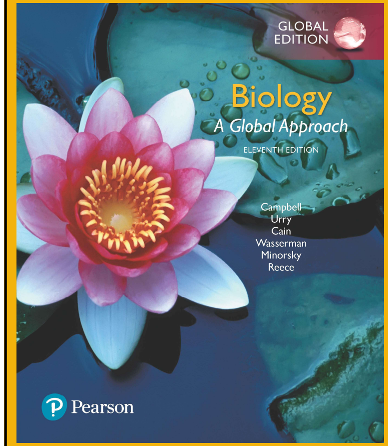


Chapter 11

Photosynthetic Processes

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

- **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 11.1

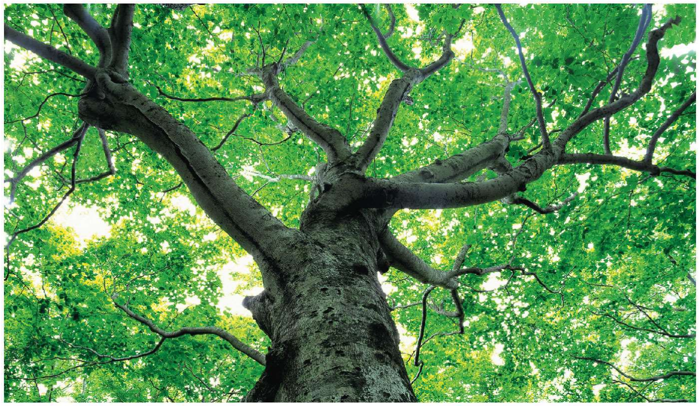
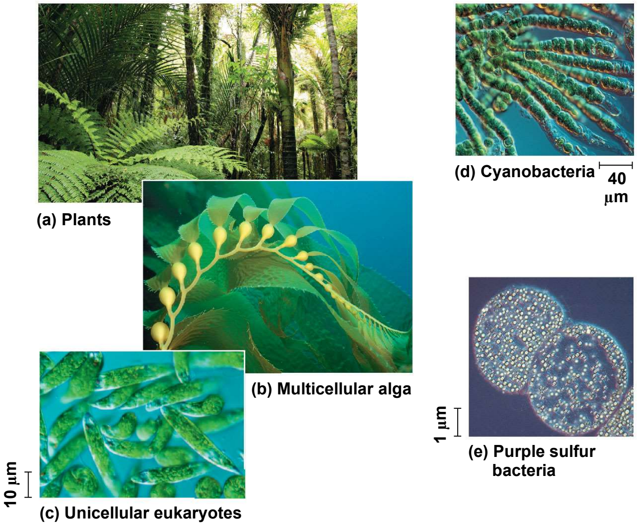


Figure 11.1a

Other organisms also benefit from photosynthesis.

- Photosynthesis occurs in plants, algae, certain other unicellular eukaryotes, and some prokaryotes

Figure 11.2



(a) Plants

(b) Multicellular alga

(c) Unicellular eukaryotes

(d) Cyanobacteria

(e) Purple sulfur bacteria

- **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

- Earth's supply of fossil fuels was formed from the remains of organisms that died hundreds of millions of years ago
- Fossil fuels are being consumed faster then they are being replenished
- Researchers are exploring methods of using the photosynthetic process to produce alternative fuels

Figure 11.3

Concept 11.1: Photosynthesis converts light energy to the chemical energy of food

- Chloroplasts are structurally similar to 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 11.4a

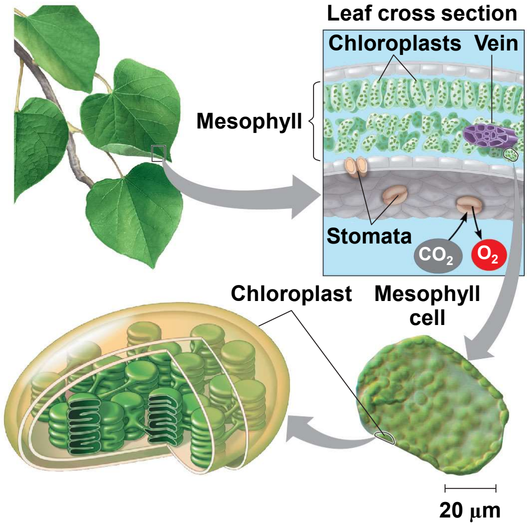
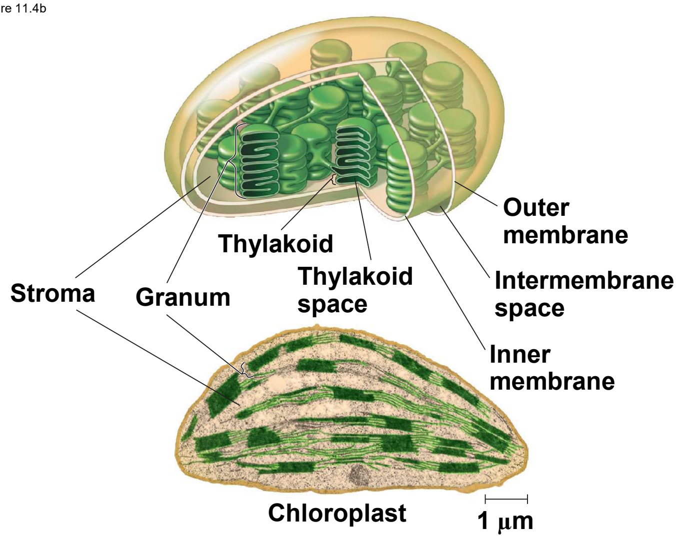


Figure 11.4b



Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

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

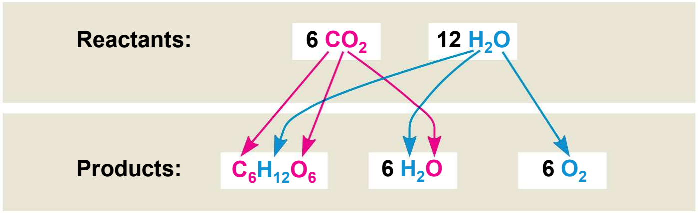
$$6\ CO_2 + 12\ H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

- The overall chemical change during **photosynthesis** is the **reverse** of the one that occurs during **cellular respiration**

The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules and releasing oxygen as a by-product

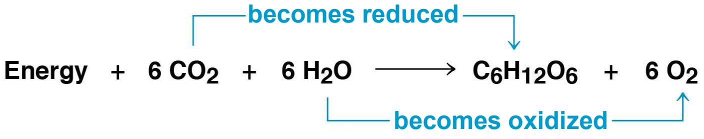
Figure 11.5



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**
- Photosynthesis is an endergonic process; the energy boost is provided by light

Figure 11.UN01



The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of two parts:
  - **light reactions** (the photo part)
  - **Calvin cycle** (the synthesis part)

The Two Stages of Photosynthesis: *A Preview*

- **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**
- **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

Figure 11.6_1

The light reactions (in the thylakoids)

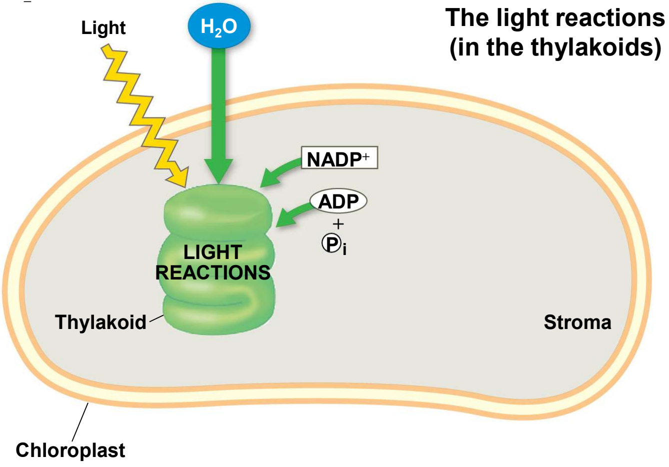


Figure 11.6_2

The light reactions (in the thylakoids)

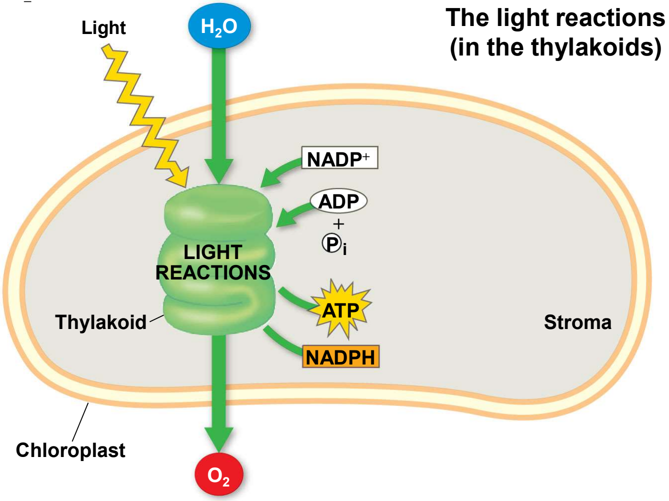


Figure 11.6_3

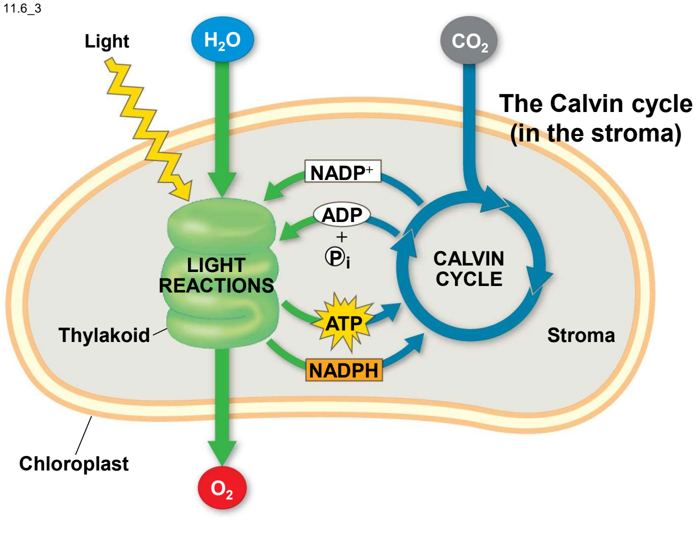
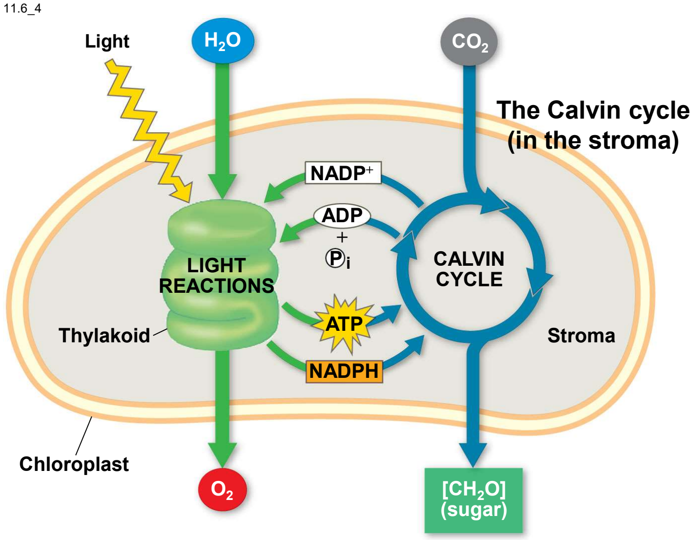


Figure 11.6_4



Concept 11.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

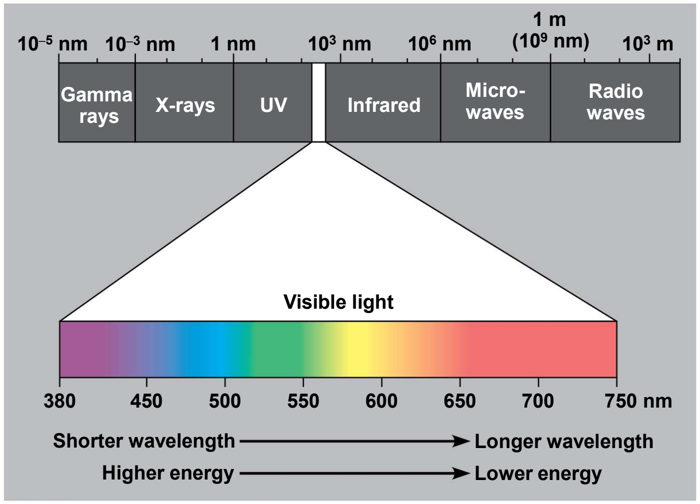
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is electromagnetic energy, also called electromagnetic radiation
- Electromagnetic energy travels in rhythmic waves
- **Wavelength** is the distance between crests of electromagnetic 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 (380 nm to 750 nm) that produce colors we can see
- Visible light also includes the wavelengths that drive photosynthesis
- Light also behaves as though it consists of discrete particles, called **photons**

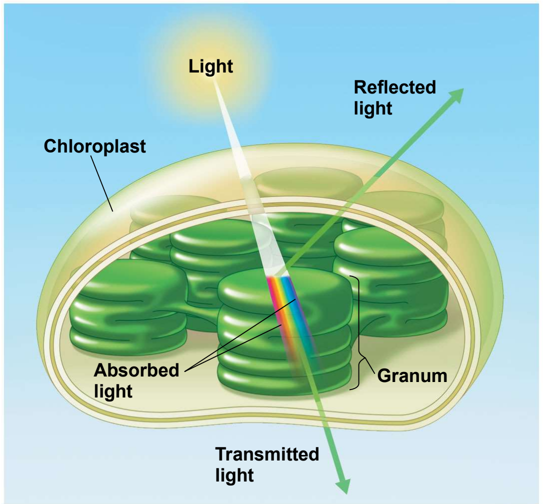
Figure 11.7



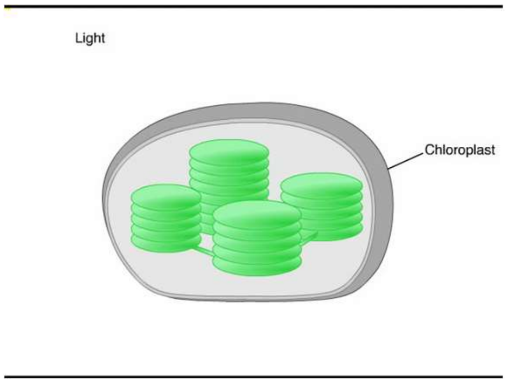
Photosynthetic Pigments: The Light Receptors

- 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 11.8



Animation: Light Energy and 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

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

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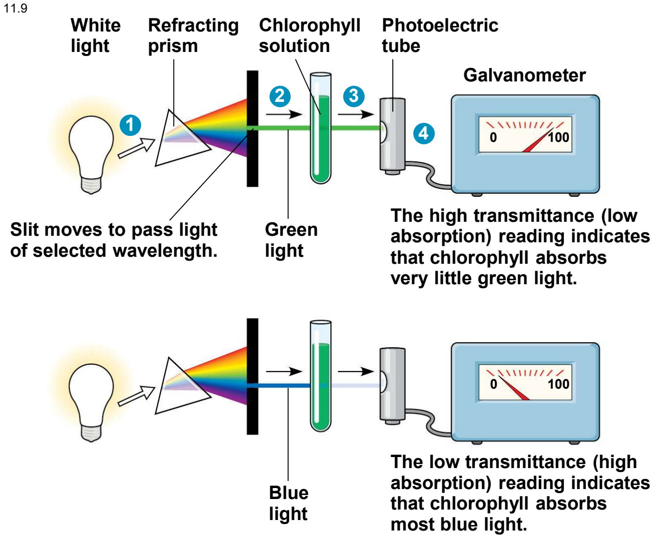
Figure 11.9



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.

- 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

- 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

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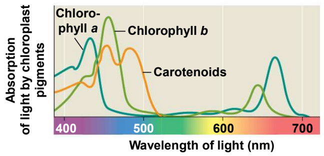
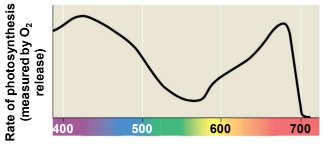
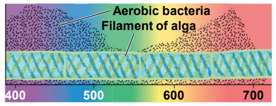
Figure 11.10



(a) Absorption spectra



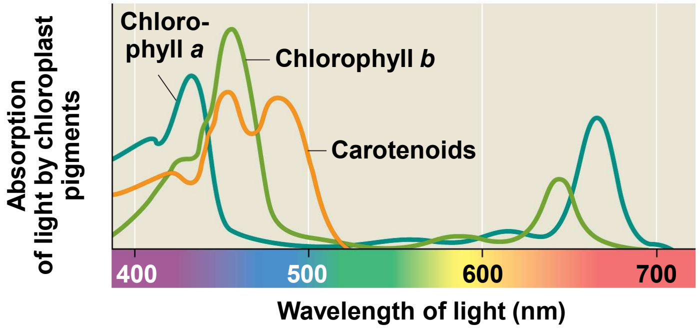
(b) Action spectrum



(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).

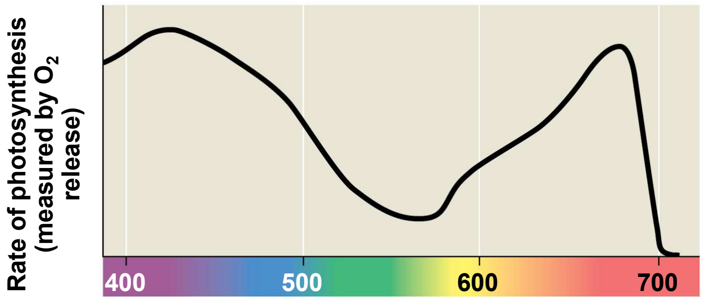
Figure 11.10a



(a) Absorption spectra

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

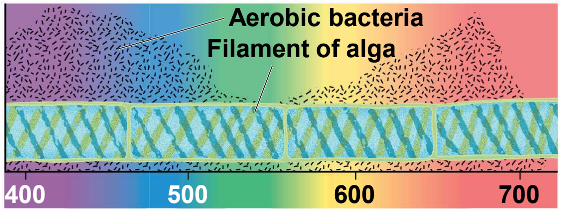
Figure 11.10b



(b) Action spectrum

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

Figure 11.10c



(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 of photosynthesis was first demonstrated in 1883 by Theodor W. Engelmann
- In his experiment, he exposed different segments of a filamentous alga to different wavelengths
- Areas receiving wavelengths favorable to photosynthesis produced excess O_2
- He used the growth of aerobic bacteria clustered along the algae as a measure of O_2 production

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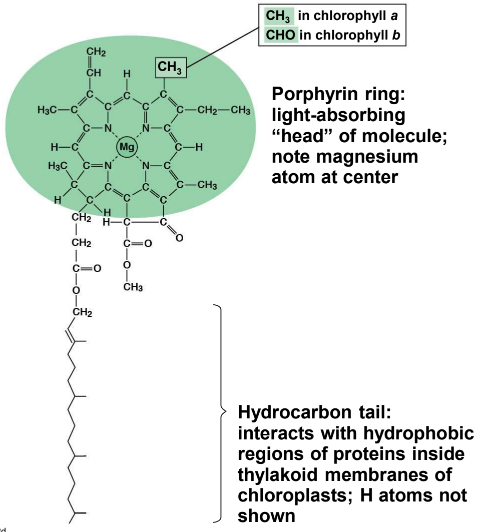
- The action spectrum for photosynthesis is broader than the absorption spectrum of chlorophyll
- Accessory pigments, such as chlorophyll *b*, broaden the spectrum used for photosynthesis
- The difference in the absorption spectrum between chlorophyll *a* and *b* is due to a slight structural difference between the pigment molecules

Figure 11.11



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

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

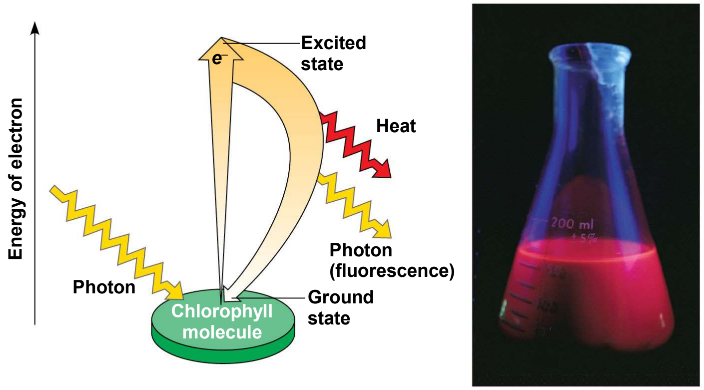
Hydrocarbon tail: interacts with hydrophobic regions of proteins inside thylakoid membranes of chloroplasts; H atoms not shown

- Accessory pigments called **carotenoids** may 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 11.12



(a) Excitation of isolated chlorophyll molecule **(b) Fluorescence**

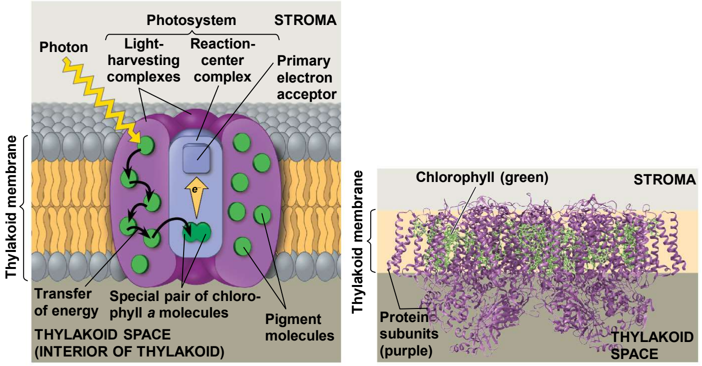
A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

- 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
- 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

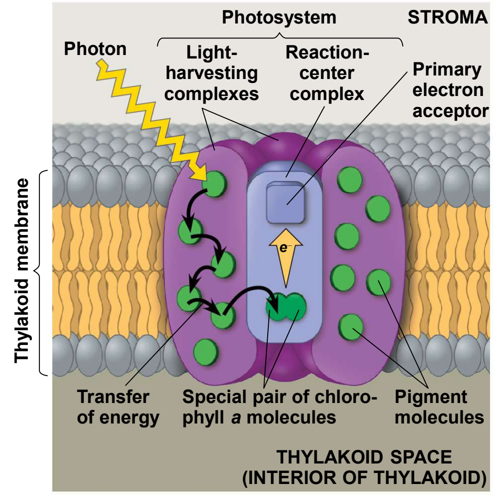
Figure 11.13



(a) How a photosystem harvests light

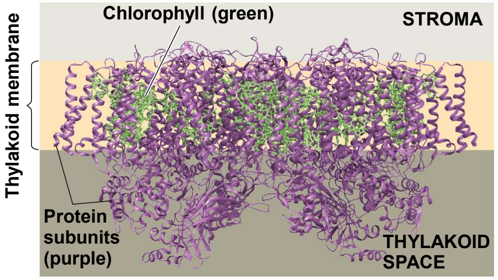
(b) Structure of a photosystem

Figure 11.13a



(a) How a photosystem harvests light

Figure 11.13b



(b) Structure of a photosystem

- 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

- 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 11.UN02

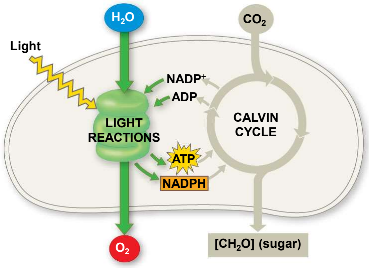


Figure 11.14_1

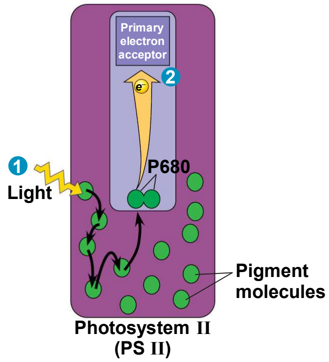


Figure 11.14_2

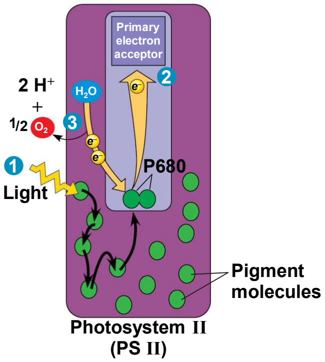
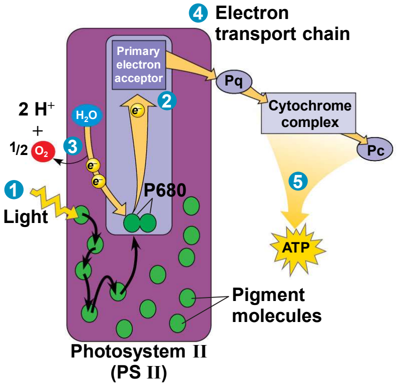
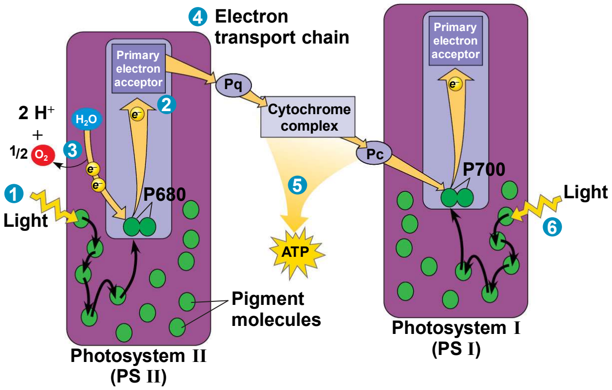


Figure 11.14_3



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 11.14_4



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

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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

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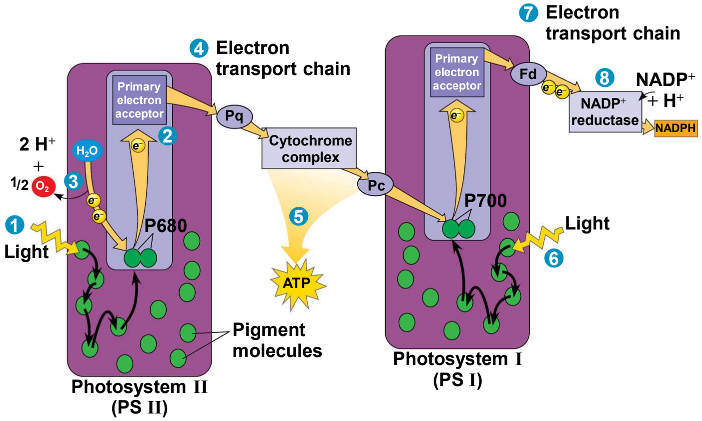
Figure 11.14_5



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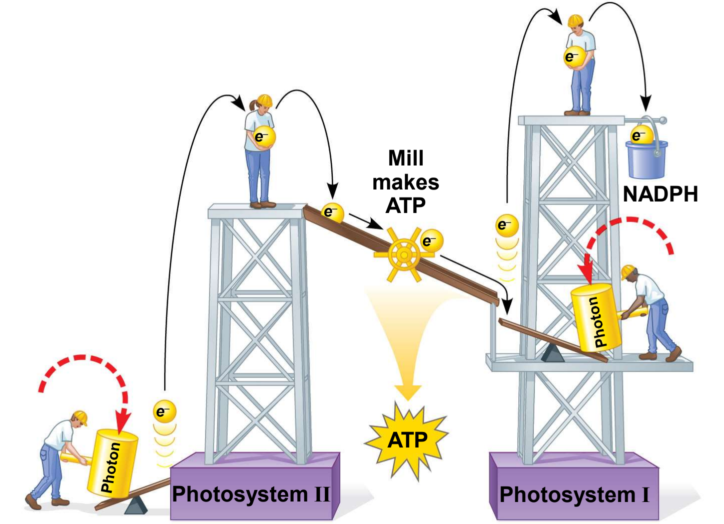
7. Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
8. NADP$^+$ reductase catalyzes the transfer of electrons to NADP$^+$, reducing it to NADPH
   - The electrons of NADPH are available for the reactions of the Calvin cycle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

- The energy changes of electrons during linear flow through the light reactions can be shown in a mechanical analogy

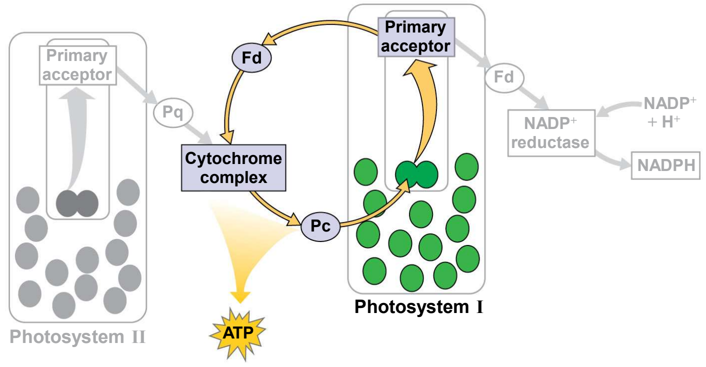
Figure 11.15



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 11.16



- 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

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

- 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

Figure 11.17

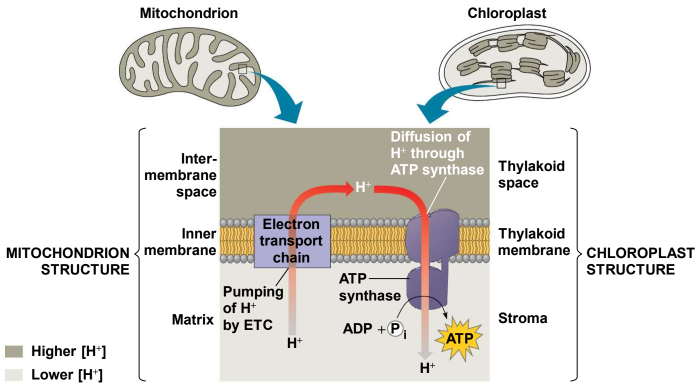
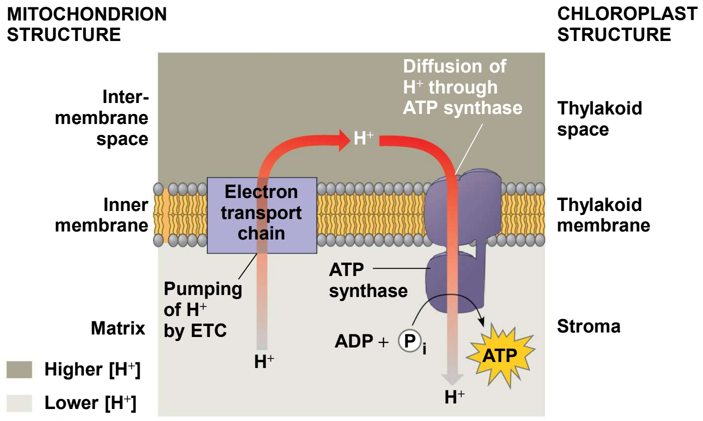


Figure 11.17a



- 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 11.UN03

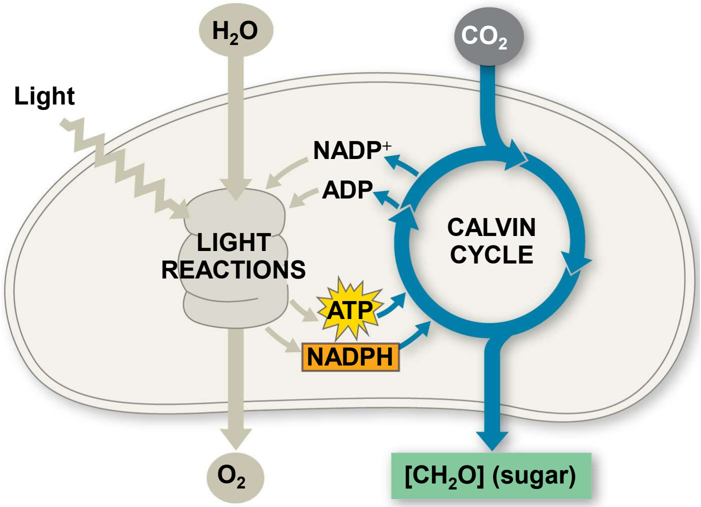


Figure 11.18

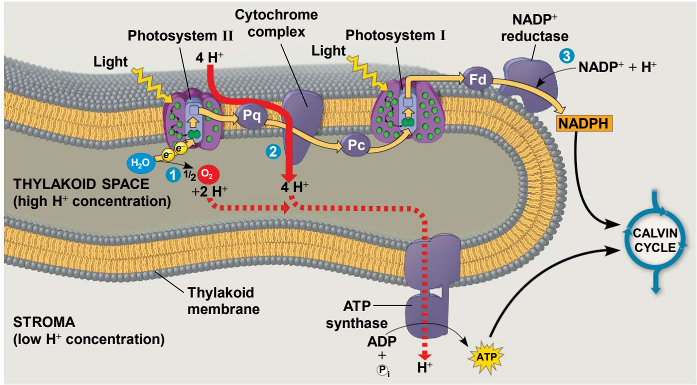


Figure 11.18a

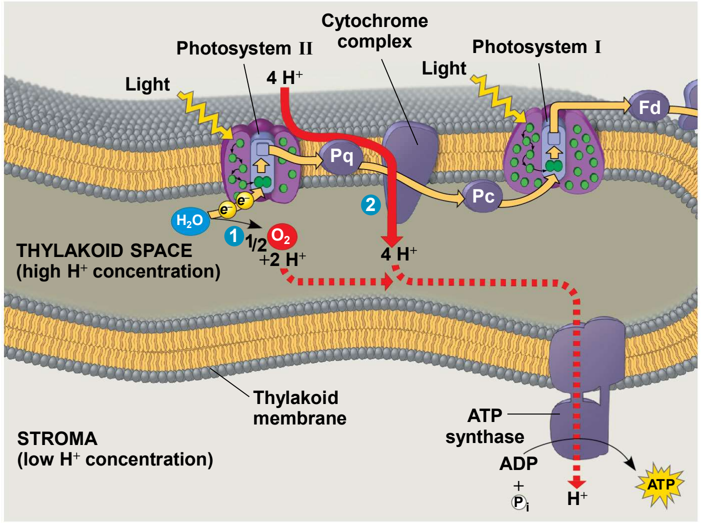
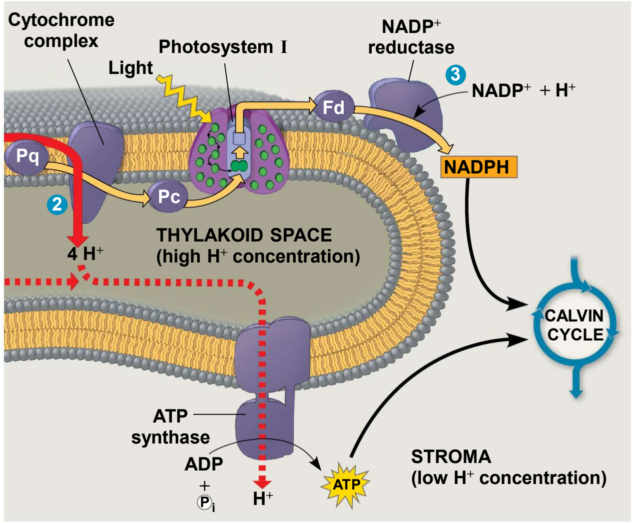


Figure 11.18b



Concept 11.3: The Calvin cycle uses the chemical energy of ATP and NADPH to reduce CO_2 to sugar

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle
- The Calvin cycle is anabolic; it 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 one G3P, the cycle must take place three times, fixing three molecules of CO_2
- The Calvin cycle has three phases:
  1. **Carbon fixation** (catalyzed by **rubisco**)
  2. **Reduction**
  3. **Regeneration of the CO_2 acceptor (RuBP)**

Figure 11.19_1

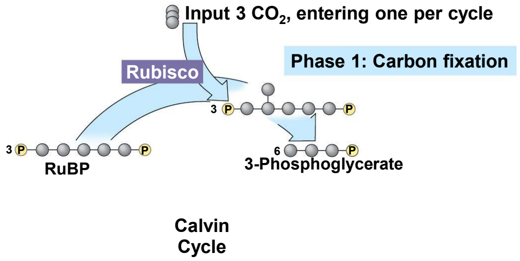


Figure 11.19_2

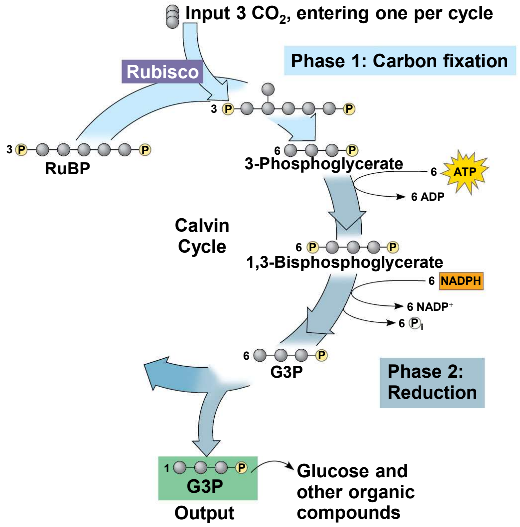
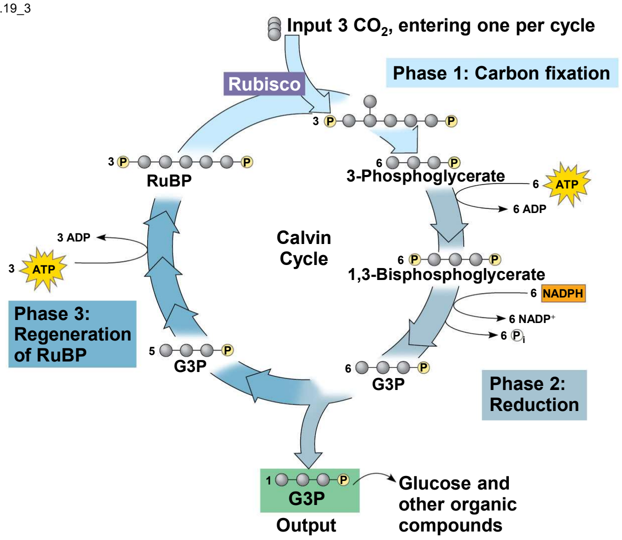


Figure 11.19_3



Concept 11.5: Life depends on photosynthesis
The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
- Plants store excess sugar as starch in chloroplasts and other structures such as roots, tubers, seeds, and fruits

Figure 11.22a

Figure 11.22b

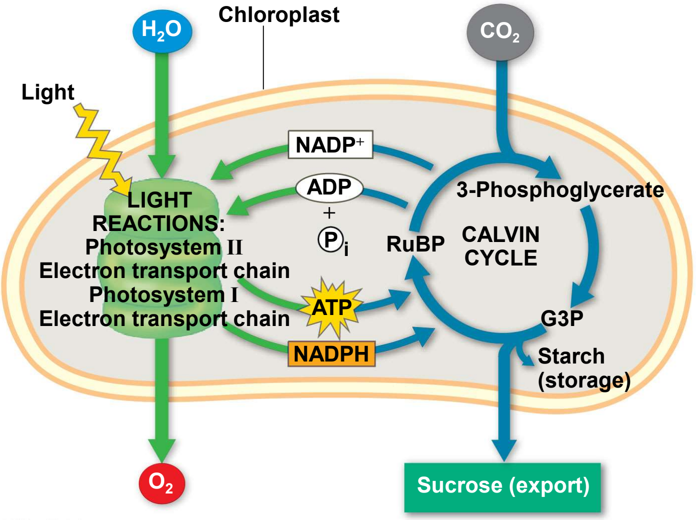


Figure 11.23

MAKE CONNECTIONS: The Working Cell

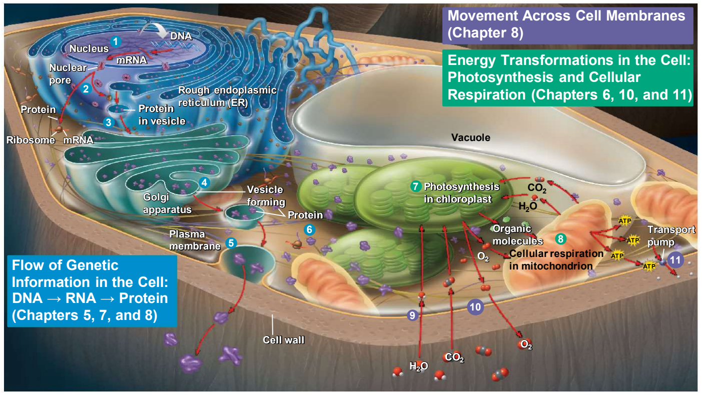


Figure 11.23a

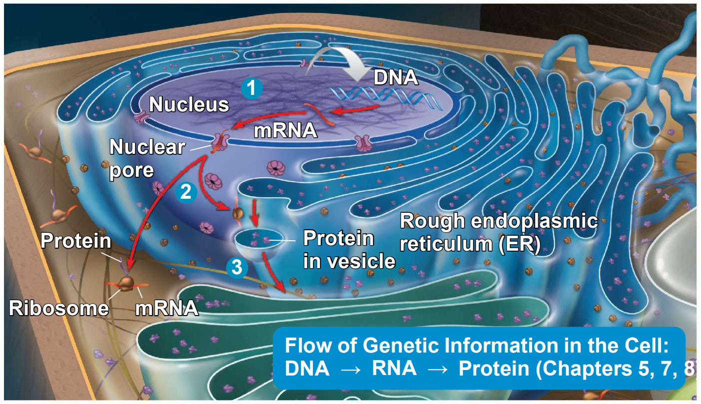
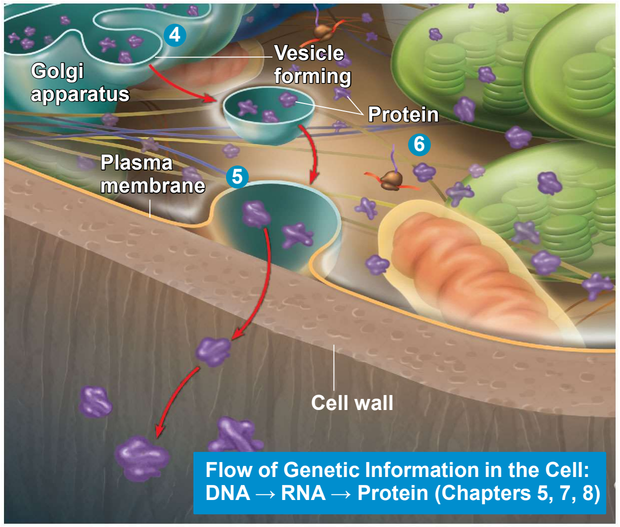
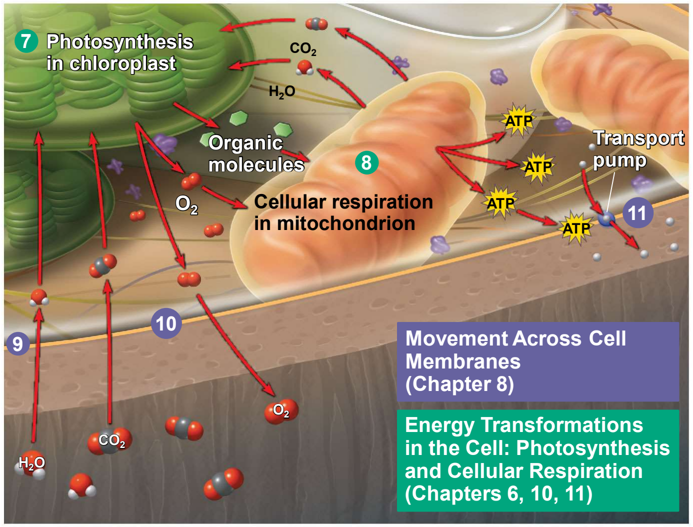


Figure 11.23b



Flow of Genetic Information in the Cell: DNA → RNA → Protein (Chapters 5, 7, 8)

Figure 11.23c



Movement Across Cell Membranes (Chapter 8)

Energy Transformations in the Cell: Photosynthesis and Cellular Respiration (Chapters 6, 10, 11)