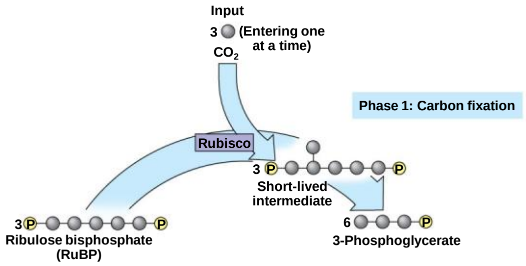
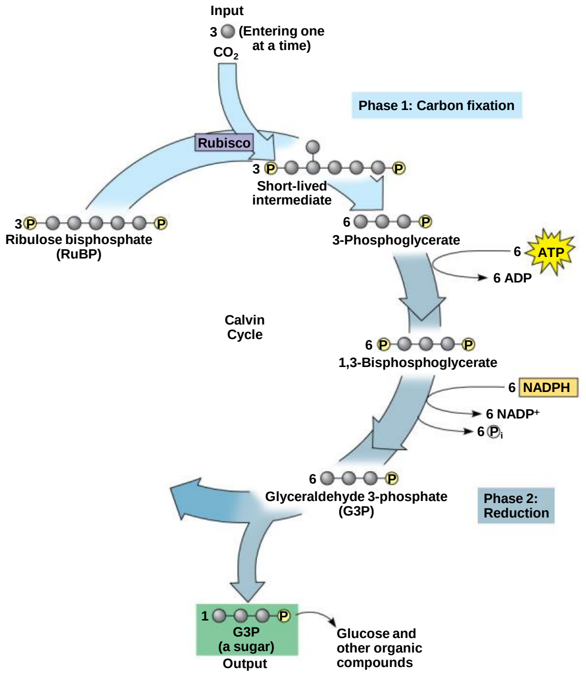


Figure 10.19-2



Input

3 (Entering one at a time)

CO_2

Phase 1: Carbon fixation

Rubisco

3 Short-lived intermediate

6 3-Phosphoglycerate

6 ATP

6 ADP

3 Ribulose bisphosphate (RuBP)

Calvin Cycle

6 1,3-Bisphosphoglycerate

6 NADPH

6 $NADP^+$

6 P_i

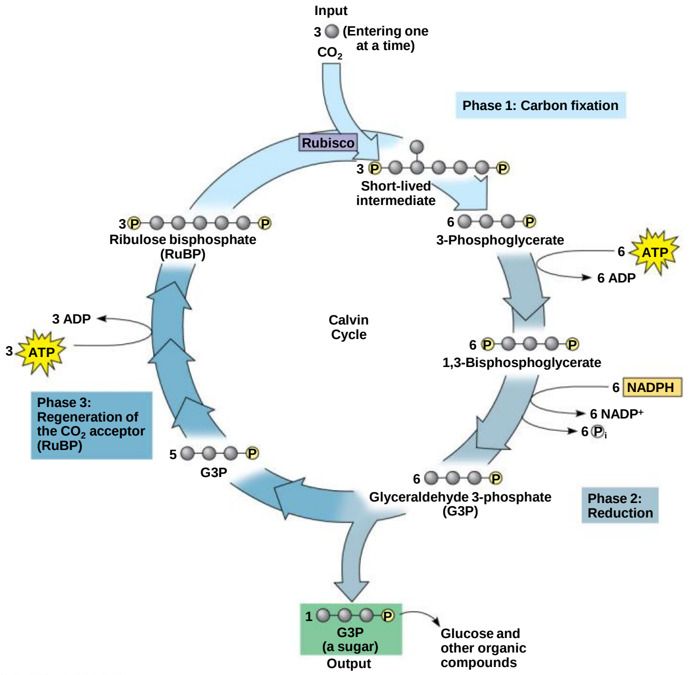
6 Glyceraldehyde 3-phosphate (G3P)

Phase 2: Reduction

1 G3P (a sugar) Output

Glucose and other organic compounds

Figure 10.19-3



Input

3 (Entering one at a time)

CO_2

Phase 1: Carbon fixation

Rubisco

3 Short-lived intermediate

6 3-Phosphoglycerate

6 ATP

6 ADP

3 Ribulose bisphosphate (RuBP)

3 ADP

3 ATP

Calvin Cycle

6 1,3-Bisphosphoglycerate

6 NADPH

6 $NADP^+$

6 P_i

Phase 3: Regeneration of the CO_2 acceptor (RuBP)

5 G3P

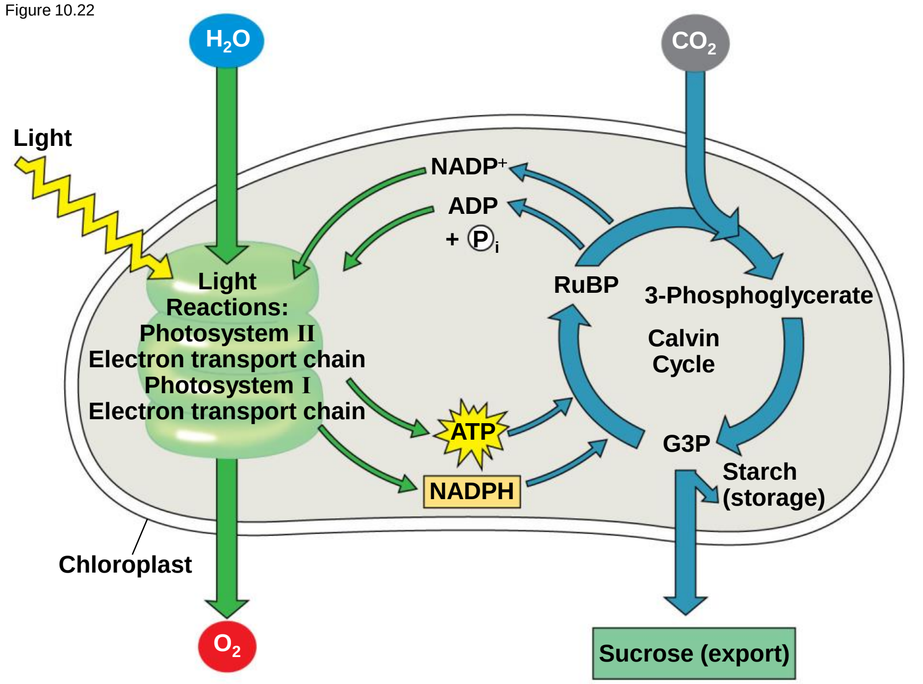
6 Glyceraldehyde 3-phosphate (G3P)

Phase 2: Reduction

1 G3P (a sugar) Output

Glucose and other organic compounds

Figure 10.22



Class activity!

- To synthesize one molecule of GLUCOSE, the Calvin cycle uses ------- molecules of CO2,------------- 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