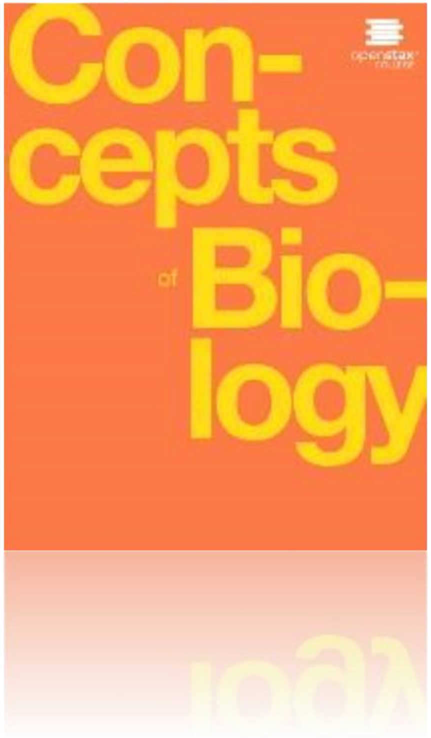
CONCEPTS OF BIOLOGY

Chapter 5 PHOTOSYNTHESIS

PowerPoint Image Slideshow



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Introduction

- Living things have many complex components and cannot do anything without energy
- This is why all organisms must “eat” in some form or another
- Every bite of every meal ingested depends of the process of photosynthesis

FIGURE 5.1

This sage thrasher’s diet, like that of almost all organisms, depends on photosynthesis. (credit: modification of work by Dave Menke, U.S. Fish and Wildlife Service)

5.1 OVERVIEW OF PHOTOSYNTHESIS

- Every cell runs on the chemical energy found mainly in carbohydrates molecules (food) and the majority of these molecules are produced by one process: photosynthesis
- Certain organisms can carry out **photosynthesis**, which converts solar energy (sunlight) into chemical energy, which is then used to build carbohydrate molecules

Overview of Photosynthesis

- The energy that is harnessed from photosynthesis is transferred from one organism to another
- Photosynthesis, directly or indirectly, provides most of the energy required by living things on Earth
- Photosynthesis releases oxygen, which humans need to breathe and eat; humans depend almost entirely on the organisms that carry out photosynthesis

Solar Dependence and Food Production

- Some organisms can carry out photosynthesis, whereas others cannot
- An **autotroph** (“self” “feeder”) is an organism that can produce its own food
- A **heterotroph** (“other” “feeder”) is an organism incapable of photosynthesis, therefore must obtain energy and carbon from food by consuming other organisms

FIGURE 5.2

(a)

(b)

(c)

(a) Plants, (b) algae, and (c) certain bacteria, called cyanobacteria, are photoautotrophs that can carry out photosynthesis. Algae can grow over enormous areas in water, at times completely covering the surface. (credit a: Steve Hillebrand, U.S. Fish and Wildlife Service; credit b: “eutrophication&hypoxia”/Flickr; credit c: NASA; scale-bar data from Matt Russell)

FIGURE 5.3

The energy stored in carbohydrate molecules from photosynthesis passes through the food chain. The predator that eats these deer is getting energy that originated in the photosynthetic vegetation that the deer consumed. (credit: Steve VanRiper, U.S. Fish and Wildlife Service)

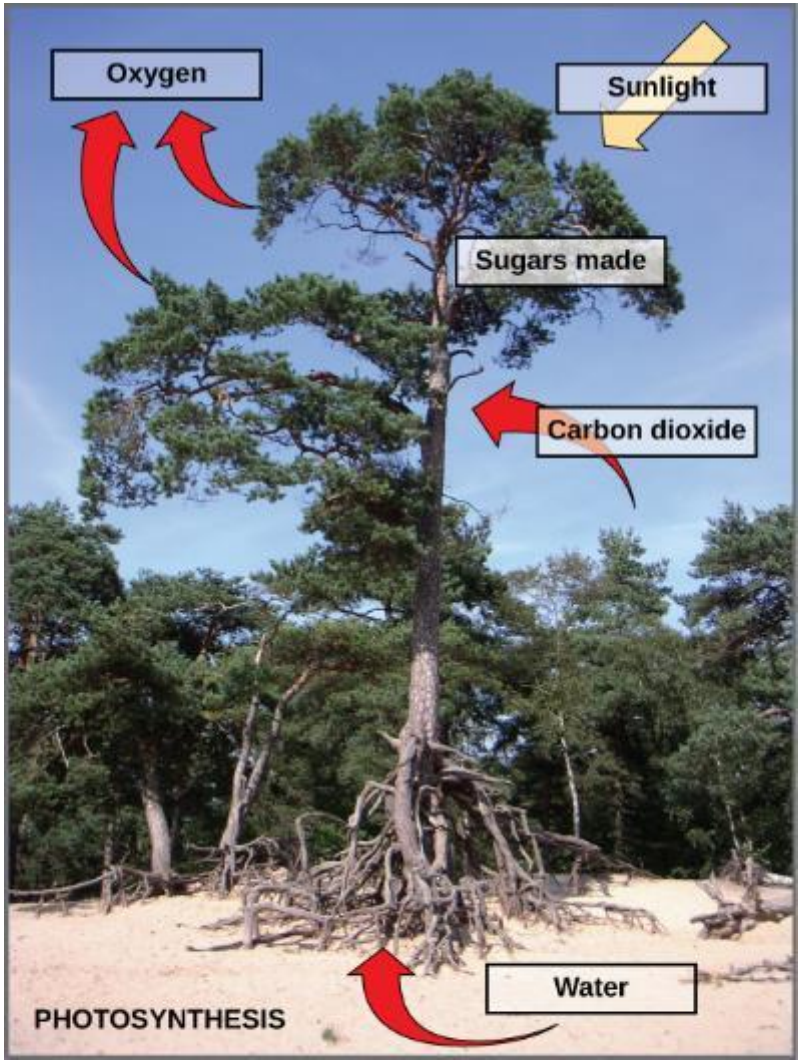
FIGURE 5.4

Photosynthesis is the origin of the products that comprise the main elements of the human diet. (credit: Associação Brasileira de Supermercados)

Main Structures and Summary of Photosynthesis (1 of 4)

- Photosynthesis requires sunlight, carbon dioxide, and water as starting reactants
- After the reactions are complete, photosynthesis releases oxygen and produces carbohydrates molecules (most commonly glucose)

FIGURE 5.5



Photosynthesis uses solar energy, carbon dioxide, and water to release oxygen and to produce energy-storing sugar molecules.

FIGURE 5.6

Photosynthesis Equation			
Carbon dioxide +	Water $\xrightarrow{\text{SUNLIGHT}}$	Sugar +	Oxygen
$6CO_2$	$6H_2O$	$C_6H_{12}O_6$	$6O_2$

The process of photosynthesis can be represented by an equation, wherein carbon dioxide and water produce sugar and oxygen using energy from sunlight.

Main Structures and Summary of Photosynthesis (2 of 4)

- Although the equation looks simple, the many steps that take place during photosynthesis are actually quite complex and involves many physical structures within the plant

Main Structures and Summary of Photosynthesis (3 of 4)

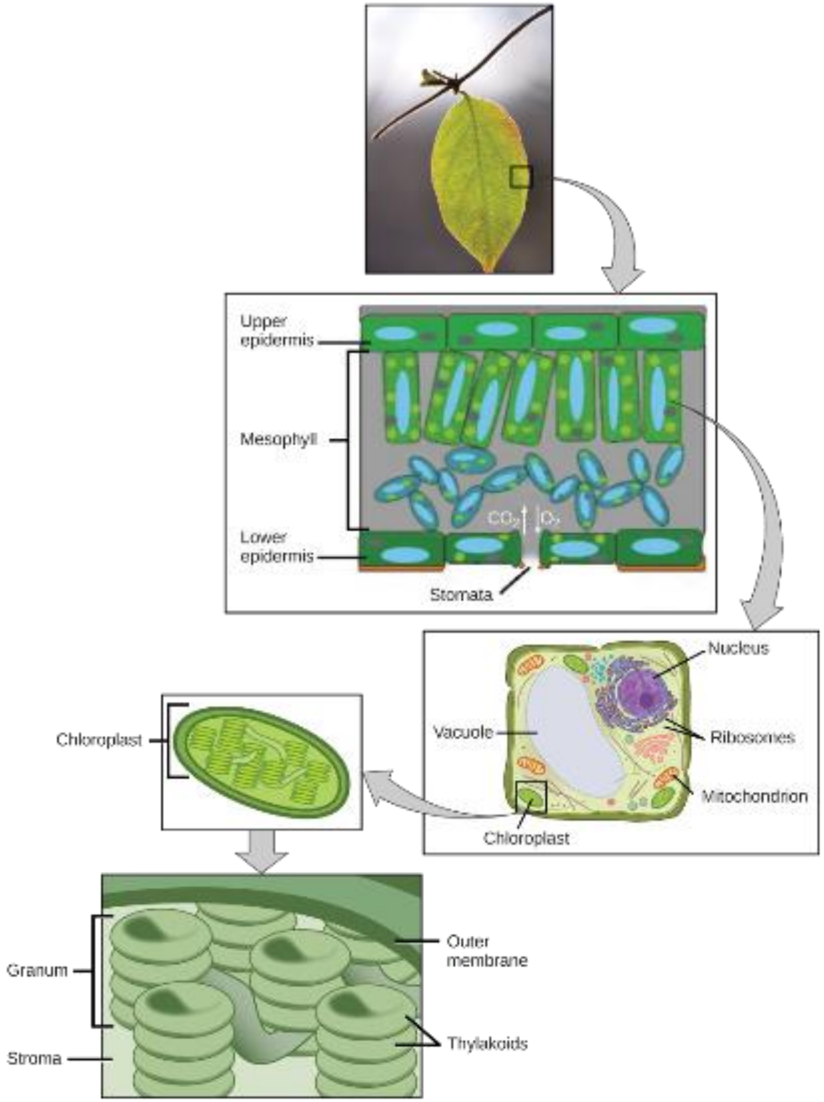
- Photosynthesis occurs primarily in the leaves of a plant, in the middle layer of the leaf, called the **mesophyll**
- The carbon dioxide enters and the oxygen exits through small, regulated openings on the leaf’s surface, called **stomata**

Main Structures and Summary of Photosynthesis (4 of 4)

- A plant’s leaf is, of course, made up of cells; the cells of the mesophyll contain organelles called **chloroplasts**
- Chloroplast have a double (inner and outer) membrane
- Within the chloroplast is a third membrane that forms stacked, disc-shaped structures called **thylakoids**
- Embedded in the thylakoid membrane are molecules of **chlorophyll**, a green pigment that absorbs light from the sun to begin the process of photosynthesis

FIGURE 5.7

Not all cells of a leaf carry out photosynthesis. Cells within the middle layer of a leaf have chloroplasts, which contain the photosynthetic apparatus. (credit “leaf”: modification of work by Cory Zanker)



The Two Parts of Photosynthesis (1 of 3)

- Photosynthesis takes place in two stages:
  - ✓ the light-dependent reactions
  - ✓ the Calvin cycle

The Two Parts of Photosynthesis (2 of 3)

- In the **light-dependent reactions**, which take place at the thylakoid membrane, chlorophyll absorbs energy from sunlight and then converts it into chemical energy with the use of water
- The light-dependent reactions release oxygen from the hydrolysis of water as a byproduct

The Two Parts of Photosynthesis (3 of 3)

- In the **Calvin cycle**, which takes place in the stroma, the chemical energy derived from the light-dependent reactions drives both the capture of carbon in carbon dioxide molecules and the subsequent assembly of sugar molecules

5.2 THE LIGHT-DEPENDENT REACTIONS OF PHOTOSYNTHESIS

- It is easy to think of light as something that exist to help us see, but light is a form of energy
- Like all energy, light can travel, change form, and be harnessed to do work
- In the case of photosynthesis, light energy is transformed into chemical energy, which autotrophs use to build carbohydrate molecules

FIGURE 5.8

Autotrophs can capture light energy from the sun, converting it into chemical energy used to build food molecules. (credit: modification of work by Gerry Atwell, U.S. Fish and Wildlife Service)

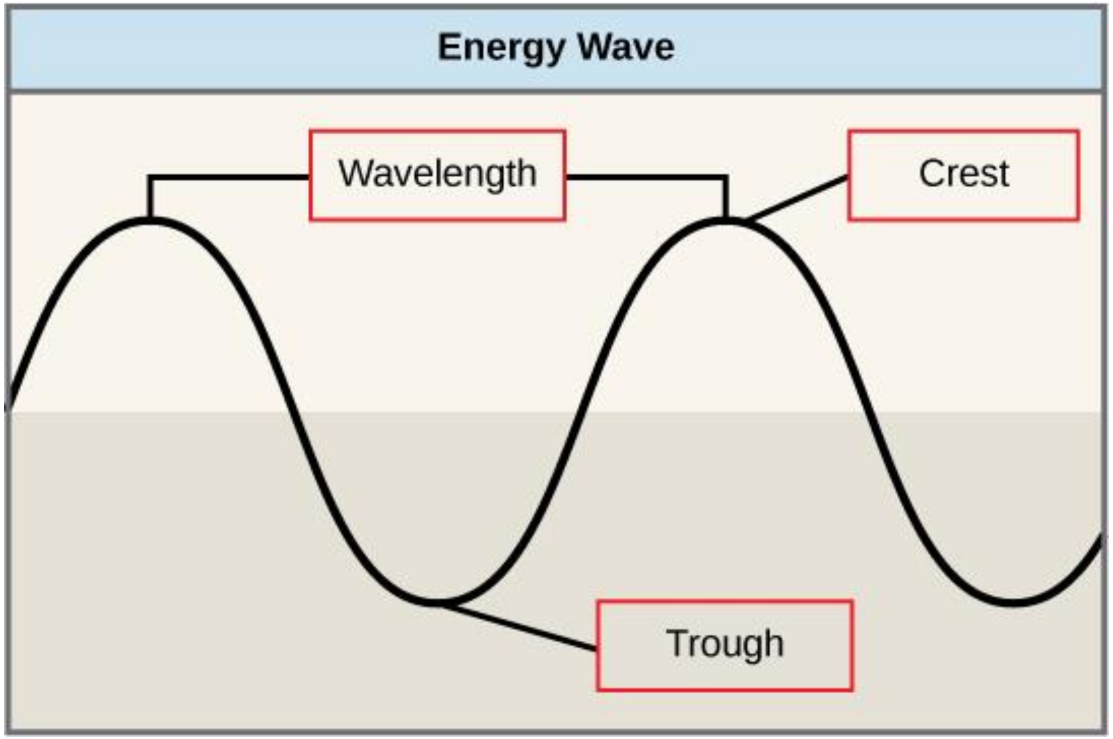
What is Light Energy? (1 of 4)

- The sun emits an enormous amount of electromagnetic radiation (solar energy)
- Humans can see only a fraction of this energy, which is referred to as “visible light”
- The manner in which solar energy travels is described and measured as waves

What is Light Energy? (2 of 4)

- Scientists can determine the amount of energy of a wave by measuring its **wavelength**, the distance between two consecutive, similar points in a series of waves, such as from crest to crest, or trough to trough

FIGURE 5.9



The wavelength of a single wave is the distance between two consecutive points along the wave.

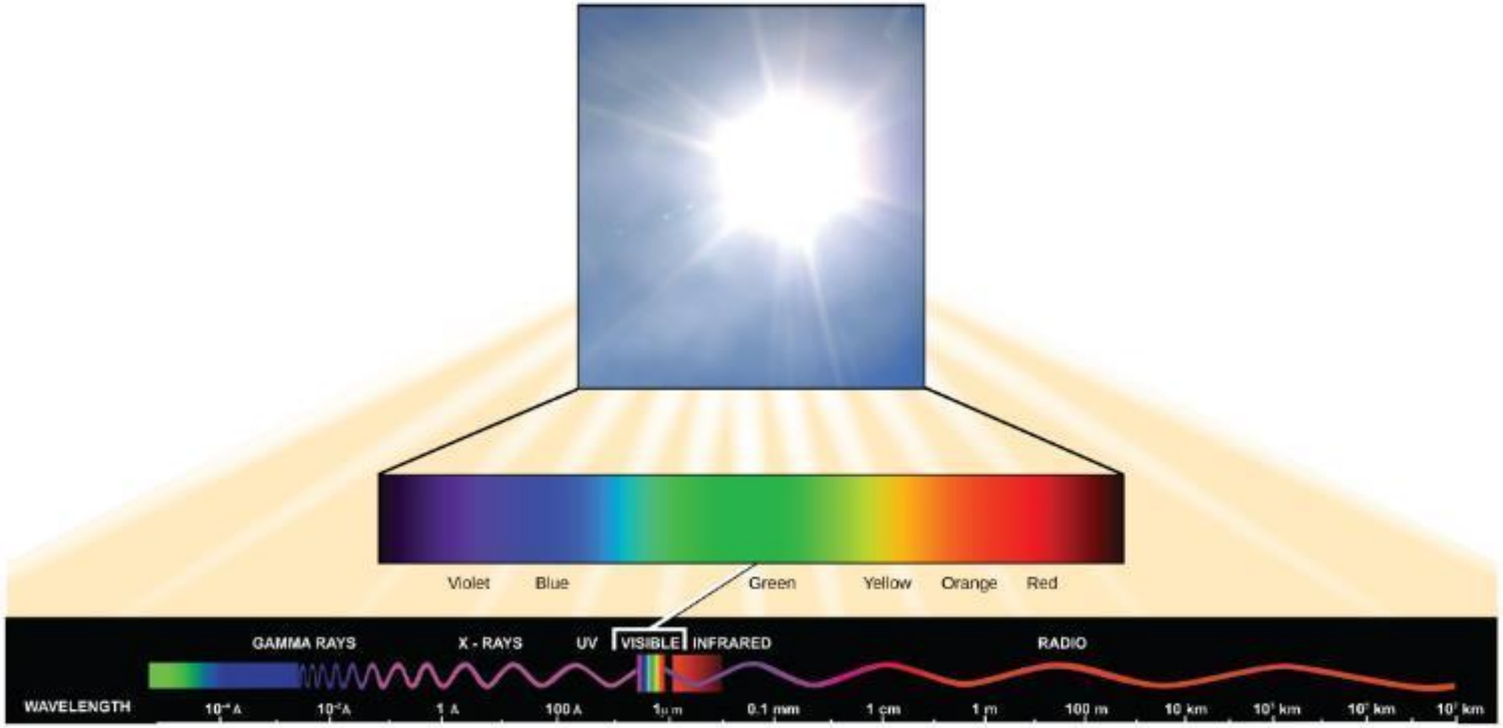
What is Light Energy? (3 of 4)

- Visible light constitutes only one of many types of electromagnetic radiation emitted from the sun
- **Electromagnetic spectrum** = the range of all possible wavelengths of radiation
- Each wavelength corresponds to a different amount of energy carried

What is Light Energy? (4 of 4)

- Each type of electromagnetic radiation has a characteristic range of wavelengths
- The longer the wavelength, the less energy is carried
- The sun emits a broad range of electromagnetic radiation, including x-rays and ultraviolet (UV) rays; the higher-energy waves are dangerous to living things

FIGURE 5.10



The sun emits energy in the form of electromagnetic radiation. This radiation exists in different wavelengths, each of which has its own characteristic energy. Visible light is one type of energy emitted from the sun.

Absorption of Light

- In plants, pigment molecules absorb only visible light for photosynthesis
- Visible light seen by humans as white light actually exists in a rainbow of colors; prisms or water droplets can reveal these colors to the human eye
- The violet color has shorter wavelengths (higher energy) as you mover toward the red color, the wavelengths get longer (lower energy)

Understanding Pigments (1 of 2)

- Different kinds of pigments exist and each absorbs only certain wavelengths (colors) of visible light
- A pigment reflects the color of the wavelengths that they cannot absorb

Understanding Pigments (2 of 2)

- All photosynthetic organisms contain a pigment called **chlorophyll *a***, which humans see as the green color associated with plants
- Chlorophyll *a* absorbs the other colors of the visible spectrum, but does not absorb the green; green is reflected, so chlorophyll *a* appears green
- Other pigments types include **chlorophyll *b*** and the **carotenoids**
- Many photosynthetic organisms have a mixture of pigments and can absorb energy from a wider range of visible-light wavelengths

FIGURE 5.11

Plants that commonly grow in the shade benefit from having a variety of light-absorbing pigments. Each pigment can absorb different wavelengths of light, which allows the plant to absorb any light that passes through the taller trees. (credit: Jason Hollinger)

How Light-Dependent Reactions Work (1 of 4)

- The overall purpose of the light-dependent reactions is to convert light energy into chemical energy
- This chemical energy will then be used by the Calvin cycle to assemble sugar molecules

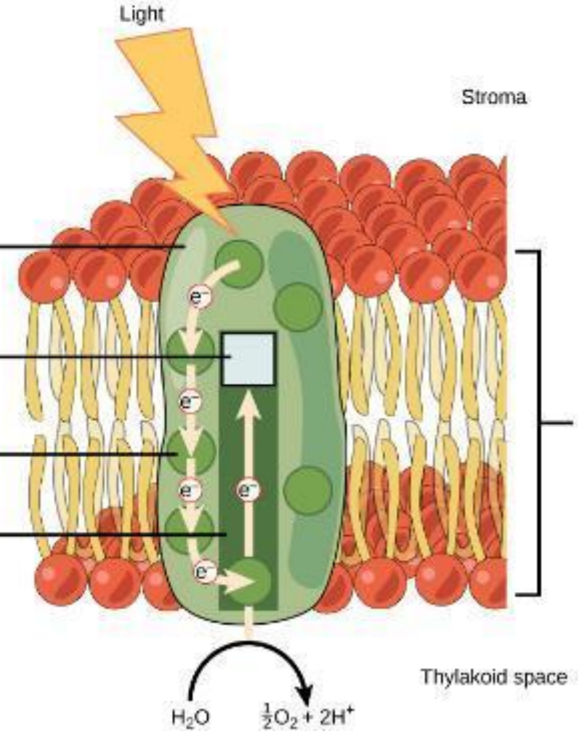
How Light Dependent Reactions Work (2 of 4)

- The light-dependent reactions begin in a grouping of pigment molecules and proteins called a **photosystem** (in the thylakoid)
- A pigment molecule in the photosystem absorbs one **photon**, a quantity or “packet” of light energy, at a time

How Light-Dependent Reactions Work (3 of 4)

- A photon of light energy travels to a molecule of chlorophyll and causes an electron in the chlorophyll to become “excited”
- The excited electron can break free from an atom of the chlorophyll molecule; therefore chlorophyll is said to “donate” an electron
- To replace the lost electron, a molecule of water splits (one water molecule can replace two donated electrons)

FIGURE 5.12

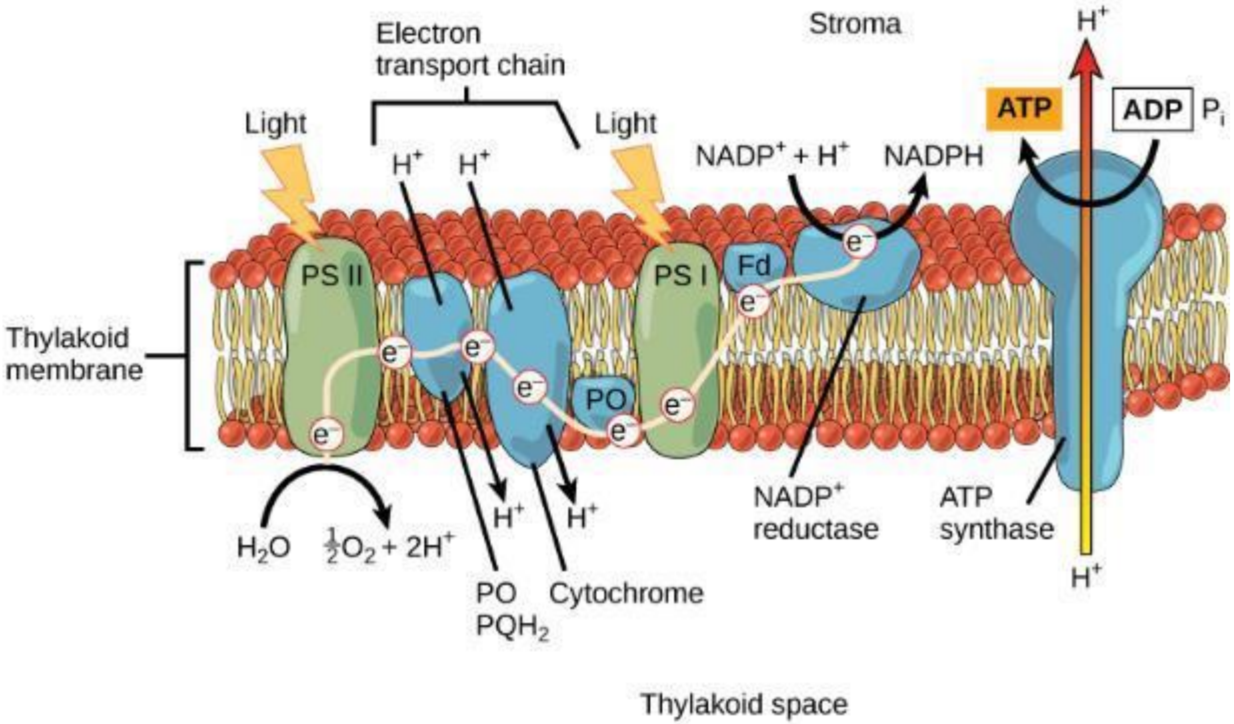


Light energy is absorbed by a chlorophyll molecule and is passed along a pathway to other chlorophyll molecules. The energy culminates in a molecule of chlorophyll found in the reaction center. The energy “excites” one of its electrons enough to leave the molecule and be transferred to a nearby primary electron acceptor. A molecule of water splits to release an electron, which is needed to replace the one donated. Oxygen and hydrogen ions are also formed from the splitting of water.

How Light-Dependent Reactions Work (4 of 4)

- Replacing of the electron enables chlorophyll to respond to another photon; the oxygen produced finds its way to the surrounding environment; the hydrogen ions play critical roles in the remainder of the light-dependent reaction
- After the photon hits, photosystem II transfers the free electron to the first in a series of proteins inside the thylakoid membrane called the electron transport chain
- As the electron passes along these proteins, energy from the electron fuels membrane pumps that actively move hydrogen ions against their concentration gradient from the stroma into the thylakoid space

FIGURE 5.13



From photosystem II, the excited electron travels along a series of proteins. This electron transport system uses the energy from the electron to pump hydrogen ions into the interior of the thylakoid. A pigment molecule in photosystem I accepts the electron.

Generating an Energy Carrier: ATP (1 of 2)

- The buildup of hydrogen ions in the thylakoid space forms an electrochemical gradient because of the difference in the concentrations of protons (H^+) and the difference in the charge across the membrane that they create
- This potential energy is harvested and stored as chemical energy in ATP through chemiosmosis, the movement of hydrogen ions down their electrochemical gradient through the transmembrane enzyme ATP synthase, just as happens in the mitochondria during aerobic cellular respiration

Generating an Energy Carrier: ATP (2 of 2)

- The hydrogen ions pass through the thylakoid membrane through the embedded protein complex called **ATP synthase**
- The energy generated by the hydrogen ion streams allows ATP synthase to attach a third phosphate to ADP, which forms a molecule of ATP in a process called **photophosphorylation**

Generating Another Energy Carrier: NADPH

- As the electron from the electron transport chain arrives at photosystem I, it is re-energized with another photon captured by chlorophyll
- The energy from this electron drives the formation of NADPH from $NADP^+$ and a H^+
- This energy stored in energy carriers can be used to make a sugar molecule

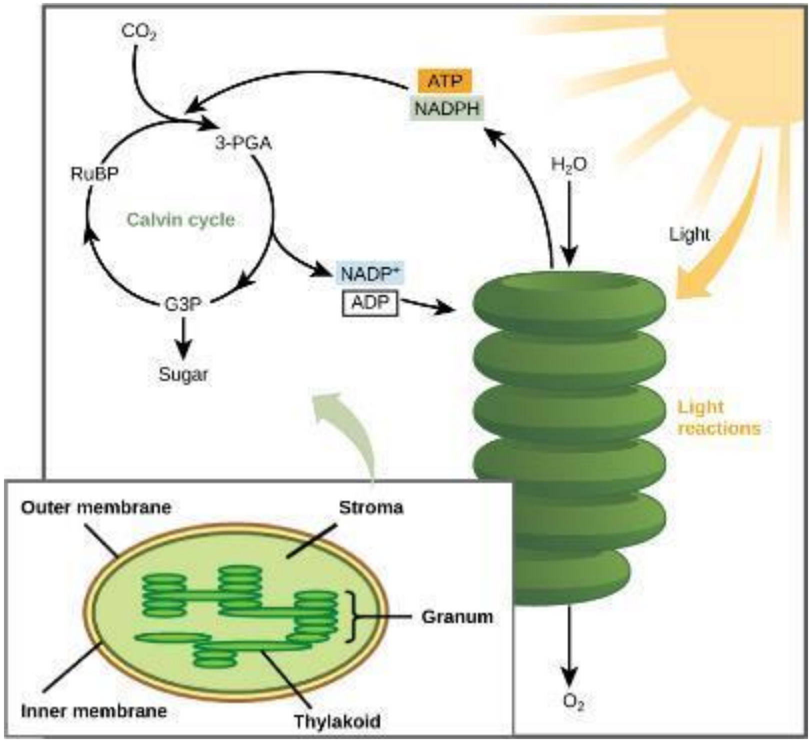
5.3 THE CALVIN CYCLE

- The Calvin cycle is the term used for the reactions of photosynthesis that use the energy stored by the light-dependent reactions to form glucose and other carbohydrate molecules

The Interworkings of the Calvin Cycle (1 of 6)

- CO_2 enters the plant leaves through the stomata and diffuses into the stroma of the chloroplast – the site of the Calvin cycle reactions where sugar is synthesized

FIGURE 5.14



Light-dependent reactions harness energy from the sun to produce ATP and NADPH. These energy-carrying molecules travel into the stroma where the Calvin cycle reactions take place.

The Interworkings of the Calvin Cycle (2 of 6)

- The Calvin cycle reactions can be organized into 3 basic stages:
  - ✓ Fixation
  - ✓ Reduction
  - ✓ Regeneration

The Interworkings of the Calvin Cycle (3 of 6)

- **Carbon fixation** is a process in which the enzyme RuBisCO catalyzes a reaction between CO_2 and RuBP (Ribulose biphosphate)
- This reactions is called carbon fixation because it “fixes” the CO_2 from its inorganic form into organic molecules

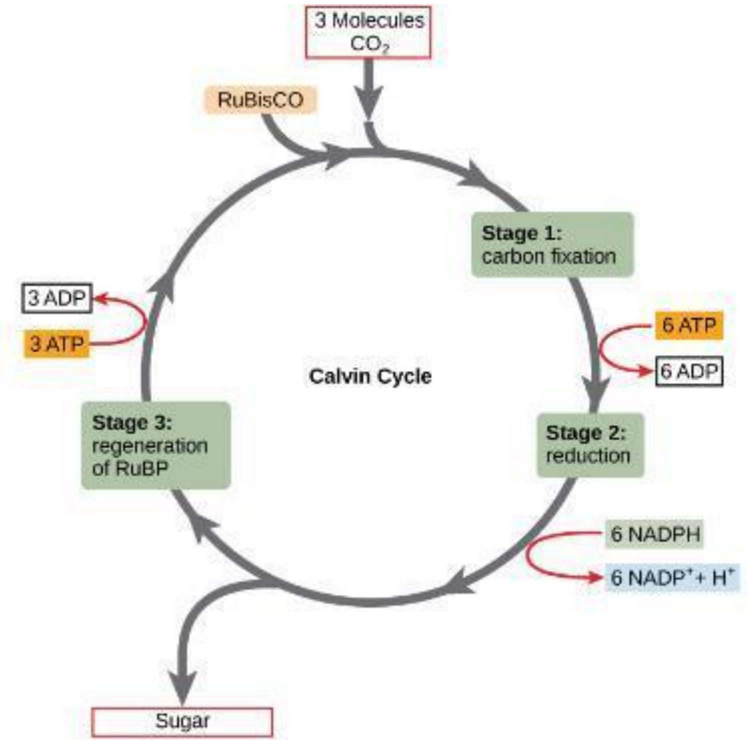
The Interworkings of the Calvin Cycle (4 of 6)

- ATP and NADPH use their stored energy to convert the three-carbon compound 3-PGA into another three-carbon compound called G3P
- This type of reaction is called a **reduction reaction** because it involves the gain of electrons (electrons are negative, so the molecules overall charge is reduced)

The Interworkings of the Calvin Cycle (5 of 6)

- One of the G3P molecules leaves the Calvin cycle to contribute to the formation of the carbohydrate molecule (commonly $C_6H_{12}O_6$), which requires six turns of the Calvin cycle (one turn for each carbon dioxide molecule fixed)
- The remaining G3P molecules regenerate RuBP, which enables the system to prepare for the carbon fixation step

FIGURE 5.15



The Calvin cycle has three stages. In stage 1, the enzyme RuBisCO incorporates carbon dioxide into an organic molecule. In stage 2, the organic molecule is reduced. In stage 3, RuBP, the molecule that starts the cycle, is regenerated so that the cycle can continue.

The Interworkings of the Calvin Cycle (6 of 6)

- In summary, it takes six turns of the Calvin cycle to fix six carbon atoms from CO_2
- These six turns require energy input from 12 ATP molecules and 12 NADPH molecules in the reduction step and 6 ATP molecules in the regeneration step

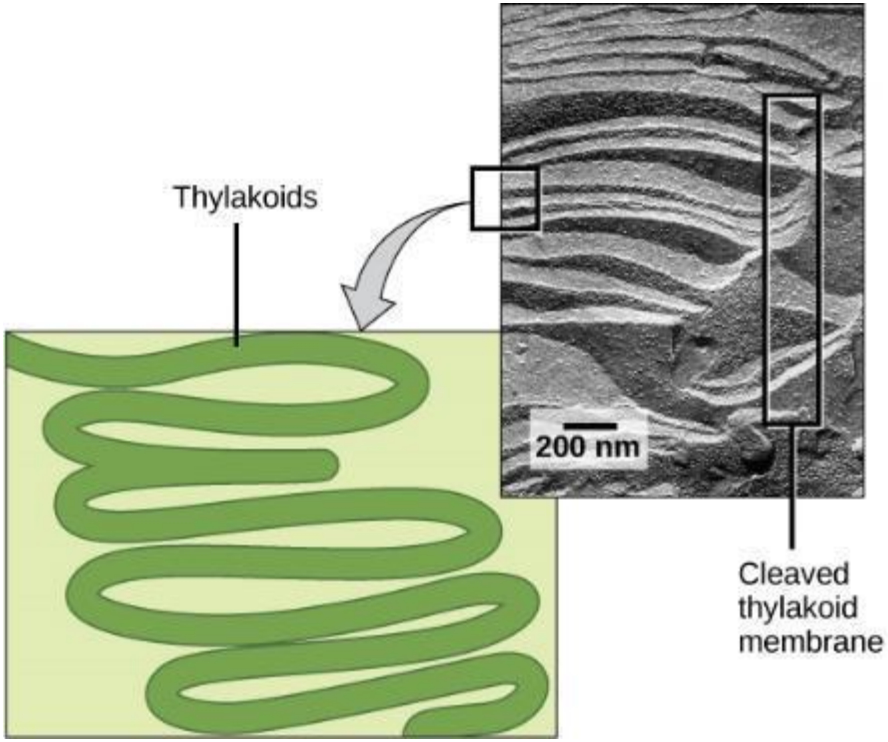
FIGURE 5.16

Living in the harsh conditions of the desert has led plants like this cactus to evolve variations in reactions outside the Calvin cycle. These variations increase efficiency and help conserve water and energy. (credit: Piotr Wojtkowski)

Photosynthesis in Prokaryotes

- Prokaryotes do not have membrane bound organelles, so they lack chloroplasts
- Prokaryotic photosynthetic autotrophic organisms have infoldings of the plasma membrane for chlorophyll attachment and photosynthesis; it is here that these organisms (such as cyanobacteria) carry out photosynthesis

FIGURE 5.17



A photosynthetic prokaryote has infolded regions of the plasma membrane that function like thylakoids. Although these are not contained in an organelle, such as a chloroplast, all of the necessary components are present to carry out photosynthesis. (credit: scale-bar data from Matt Russell)

The Energy Cycle (1 of 4)

- Living things can store energy as carbohydrates or as ATP; carbohydrates are much more stable and efficient reservoirs for chemical energy
- Photosynthetic organisms like plants, have mitochondria to carry out reactions of respiration and chloroplast to carry out photosynthesis

The Energy Cycle (2 of 4)

- You may have noticed, the overall reaction for photosynthesis:

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

  is the reverse of the overall reaction for cellular respiration:

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

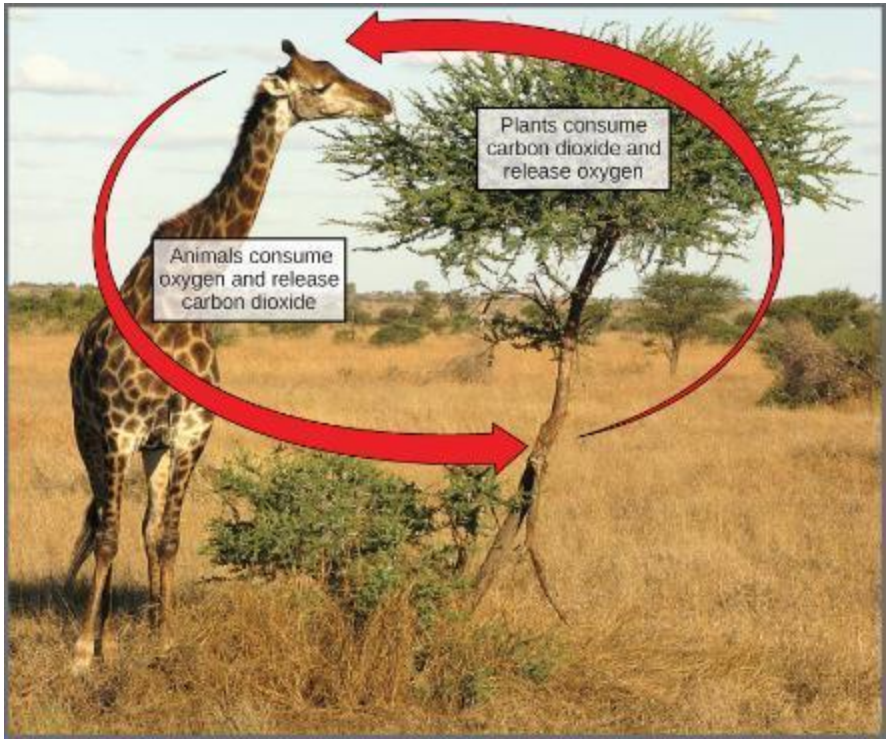
The Energy Cycle (3 of 4)

- In nature, there is no such thing as waste – every single atom of matter is conserved, recycling indefinitely
- Substances change from or move from one type of molecule to another, but never disappear

The Energy Cycle (4 of 4)

- Photosynthesis absorbs energy to build carbohydrates in chloroplasts, and aerobic cellular respirations uses oxygen to break down the carbohydrates and release the energy in the mitochondria
- Photosynthesis and cellular respiration function in a biological cycle, allowing organisms to access life-sustaining energy that originates millions of miles away in a star

FIGURE 5.18



In the carbon cycle, the reactions of photosynthesis and cellular respiration share reciprocal reactants and products. (credit: modification of work by Stuart Bassil)