Photosynthesis
From sunlight to biosphere...

What is Photosynthesis?
The fixation of carbon dioxide (gas) to carbohydrate (solid) using water and the energy from light.

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

The process by which light energy is converted into chemical energy stored in organic molecules necessary for life. Responsible for atmospheric \( \text{O}_2 \).

Sunlight – The Energy Source
Total radiation reaching Earth
1324-1417 W/m²
Average radiation due to rotation
~342 W/m²
~1/3 is reflected back to space
Some is absorbed or scattered by the atmosphere
• water vapor, ozone
Insolation = radiation reaching the earth’s surface
• diffuse
• direct

Sunlight vs. PAR
Sunlight contains a wide electromagnetic spectrum
Most is between 400–700 nm (“visible light”)
Photosynthetically Active Radiation (PAR) = 400–700nm

The Leaf – Primary site of photosynthesis
1. Large surface area for light interception
2. Stomata – entry points for \( \text{CO}_2 \)
3. Chloroplasts in mesophyll
   • contain pigments for light capture

The Chloroplast
• membrane-bound organelle
• contains photosynthetic machinery
• pigment proteins embedded in stacks of thylakoid (grana).
Photosynthesis Overview

Light-dependent Reactions:
- occur in grana of thylakoid membranes
- conversion of light energy to chemical energy
  \[ H_2O + NADP^+ \rightarrow NADPH + H^+ + \frac{1}{2}O_2 \]
- \( H^+ \) gradient drives production of ATP

Light-Independent Reactions:
- reduction of \( CO_2 \) to glucose
- uses NADPH & ATP from light reactions
- occurs in stroma of chloroplast

THE LIGHT REACTIONS – PHOTOSYSTEM II
Light energy excites \( e^- \) in PSI chlorophyll (P700)
\( e^- \) passes to primary \( e^- \) acceptor and down transport chain to NADP+
2 \( e^- \) are needed to reduce NADP+ to NADPH (4 photons)

THE LIGHT REACTIONS – PHOTOSYSTEM II
Light energy excites \( e^- \) in PSI chlorophyll (P700)
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water is split to replace \( e^- \) in P680, \( O_2 \) is formed

THE LIGHT REACTIONS – PHOTOSYSTEM I
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THE LIGHT REACTIONS – PHOTOSYSTEM I

Light energy excites e- in PSI chlorophyll (P700)
e- passes to primary e- acceptor and down transport chain to NADP+
2 e- are needed to reduce NADP+ to NADPH (4 photons)

THE LIGHT REACTIONS – PHOTOSYSTEMS I & II

H+ gradient drives photophosphorylation
Products of light reactions are NADPH, ATP and ½ O2

The Calvin Cycle
- light-independent
- reduces CO2 to glucose (C6H12O6)
- uses 3 ATP for energy source
- uses 6 NADPH as reducing agent
- RuBisCO is the most abundant protein on Earth (Cooper 2000)

Major Pigments for Light Capture

<table>
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<tr>
<th>PIGMENT</th>
<th>ABSORBS</th>
<th>REFLECTS</th>
<th>NOTES</th>
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<tr>
<td>Chlorophyll a</td>
<td>430 &amp; 680 nm</td>
<td>green</td>
<td>most abundant in green plants; reaction center pigment</td>
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<tr>
<td>Chlorophyll b</td>
<td>460 &amp; 690 nm</td>
<td>green</td>
<td>reduces the &quot;green gap&quot; (400 – 600 nm)</td>
</tr>
<tr>
<td>&quot;Carotenoids&quot; (include carotenes, xanthophylls)</td>
<td>400 – 500 nm</td>
<td>yellow to orange</td>
<td>over 100 different pigments; low efficiency (~30%); accessory &amp; protective function</td>
</tr>
<tr>
<td>Phycobilins</td>
<td>450 – 600 nm</td>
<td>red</td>
<td>found in cyanobacteria, red algae, dinoflagellates</td>
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Chlorophyll
- Porphyrin structure with central Mg
  - up to 100% energy efficiency!
- Strong absorption of red and blue light
  - chlorophyll-a: peaks at 430 and 660 nm
  - chlorophyll-b: peaks at 460 and 650 nm
- Low energy excited-state
  - acceptor of energy from pigments that absorb at shorter (higher energy) wavelengths.

The Antenna Complex
Light-harvesting apparatus

Functions:
1. absorb-light efficiently
2. transfer excitation energy to reaction centers
3. protect photosynthetic apparatus

Structural Components:
Reaction center
- chlorophyll 680 or 700 dimer

Accessory pigments
- carotenoids, chlorophyll b
The Antenna Complex

**LIGHT HARVEST**

- Increases cross-sectional area for light absorption
- Many pigments help cover full spectrum of PAR
- Land plants: 330-550 & 630-700 nm
- "Green gap" – filled by phycobilin in aquatic habitats

\[ \Delta E = E_e - E_g = h \nu \]

\( h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} \)

\[ \text{Amount of light absorbed} \]

\[ \text{Wavelength of light (nm)} \]

\[ \text{Chlorophyll} \]

\[ \text{Carotenoids} \]

\[ \text{Chlorophyll} \]

\[ \Delta \]

\[ E_e \]

\[ E_g \]

\[ \nu \]

\[ \Phi_q = \frac{n_{RC}}{n_{abs}} \]

\[ \Phi_e = \frac{e_{RC}}{e_{abs}} \]

\( \Phi_e \approx 65\% - 106\% \)

\( \text{e.g. chlorophyll excitation at 700 nm; antenna absorption peak at 740 nm.} \)

\[ \Phi_e = 106\% \]

\[ \text{ENERGY TRANSFER TO R.C.} \]

Radiationless transfer
1. High quantum efficiency (~100%)
   \( \Phi_q = \frac{\text{RC}}{\text{abs}} \)
2. Variable energy efficiency
   \( \Phi_e = \frac{e_{RC}}{e_{abs}} \)
   - 65% - 106%
   - e.g. chlorophyll excitation at 700 nm; antenna absorption peak at 740 nm. \( \Phi_e = 106\% \)

The Antenna Complex

**ENERGY TRANSFER TO R.C.**

Radiationless transfer
1. Resonance energy transfer
   - Long distances (up to 10 nm)
   - Dipole coupling between pigments
2. Exciton coupling
   - Intermediate distances (≤2 nm)
   - Delocalized excitation of similar pigments
3. Dexter exchange coupling
   - Electron exchange over short (contact) distances
   - Carotenoid to chlorophyll \( e^- \) orbitals

The Antenna Complex

**PROTECTION AGAINST LIGHT-INDUCED DAMAGE**

Carotenoids
1. Filter blue and near-UV light
2. Conjugated system: can switch from \( e^- \) donors to \( e^- \) acceptors
   - Addition or removal of double bonds
   - Incr. double bonds = incr. wavelengths absorbed (lower energy)
   - Act as "lightning rods" of Chl is overexcited
3. Quenching of reactive oxygen species (\( \text{O}_2^-, \text{OH}^- \)): little is known

The Antenna Complex

**ENERGY OF PHOTOSYNTHESIS**

Quantum yield = 8 - 10 photons per \( \text{O}_2 \) evolved (or \( \text{CO}_2 \) fixed)

- 460 kJ/mol to reduce one \( \text{CO}_2 \)
- 3 photons of red light (680 nm), 174 kJ/mol
- But PSI and II operate together so 8 is minimum
- 8 photons (680 nm) = 1.4 MJ/mol
- Overall efficiency = 34% (38% with ATP production)
- Under intense illumination, efficiency as low as 5%
  - Kinetic limitation of photosystem (10^-5 s)

Then why is energy transfer in antenna complex so efficient?

The Antenna Complex

**PHOTOSYNTHETIC ADAPTATIONS**

Net photosynthetic rate:

\[ \text{Assimilation of carbon (A)} = \mu \text{mol C} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \]

- Photon flux (\( \text{PF}_{\text{PAR}} \))
- Function of [\( \text{CO}_2 \)] and diffusion rate
- Redox & enzyme kinetics (e- flow, Rubisco, etc.)
- Temperature, nutrient, water availability
- Respiration (loss of \( \text{CO}_2 \))
Photosynthetic Adaptations

Low light environments
“shade plants”
• less plastoquinone (primary e- acceptor)
• lower $A_{	ext{max}}$
• rate of e- flow limits PS rate
• saves energy to produce fewer enzymes

Photosynthetic Adaptations

Dry Environments
• preventing water loss
• embedded stomata
• hairs on leaf
• high root:shoot ratio
• succulence
• CAM photosynthesis

Monitoring Photosynthesis

Remote sensing
• PAR absorption
• chlorophyll content
• vegetation cover change
• response to climate change