Chapter 7
Photosynthesis
THE BASICS OF PHOTOSYNTHESIS

• Photosynthesis
  – is used by plants, algae (protists), and some bacteria,
  – transforms light energy into chemical energy, and
  – uses carbon dioxide and water as starting materials.
The chemical energy produced via photosynthesis is stored in the bonds of sugar molecules.

Organisms that use photosynthesis are

- photosynthetic autotrophs and
- the producers for most ecosystems.
### PHOTOSYNTHETIC AUTOTROPHS

<table>
<thead>
<tr>
<th>Plants (mostly on land)</th>
<th>Photosynthetic Protists (aquatic)</th>
<th>Photosynthetic Bacteria (aquatic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest plants</td>
<td>Kelp, a large, multicellular alga</td>
<td>Micrograph of cyanobacteria</td>
</tr>
</tbody>
</table>

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Chloroplasts: Sites of Photosynthesis

• **Chloroplasts** are
  – the site of photosynthesis
  – found mostly in the interior cells of leaves

• Inside chloroplasts are sacs called **thylakoids**
  – suspended in a thick fluid called **stroma**

• Thylakoids are in stacks called **grana**
The green color of chloroplasts is from **chlorophyll**
- a light-absorbing pigment that helps convert solar energy to chemical energy (sugar)

**Stomata** are tiny pores in leaves where:
- carbon dioxide enters
- oxygen exits
Figure 7.2-3

Photosynthetic cells

Vein

Leaf cross section

CO₂

O₂

Stomata

Chloroplast

Inner and outer membranes

Stroma

Thylakoid space

Granum

Colorized TEM

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The reactants of photosynthesis are the waste products of cellular respiration.
In photosynthesis, sunlight provides the energy, electrons are boosted “uphill” and added to carbon dioxide, and sugar is produced.
During photosynthesis, water is split into:

- hydrogen
- oxygen

Hydrogen is transferred along with electrons and added to carbon dioxide to produce sugar.

Oxygen escapes through stomata into the atmosphere.
A Photosynthesis Road Map

- Photosynthesis occurs in two multistep stages:

  1. **Light reactions**: use solar energy to convert water into oxygen, ATP, and NADPH

  2. **Calvin cycle**: uses ATP, NADPH, and CO$_2$ to make sugar
Figure 7.3-1

Light reactions

Chloroplast

H₂O

O₂

ATP

NADPH
Figure 7.3-2

Light reactions

H₂O + Light → ATP + NADPH + O₂

Calvin cycle

CO₂ + ATP + NADPH → Sugar

Chloroplast
The Nature of Sunlight

- Sunlight is a type of energy called radiation, or electromagnetic energy.
- The distance between the crests of two adjacent waves is called a **wavelength**.
- The full range of radiation is called the **electromagnetic spectrum**.
Figure 7.4

Increasing wavelength

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>380</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>750</th>
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<tbody>
<tr>
<td>Infrared</td>
<td>X-rays</td>
<td>UV</td>
<td>Infrared</td>
<td>Microwaves</td>
<td>Radio waves</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Wavelength = 580 nm</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Figure 7.5

Light

Chloroplast

Absorbed light

Transmitted light (detected by your eye)

Reflected light
Chloroplast Pigments

- Chloroplasts contain several pigments:

  1. Chlorophyll $a$
     - absorbs mainly blue-violet and red light and
     - participates directly in the light reactions.

  2. Chlorophyll $b$
     - absorbs mainly blue and orange light and
     - participates indirectly in the light reactions.
Chloroplast Pigments

• Carotenoids
  – absorb mainly blue-green light
  – participate indirectly in the light reactions
  – absorb and dissipate excessive light energy that might damage chlorophyll

• The spectacular colors of fall foliage are due partly to the yellow-orange light reflected from carotenoids.
Harvesting Light Energy

• What is light, exactly?

• Light behaves as photons: discrete packets of energy

• Chlorophyll molecules absorb photons.
  – Electrons in the pigment gain energy.
  – As the electrons fall back to their ground state, energy is released as heat or light.
Figure 7.8a

(a) Absorption of a photon

Light

Photon

Chlorophyll molecule

Ground state

Excited state

Heat

Light (fluorescence)
A **photosystem** is a group of chlorophyll and other molecules that function as a light-gathering antenna.

- Chloroplast
- Thylakoid membrane
- Photosystem
- Pigment molecules
- Primary electron acceptor
- Reaction center chlorophyll a
- Antenna pigment molecules
- Electron transfer
- Transfer of energy
- Photon
Light Reactions Generate: ATP and NADPH

- The light reactions are located in the thylakoid membrane.

- Two types of photosystems cooperate in the light reactions:
  - The water-splitting photosystem (PS2)
  - The NADPH-producing photosystem (PS1)

- Connected by an electron transport chain:
  - Connects the two photosystems
  - Releases energy that the chloroplast uses to make ATP
Figure 7.10-3

Light

H₂O

2 H⁺ + \frac{1}{2} O₂

Water-splitting photosystem

Reaction-center chlorophyll

Primary electron acceptor

2e⁻

Energy to make ATP

Electron transport chain

Primary electron acceptor

2e⁻

NADP⁺

NADPH

Reaction-center chlorophyll

NADPH-producing photosystem

Light

2e⁻
Light Reactions (Light Dependent Reactions)

1. Photon (light particle) enters PS2

2. Splits water (H$_2$O) into: oxygen & H$^+$
   - Oxygen leaves as a waste product

3. Photon “excites” electron, sending it down the transport chain

4. Electron passes through proteins that pump H$^+$ into the thylakoid

5. Ends up at PS1
1. Another photon enters PS1 and “excites” the electron again

2. Electron is given to NADP $\rightarrow$ NADPH

3. H+ inside thylakoid flows through ATP Synthase to make ATP

4. NADPH & ATP continue into stroma for the Calvin Cycle
Light

H₂O

Thylakoid membrane

Inside thylakoid

Photosystem

Electron transport chain

Photosystem

ATP synthase

Electron flow

To Calvin cycle

NADP⁺

ADP + P

H⁺

NADPH

ATP

H₂O

1/2 O₂

Figures 7.11a
THE CALVIN CYCLE: MAKING SUGAR FROM CARBON DIOXIDE

• The Calvin cycle:
  – Functions like a sugar factory within the stroma of a chloroplast
  – Regenerates the starting material with each turn
THE CALVIN CYCLE: MAKING SUGAR FROM CARBON DIOXIDE

Where: stroma (liquid portion) of the thylakoid
What: ATP, NADPH, RuBP (5-carbon), RuBisCo enzyme, CO₂
How:

1. RuBisCo joins RuBP to CO₂ (5 carbon + 1 carbon)
2. 6-carbon splits into 2 3-carbon molecules
3. 3-carbon + ATP & NADPH = G₃P
   - G₃P can be made into: glucose, cellulose, starch
4. Leftover G₃P → RuBP
5. Cycle starts over again
Figure 7.13-4

CO₂ (from air)

RuBP sugar → Three-carbon molecule

ADP + P → ATP

ATP → ADP + P

RuBP sugar

G3P sugar

G3P sugar

G3P sugar

Glucose (and other organic compounds)
The Problem with Photorespiration

- **Photorespiration**: uses oxygen instead of CO$_2$
  - Lack of CO$_2$
  - Creates a toxin in the plant = BAD

- When is there a lack of CO$_2$?

- When the **stomata** are closed.

- **Stomata**: pores in a leaf
  - Let CO$_2$ in, but **water out**
  - Losing water = shrivel & die
The Problem with Photorespiration

- Plants in **hot environments** close their stomata during the day
  - Stops water from leaving

- But, what about CO$_2$?

- **Two Strategies:**
  1. C$_4$ plants
  2. CAM plants
C₄ vs CAM Plants

1. C₄ plants:
   - Close stomata when weather = hot & dry
   - **Spatial separation** of RuBisCo & oxygen
   - Guard cells store CO₂ as a 4-carbon molecule
   - 4-carbon → CO₂ → RuBisCo

2. CAM plants:
   - **Temporal separation**
   - Open stomata at night
   - Store CO₂ as **malic acid** → CO₂ during the day