CHAPTER 10 - Photosynthesis

Life on Earth is solar powered.

Photosynthesis nourishes almost all the living world directly or indirectly.
- All organisms use organic compounds for energy and for carbon skeletons.
- Organisms obtain organic compounds by one of two major modes: autotrophic or heterotrophic.

AUTOTROPHS (=producers)
- produce organic molecules from CO₂ and other inorganic raw materials obtained from the environment.
- ultimate source of organic compounds for heterotrophs.

Photosynthetic organisms use light as a source of energy to synthesize organic compounds.
- Photosynthesis occurs in plants, algae, some other protists, and some prokaryotes.

Chemoautotrophs:
- harvest energy from oxidizing inorganic substances, such as sulfur and ammonia.
- unique to prokaryotes.

HETEROTROPHS (=consumers)
- live on organic compounds produced by other organisms.
- dependent on photoautotrophs for food and for oxygen (by-product of photosynthesis).

Photosynthesis:
- converts light energy to the chemical energy of food.
  \[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]
- Happens in all green parts of plants but leaves = major site.
- \(~\) about half a million chloroplasts/mm² of leaf surface.
- Color of leaf due to green pigment chlorophyll.

Chloroplasts mainly in mesophyll cells in the interior of the leaf.
- 30-40 chloroplasts/typical mesophyll cell.
- O₂ and water vapor exits and CO₂ enters leaf through microscopic pores on underside of leaf = stoma (pl. stomata).

GUARD CELLS control openings - OPEN if TURGID; CLOSED if FLACCID.

VEINS bring water from the roots and carry off sugar from mesophyll cells to nonphotosynthetic areas of plant.
- XYLEM - carries water.
- PHLOEM carries sugar/nutrients.

CHLOROPLAST:
- Surrounded by DOUBLE membrane.
- Central fluid filled space = STROMA.
- System of interconnected membranous sacs = THYLAKOIDS.
- Stack of thylakoids = GRANUM (pl. GRANA).
- Fluid filled compartment inside thylakoid = THYLAKOID SPACE (lumen).
- Chlorophyll is located in membranes of thylakoid sacs.

Photosynthetic prokaryotes lack chloroplasts.
- photosynthetic membranes = infolded regions of the plasma membrane.

LIGHT = form of electromagnetic radiation.

Energy = inversely related to its wavelength (ie, shorter wavelengths pack more energy).

Visible light = 380-750 nm.
PIGMENTS = light absorbing molecules
- Only chlorophyll a participates directly in the light reactions;
- Other pigments have different absorption spectra;
  - funnel energy to chlorophyll a
Chlorophyll a (the dominant pigment)
- ABSORBS best in the red & violet-blue wavelengths;
- REFLECTS green wavelengths = reason plants "look" green
Chlorophyll b- slightly different structure
  - funnels energy to chlorophyll a
CAROTENOIDS = accessory pigments (red, yellow, orange):
  - Include: CAROTENES (orange) and XANTHOPHYLLS (yellow)
  - funnel the energy to chlorophyll a
  - photoprotection- protect chlorophyll from excessive light

CHLOROPHYLL
Porphin ring with MAGNESIUM cofactor in center
Plants have a and b forms- slight difference in functional groups
  - Chlorophyll a is universal
  - Other forms found in algae and cyanobacteria

SPECTROPHOTOMETER
- measures the ability of pigment to absorb various wavelengths of light
- beams narrow wavelengths of light through a solution containing the pigment
- measures the fraction of light transmitted at each wavelength
- Absorption spectrum plots a pigment's light absorption versus wavelength.

EXCITING ELECTRONS:
When a molecule absorbs a photon of light an electron is elevated to an orbital with more potential energy
  - Electron moves from ground state → excited state
  - Excited electrons are unstable
  - They drop to their ground state in a billionth of a second, releasing heat energy
Some pigments, including chlorophyll, can also release a photon of light when excited (= FLUORESCENCE)
  - Outside of chloroplasts, if chlorophyll is illuminated, it will fluoresce and give off heat

PHOTOSYSTEMS in thylakoid membranes
- reaction center containing chlorophyll a and "primary electron acceptor"
- surrounded by a light-harvesting complex of other pigments and proteins (chlorophyll b, carotenoids)
- act as "antenna" to collect light energy → chlorophyll a → "primary electron acceptor"
Photosystem I (PS I) reaction center absorption peak at 700 nm (P700)
Photosystem II (PS II) reaction center absorption peak at 680 nm (P680)

TWO STAGES OF PHOTOSYNTHESIS:
1) LIGHT REACTIONS (Light dependent reactions)
  - convert solar energy to the chemical energy of ATP and NADPH
2) CALVIN CYCLE (Light independent reactions)
  - uses energy from the light reactions to incorporate CO₂ from the atmosphere into sugar.
  - Named for Melvin Calvin (Got Nobel in 1961 for figuring out pathway)
LIGHT REACTIONS:

- Use solar power to store chemical energy in ATP and reducing power in electron carrier NADPH
- REQUIRE sunlight
- Two possible routes

1) NONCYCLIC ELECTRON FLOW (= predominant route) produces both ATP and NADPH
   - Photosystem II absorbs a photon of light
   - One of the electrons of P₅₇₀ reaction center is excited to a higher energy state
   - Electron is captured by the primary electron acceptor, leaving the reaction center oxidized
   - Electrons are replaced by splitting a water molecule in thylakoid space
   - Oxygen released from water splitting combines with another oxygen atom; released as O₂ to atmosphere
   - Hydrogen released from water splitting accumulates in thylakoid space
   - Photoexcited electrons pass along electron transport chain ending up at Photosystem I reaction center
     - energy from electrons “falling down” ETC is used by CYTOCHROMES to pump H⁺ ions into thylakoid space
     - When chloroplasts are illuminated, thylakoid space pH ~5; stroma pH ~ 8 (1000 fold difference)
   - Photosystem I absorbs a photon of light
   - One of the electrons of P₇₀₀ reaction center is excited to a higher energy state
   - Electron is captured by the primary electron acceptor, leaving the reaction center oxidized
   - Electrons are replaced by electrons passed from PS II down ETC
   - Photoexcited electrons pass down a second electron transport chain through the protein FERRIDOXIN (Fd)
   - Enzyme transfers 2 electrons to NADP⁺ (nicotinamide adenine dinucleotide phosphate) to produce NADPH
   - H⁺ ions in thylakoid space provide energy to produce ATP as they diffuse down their gradient (ELECTROMOTIVE FORCE) back into the stroma through ATP SYNTHASE

2) CYCLIC ELECTRON FLOW
   - alternative pathway for photoexcited electrons from photosystem I = CYCLIC PHOTOPHOSPHORYLATION
   - Photoexcited electrons return to CYTOCHROMES instead of passing to Ferridoxin
   - So produces only ATP; NO NADPH; no OXYGEN
   - Used because NON CYCLIC FLOW makes equal amounts of ATP and NADPH
     - Calvin cycle requires more ATP than NADPH
     - Way to regulate amounts of ATP and NADPH needed for Calvin cycle
CHEMIOSMOSIS IN CHLOROPLASTS AND MITOCHONDRIA

SIMILARITIES
- Used by chloroplasts and mitochondria to generate ATP
- Energy from ELECTRON TRANSPORT CHAIN used to pump protons across a membrane
- Creates a H⁺ gradient across membrane
- ATP SYNTHASE uses energy from diffusion of H⁺ ions back across membrane to generate ATP
- Some electron carriers (cytochromes) are similar in both chloroplasts/mitochondria

DIFFERENCES:
OXIDATIVE PHOSPHORYLATION in MITOCHONDRIA
- Mitochondria transfer chemical energy from food molecules to ATP
- Mitochondrial INNER MEMBRANE pumps protons from MATRIX out to the INTERMEMBRANE SPACE
- ATP made as H⁺ ions diffuse back to stroma

PHOTOPHOSPHORYLATION in CHLOROPLASTS
- Chloroplasts transform light energy into the chemical energy of ATP
- Chloroplast THYLAKOID membrane pumps protons from the stroma into the thylakoid space

CALVIN CYCLE (= LIGHT INDEPENDENT PHASE)
Originally called "Dark reactions" but don't just happen at night
Happens in stroma
Uses ATP and NADPH (made in Light Reactions) to convert CO₂ to sugar
regenerates its starting material after molecules enter and leave the cycle
= anabolic - uses energy to build sugar from smaller molecules
Carbon enters the cycle as CO₂ and leaves as sugar
Actual sugar product = three-carbon sugar, glyceraldehyde-3-phosphate (G3P)
Each turn of the Calvin cycle fixes carbon from 1 CO₂; 3 turns to make 1 G3P; 6 turns to make 1 glucose
Uses 18 ATP's and 12 NADPH's to make 1 glucose
**CALVIN CYCLE**

**Phase 1: Carbon fixation**

Each CO$_2$ molecule is attached to a five-carbon sugar, RIBULOSE BISPHOSPHATE (RuBP)
- This is catalyzed by RuBP carboxylase (=RUBISCO)
- Rubisco = most abundant protein in chloroplasts; probably the most abundant protein on Earth
- Unstable six-carbon intermediate splits in half to form two three carbon 3-phosphoglycerate for each CO$_2$

**Phase 2: Reduction**

ATP provides energy; NADPH provides reducing power to reduce intermediates

Three carbon GLYCERALDEHYDE-3-PHOSPHATE (G3P) is produced

G3P exits the cycle; = starting material for metabolic pathways that synthesize other organic compounds, including glucose and other carbohydrates

**Phase 3: Regeneration**

Rest of molecules rearrange to regenerate the starting RuBP molecules

For the net synthesis of one G3P molecule, the Calvin cycle consumes nine ATP and six NADPH (X 2 for glucose)

Light reactions regenerate ATP and NADPH

WHERE DOES THE OXYGEN IN SUGAR COME FROM: H$_2$O or CO$_2$?

CO$_2$ + H$_2$O + light energy \(\rightarrow\) [CH$_2$O] + O$_2$

[CH$_2$O] represents the general formula for a sugar

Before 1930’s thought splitting H$_2$O provided oxygen for sugar

Experiments with radio-labeled oxygen isotopes in H$_2$O and CO$_2$ showed oxygen in carbo’s comes from CO$_2$

Evidence that chloroplasts split water molecules enabled researchers to track atoms through photosynthesis.

Powered by light, the green parts of plants produce organic compounds and O$_2$ from CO$_2$ and H$_2$O

Photosynthesis is a REDOX REACTION
- It reverses the direction of electron flow in cellular respiration
- H$_2$O is OXIDIZED (loses electrons)
- CO$_2$ is REDUCED (gains electrons) to make sugar
- Process requires energy (provided by light)

C$_3$ PLANTS = Most plants (EX: rice, wheat, and soybeans)

Rubisco fixes CO$_2$ into three carbon compound (3PGA)

Calvin cycle happens during day when ATP and NADPH are available from light reactions

PROBLEM: Closing stomata on hot dry days to conserve water, reduces CO$_2$ needed for photosynthesis

When CO$_2$ is low Rubisco adds O$_2$ to RuBP instead of CO$_2$

= PHOTORESPiration

Rubisco adds O$_2$ to RuBP, RuBP splits into a three-carbon piece and a two-carbon piece

Two-carbon fragment is exported from chloroplast and degraded to CO$_2$ by mitochondria and peroxisomes.
- Unlike normal respiration, consumes ATP instead of making it
- Unlike photosynthesis, siphons organic material from the Calvin cycle instead of making sugar
- Photorespiration can drain away as much as 50% of the carbon fixed by the Calvin cycle on a hot, dry day.

PHOTORESPiration may be evolutionary baggage

When rubisco first evolved, the atmosphere had far less O$_2$ and more CO$_2$ than it does today

Inability of the active site of rubisco to exclude O$_2$ would have made little difference then,

BUT makes a difference today when O$_2$ in atmosphere is higher
Alternative mechanisms of carbon fixation

Certain plant species have evolved alternate modes of carbon fixation to minimize photorespiration.

**C₄ PLANTS** - EX: sugarcane and corn

- Minimizes photorespiration and allows plant to efficiently fix CO₂ at low concentrations
- Allows plants to thrive in hot regions with intense sunlight
- Unique leaf anatomy; spatial separation of CO₂ fixation from air/into sugar
- BUNDLE SHEATH cells arranged into tightly packed sheaths around leaf veins
- MESOPHYLL cells more loosely arranged cells located between bundle sheath cells and leaf surface

- **PEP CARBOXYLASE in mesophyll cells** has very high affinity for CO₂; can fix CO₂ efficiently at low levels when rubisco can’t
- CO₂ fixed into a **FOUR CARBON** compound/pumped into BUNDLE SHEATH cells
- CO₂ is released in Bundle sheath cells, keeping CO₂ levels high enough for rubisco to work in Calvin cycle

- PEP Carboxylase also found in some bacteria, but not animals or fungi.

**CRASSULACEAN ACID METABOLISM (CAM) PLANTS** - EX: Succulents, cacti, pineapples

- Evolved in hot, dry environments
- **TEMPORAL separation of CO₂ fixation from air/into sugar**
- Open stomata during night when temps are lower and humidity higher
- Close them during the day to save water
- **AT NIGHT:** Fix CO₂ in mesophyll cells
  - Use **PEP carboxylase**, like C₄ plants, to fix CO₂ forming four carbon compounds
  - Stored in vacuoles
- **DURING DAY:**
  - Light reactions supply ATP & NADPH;
  - CO₂ is released from organic acids to complete Calvin cycle

**IMPORTANCE OF PHOTOSYNTHESIS:***

- Energy from sunlight = stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies the entire plant with chemical energy
- AND with carbon skeletons to synthesize all the major organic molecules of cells
  - Carbohydrate (as disaccharide sucrose) travels via the veins to nonphotosynthetic cells
  - About 50% = consumed as fuel for cellular respiration in plant mitochondria
  - Also provides raw materials for anabolic pathways, including synthesis of proteins and lipids and formation of the extracellular polysaccharide cellulose
- Cellulose = main ingredient of cell walls; = most abundant organic molecule in the plant, maybe on Earth
- Plants also store excess sugar by synthesis of starch
  - in chloroplasts and in storage cells in roots, tubers, seeds, and fruits.

On a global scale, photosynthesis is the most important process on Earth

- Provides food energy for heterotrophs, including humans
- It is responsible for the presence of oxygen in our atmosphere.
- Each year, photosynthesis synthesizes 160 billion metric tons of carbohydrate