Chapter 10

Photosynthesis

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PowerPoint® Lecture Presentations for

Biology

Eighth Edition
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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$_2$O and CO$_2$
• Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes

• These organisms feed not only themselves but also most of the living world
Fig. 10-2

(a) Plants

(b) Multicellular alga

(c) Unicellular protist

(d) Cyanobacteria

(e) Purple sulfur bacteria
• **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
Trophic Levels – Food Chains

![Trophic Levels Diagram]

### Major Trophic Levels

<table>
<thead>
<tr>
<th>Trophic Level</th>
<th>Source of Energy</th>
<th>Examples</th>
</tr>
</thead>
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<tr>
<td>Producers</td>
<td>Solar energy</td>
<td>Green plants, photosynthetic protists and bacteria</td>
</tr>
<tr>
<td>Herbivores</td>
<td>Producers</td>
<td>Grasshoppers, water fleas, antelope, termites</td>
</tr>
<tr>
<td>Primary Carnivores</td>
<td>Herbivores</td>
<td>Wolves, spiders, some snakes, warblers</td>
</tr>
<tr>
<td>Secondary Carnivores</td>
<td>Primary carnivores</td>
<td>Killer whales, tuna, falcons</td>
</tr>
<tr>
<td>Omnivores</td>
<td>Several trophic levels</td>
<td>Humans, rats, opossums, bears, raccoons, crabs</td>
</tr>
<tr>
<td>Detritivores and Decomposers</td>
<td>Wastes and dead bodies of other organisms</td>
<td>Fungi, many bacteria, earthworms, vultures</td>
</tr>
</tbody>
</table>
Concept 10.1: Photosynthesis converts light energy to the chemical energy of food

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria (endosymbiotic theory)
- 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

• \( \text{CO}_2 \) enters and \( \text{O}_2 \) exits the leaf through microscopic pores called **stomata** (**stomates**).
• 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 analogous to the mitochondrial matrix
Fig. 10-3

Leaf cross section

Vein
Stomata
CO₂, O₂

Chloroplast
Mesophyll cell

Outer membrane
Intermembrane space
Inner membrane
Thylakoid space
Stroma
Granum
Thylakoid

1 µm
5 µm
Tracking Atoms Through Photosynthesis: Scientific Inquiry

• Photosynthesis can be summarized as the following equation:

\[
6 \text{ CO}_2 + 12 \text{ H}_2\text{O} + \text{Light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2 + 6 \text{ H}_2\text{O}
\]

• The simplified equation:

\[
6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \text{Light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2
\]

• Look familiar?
The Splitting of Water

- Chloroplasts split H$_2$O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules
Reactants: 6 CO_2 12 H_2O

Products: C_6H_{12}O_6 6 H_2O 6 O_2
Photosynthesis as a Redox Process

- Photosynthesis is a redox process in which $\text{H}_2\text{O}$ is oxidized and $\text{CO}_2$ is reduced
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 $\text{H}_2\text{O}$
  - Release $\text{O}_2$
  - Reduce $\text{NADP}^+$ to NADPH (What is this carrying? To where? – not ETC!)
  - 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
Light

Fig. 10-5-1

H₂O

Chloroplast

Light Reactions

NADP⁺

ADP + Pᵢ
Chloroplast

Light

H$_2$O

Light Reactions

NADP$^+$

ADP + $P_i$

ATP

NADPH

O$_2$
Fig. 10-5-3

Light

H₂O

\[ \text{Light Reactions} \]

\[ \text{NADP}^+ \]

\[ \text{ADP} \]

\[ \text{P}_i \]

\[ \text{ATP} \]

\[ \text{NADPH} \]

Calvin Cycle

CO₂

O₂

Chloroplast
Light Reactions

H₂O → O₂

Calvin Cycle

CO₂ + ATP + NADPH → [CH₂O] (sugar)
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 (peak to peak)

• 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 (ROY G BIV, really VIB G YOR!)

• Light also behaves as though it consists of discrete particles, called **photons**
Fig. 10-6

UV

Visible light

Infrared

Radio waves

Gamma rays

X-rays

Shorter wavelength

Higher energy

Longer wavelength

Lower energy

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 (these are the colors that we see)

• Leaves appear green because chlorophyll reflects and transmits green light
Fig. 10-7

- Light
- Reflected light
- Chloroplast
- Absorbed light
- Granum
- Transmitted light
Leaf Pigments Separated by Chromotography

- Declining chlorophyll
- Unmasked carotene
- Formation of anthocyanin

- Carotene
- Xanthophyll
- Chlorophyll a
- Chlorophyll b
- Loading Line
• 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
The low transmittance (high absorption) reading indicates that chlorophyll absorbs most blue light.

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

• An action spectrum profiles the relative effectiveness of different wavelengths of radiation in driving a process.
RESULTS

(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
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

- Chlorophyll molecule
- Excited state
- Energy of electron
- Photon (fluorescence)
- Ground state
- Heat

(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.
• **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
THYLAKOID SPACE
(INTERIOR OF THYLAKOID)

- THYLAKOID membrane
- Photon
- Photosystem
  - Light-harvesting complexes
  - Reaction-center complex
  - Primary electron acceptor
- STROMA
- Pigment molecules
- Special pair of chlorophyll a molecules
- Transfer of energy
• 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 (reaction center).

An excited electron from P680 is transferred to the primary electron acceptor.
**Fig. 10-13-1**

Photosystem II (PS II)

- **Primary acceptor**
- **P680**
- **Light**
- **Pigment molecules**
• P680$^+$ (P680 that is missing an electron) is a very strong oxidizing agent

• H$_2$O 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
Pigment molecules

Light

$\text{P680}$

$e^-$

$2 \text{H}^+$

$\frac{1}{2} \text{O}_2$

$\text{H}_2\text{O}$

$e^-$

$3 \text{H}_2\text{O}$

$\frac{1}{2}$

Fig. 10-13-2

Photosystem II (PS II)
• 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
Pigment molecules

Light

P680

Primary acceptor

2 $\text{H}^+$ + $^{1/2}$ $\text{O}_2$

3 $\text{H}_2\text{O} + 2 \text{e}^-$

4 Electron transport chain

5 ATP

Cytochrome complex

Pq

Pc

Fig. 10-13-3

Photosystem II (PS II)
• In PS I (like PS II), transferred light energy excites P700 (reaction center), 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.
Pigment molecules

Light

P680

2 H⁺ + \( \frac{1}{2} \) O₂ → H₂O + 3 H₂O + \( \frac{1}{2} \) O₂

Primary acceptor

2

1

2 H⁺ + \( \frac{1}{2} \) O₂ → H₂O + 3 H₂O + \( \frac{1}{2} \) O₂

Primary acceptor

2

1

Fig. 10-13-4

Photosystem II (PS II)
• 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
Fig. 10-13-5

Photosystem II (PS II)

1. Light

2. P680

3. $2H^+ + \frac{1}{2}O_2$

4. Electron transport chain

5. ATP

6. Pigment molecules

Photosystem I (PS I)

7. Electron transport chain

8. NADP$^+$ + H$^+$

NADPH

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Fig. 10-14
https://www.youtube.com/watch?v=1Dn_zdAZN0I

Photosystem II Photosystem I

Mill makes ATP

ATP

e–

NADPH

e–

e–

e–

e–

Photo,ton

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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.
Fig. 10-15

ATP
Photosystem II

Primary acceptor

Pq

Cytochrome complex

Fd

Primary acceptor

Fd

NADP+ reductase

NADP+ + H+

NADPH

Photosystem I

Pc

ATP

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• 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
Light Causes Damage to Photosystems

- The absorption of light (photons) causes damage to photosystems especially PSII
- Damage leads to photoinhibition (reduction in photosynthesis)
- Normally photosystems are rapidly repaired by the cell
- All light intensities cause damage but damage increases with increasing intensity
Light Causes Damage to Photosystems

- Reactive Oxygen Species (ROS)
- Free radicals – cause damage
- UV radiation contributes to 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
Fig. 10-16

Key

- Higher [H+]
- Lower [H+]

Mitochondrion

Chloroplast

MITOCHONDRION STRUCTURE

CHLOROPLAST STRUCTURE

Intermembrane space

Thylakoid space

Inner membrane

Thylakoid membrane

Electron transport chain

H+ Diffusion

ATP synthase

ADP + P_i

H+

ATP

Matrix

Stroma

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• 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 H₂O to NADPH
Photosystem II

\[ 4 \text{H}^+ \]

Photosystem I

\[ 4 \text{H}^+ \]

Cytochrome complex

ATP synthase

ADP + \( P_i \) → ATP

NADP\(^+\) reductase

NADP\(^+\) + H\(^+\) → NADPH

To Calvin Cycle

STROMA (low H\(^+\) concentration)

THYLAKOID SPACE (high H\(^+\) concentration)

H\(_2\)O

\[ \text{O}_2 \]

\[ \text{NADP}^+ + \text{H}^+ \]

\[ \text{NADPH} \]

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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 - Ribulose-1,5-bisphosphate carboxylase/oxygenase)
  – **Reduction**
  – **Regeneration of the CO$_2$ acceptor** (RuBP)
Fig. 10-18-1

Input CO₂ (Entering one at a time)

Phases:

1. Carbon fixation
   - Rubisco
   - Input CO₂
   - Short-lived intermediate
   - Ribulose bisphosphate (RuBP)
   - 3-Phosphoglycerate

Phase 1: Carbon fixation

Input CO₂ (Entering one at a time)

Phases:

1. Carbon fixation
   - Rubisco
   - Input CO₂
   - Short-lived intermediate
   - Ribulose bisphosphate (RuBP)
   - 3-Phosphoglycerate
**Phase 1: Carbon fixation**

- Ribulose bisphosphate (RuBP) → 3-Phosphoglycerate

**Short-lived intermediate**

**Phase 2: Reduction**

- 3-Phosphoglycerate → 1,3-Bisphosphoglycerate
- 1,3-Bisphosphoglycerate → Glyceraldehyde-3-phosphate (G3P)
- G3P → Glucose and other organic compounds

**Input**

- CO₂ (Entering one at a time)

**Output**

- G3P (a sugar)
**Fig. 10-18-3**

**Ribulose bisphosphate (RuBP)**

**Phase 1: Carbon fixation**
- Input: CO₂
- **Rubisco**
- **1,3-Bisphosphoglycerate (P₃P)**
- Output: **G3P** (a sugar)

**Phase 2: Reduction**
- **G3P** + NADPH + ATP → Glucose and other organic compounds

**Phase 3: Regeneration of the CO₂ acceptor (RuBP)**
- **G3P** → **RuBP**

**Short-lived intermediate**
- **3-Phosphoglycerate**
Calvin Cycle Summary

Steps

The steps in the cycle are as follows:


2. Split: the enzyme RuBisCO (with the energy of ATP and NADPH molecules) breaks the six-carbon molecule into two equal parts.
Calvin Cycle Summary

• 3. Leave: A trio of three carbons leave and become sugar. The other trio moves on to the next step.

• 4. Switch: Using ATP and NADPH, the three carbon molecule is changed into a five carbon molecule.

• 5. The cycle starts over again.
Calvin Cycle Summary

• The product

• The carbohydrate products of the Calvin cycle are three-carbon sugar phosphate molecules, or 'triose phosphates' (G3P). Each step of the cycle has its own enzyme which speeds up the reaction.
Concept 10.4: Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- Dehydration is a problem for plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis.
- On hot, dry days, plants close stomata, which conserves H₂O but also limits photosynthesis.
- The closing of stomata reduces access to CO₂ and causes O₂ to build up.
- These conditions favor a seemingly wasteful process called photorespiration.
Photorespiration: An Evolutionary Relic?

- In most plants (C₃ plants), initial fixation of CO₂, via rubisco, forms a three-carbon compound.

- In photorespiration, rubisco adds O₂ instead of CO₂ in the Calvin cycle.

- Photorespiration consumes O₂ and organic fuel and releases CO₂ without producing ATP or sugar.
• Photorespiration may be an evolutionary relic because rubisco first evolved at a time when the atmosphere had far less $O_2$ and more $CO_2$

• Photorespiration limits damaging products of light reactions that build up in the absence of the Calvin cycle

• In many plants, photorespiration is a problem because on a hot, dry day it can drain as much as 50% of the carbon fixed by the Calvin cycle
C₄ Plants

- **C₄ plants** minimize the cost of photorespiration by incorporating CO₂ into four-carbon compounds in mesophyll cells.

- This step requires the enzyme **PEP carboxylase**.

- PEP carboxylase has a higher affinity for CO₂ than rubisco does; it can fix CO₂ even when CO₂ concentrations are low.

- These four-carbon compounds are exported to **bundle-sheath cells**, where they release CO₂ that is then used in the Calvin cycle.
CAM Plants

• Some plants, (including orchids, bromeliads, cacti, and succulents), use crassulacean acid metabolism (CAM) to fix carbon

• CAM plants open their stomata at night, incorporating CO$_2$ into organic acids

• Stomata close during the day, and CO$_2$ is released from organic acids and used in the Calvin cycle
Plants have Variety

• Most plants use $C_3$ metabolism.
• Some plants use only $C_3$ or $C_4$ or CAM.
• Some plants are flexible and can switch the type of metabolism depending on environmental conditions.
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 structures such as roots, tubers, seeds, and fruits.
- In addition to food production, photosynthesis produces the O$_2$ in our atmosphere.
Fig. 10-21

Light Reactions:
- Photosystem II
- Photosystem I
- Electron transport chain

Calvin Cycle:
- RuBP
- 3-Phosphoglycerate
- Calvin Cycle
- G3P
- Starch (storage)

ATP
NADPH

ADP + P_i

Chloroplast

H₂O
CO₂

O₂

Sucrose (export)
You should now be able to:

1. Describe the structure of a chloroplast
2. Describe the relationship between an action spectrum and an absorption spectrum
3. Trace the movement of electrons in linear electron flow
4. Trace the movement of electrons in cyclic electron flow
5. Describe the similarities and differences between oxidative phosphorylation in mitochondria and photophosphorylation in chloroplasts

6. Describe the role of ATP and NADPH in the Calvin cycle

7. Describe the major consequences of photorespiration

8. Describe two important photosynthetic adaptations that minimize photorespiration