Lecture Notes
Photosynthesis

Introduction

Van Helmont (about 1650's), willow tree in a pot, added nothing to soil except water. Five years later, found tree had gained 75 kg (150 lbs) while soil LOST only 1/000th this much mass. He (incorrectly??) concluded that a plant gets most of its substance from water.

Priestley (1780)**,** candle in closed container burns out, but if container is connected to container growing mint candle continues burning, can also sustain a mouse. O_2 not yet discovered but recognized plant "restores" the dead air. Not reproducible always because he didn't control for **light**

Jan Ingenhousz (1780's, but after Priestly), showed plants can "restore" air only when exposed to **LIGHT**.

Later, **Jean Senebier** discovered that CO_2 is taken up from air during photosynthesis.

Photosynthesis— CONVERSION of **radiant energy** from sunlight to **chemical energy** in the bonds of fuel molecules, consumes CO_2, and **generates oxygen**, the "restoring principle" in Priestly's experiments.

Photosynthesis provides the food supply for virtually ALL organisms. Plants are **autotrophs**, they MAKE THEIR OWN FOOD. Most other organisms get their food by consuming plants (except a few like bacteria that get their energy by breaking down **chemical compounds** such as sulfur-containing compounds in thermal vents in ocean floor)

Overall: $$6\ CO_2 + 6\ H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6\ O_2$$

<u>Unit 7.1 – Autotrophs are the Producers of the Biosphere</u>

On **land**, the main food producers are **plants**
In **aquatic** environment, main food producers are **algae** (photosynthetic protists) and **photosynthetic bacteria**. In plants and algae, photosynthesis occurs in the **chloroplasts**.

<u>Unit 7.2 – Photosynthesis Occurs in the Chloroplasts</u>

Green color comes from pigment **chlorophyll** which is the molecular "antenna" that captures light energy.

Mesophyll—green tissue in leaf interior
Stomata—openings for gas exchange, intake CO_2, release of O_2
Chloroplasts—
(**inner** and **outer** membranes and **thylakoid membranes** create compartments where different reactions occur).
Thylakoids—membranous sacks, stacked in **grana**

Intermembrane space
Stroma—enclosed by inner membrane—SUGARS MADE HERE!!
Thylakoid compartment

CHLOROPHYLL MOLECULES (to capture light energy) are embedded in **thylakoid membrane**, as are other important molecular components that convert light energy to chemical energy.

Unit 7.3 – Plants Produce O_2 Gas by "Splitting Water"

In 1700's Ingenhousz (the one who showed **light** required for plants to produce oxygen), thought plants produce O_2 by extracting it from CO_2—HE WAS WRONG! It wasn't until 1950's that scientists showed O_2 is extracted from **water**. This was accomplished using a radioactive isotope of oxygen as a **"tracer"**. Similar experiments have shown that the **carbon in CO_2** is incorporated into **glucose**.

Unit 7.4 – Photosynthesis is a Redox Process, as is Cellular Respiration

Like cellular respiration, photosynthesis involves a series of **electron transfer** or REDOX reactions. Recall that:

Oxidation involves LOSS of electrons
Reduction involves GAIN of electrons

The two are always coupled together.

In contrast to respiration, in photosynthesis, the electrons are boosted UP instead of DOWN an energy hill!

Energy is transferred from sunlight to the electrons involved in atomic bonds in glucose.

In respiration, glucose was oxidized to CO_2, and oxygen reduced to water
In photosynthesis, CO_2 is reduced to glucose, and water oxidized to oxygen

Unit 7.5 – Overview – Photosynthesis Occurs in Two Stages, Linked by ATP and NADPH
Two stages:

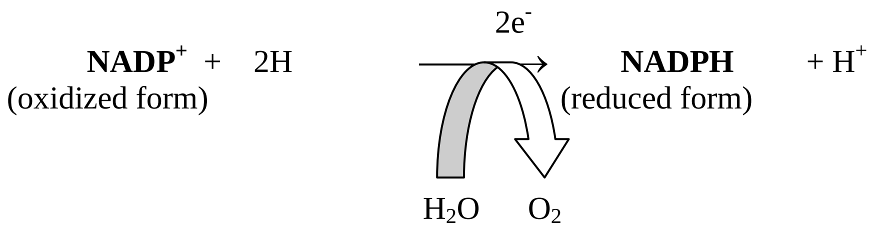
1) "photo" -- the "**Light Reactions**" (occur in the THYLAKOID MEMBRANES of grana), captures light energy, produces ATP (energy) and NADPH (high energy electrons) for...

2) "synthesis" – the "**Dark Reactions**" (The **Calvin-Benson Cycle**) occur in the STROMA, building of glucose from CO_2

SUMMARY OF LIGHT REACTIONS

In the "light reactions" (which occur in the thylakoid membrane), light energy is absorbed by **chlorophyll**:

$$\text{ADP} + \text{P} \longrightarrow \text{ATP (high energy currency)}$$



NADPH is an **electron and hydrogen "shuttle",** structurally related to the NADH molecule seen in cellular respiration. However, the function of NADPH is to help ASSIMILATE energy into glucose in photosynthesis, the function of NADH is to help EXTRACT energy FROM glucose in cellular respiration.

Note that in photosynthesis, the ultimate **SOURCE of electrons** for reducing $NADP^+$ is **WATER**!! The splitting of water occurs during the "light reactions".

SUMMARY OF CALVIN CYCLE (DARK REACTIONS)

The process of capturing carbon dioxide from the atmosphere and incorporating it into biological molecules is called **carbon fixation**. In the Calvin cycle, which occurs in the STROMA, carbon is fixed, then incorporated into GLUCOSE. The source of high-energy electrons is **NADPH**, and the source of energy for this process is **ATP**.

NOTE: the NADPH and ATP used in the Calvin cycle was generated earlier, in the light reactions!!
The Calvin cycle does *not* require light directly (which is why the Calvin cycle is said to consist of the "dark reactions"). Think of the light reactions as the power plant that provides the energy, and the Calvin cycle as the "factory" where glucose is made.

Unit 7.6 – Visible Radiation Drives the Light Reactions

The distance between the crests of two adjacent waves is called the **wavelength**. The smaller the wavelength, the higher the energy of the light!
DIFFERENT COLORS of light represent DIFFERENT WAVELENGTHS in the **spectrum** of visible light.

Pigments are molecules that absorb light. Chloroplasts contain several important pigments, each absorbs light of different wavelengths:

Chlorophyll *a* -- participates directly in the light reactions

Chlorophyll *b*
Carotenoids
} broadens range of useful wavelengths, conveying light they absorb to chlorophyll *a*

Wavelengths that are not absorbed by these pigments are transmitted THROUGH the leaf, or REFLECTED by the leaf, giving the characteristic GREEN color.

Unit 7.7 – Photosystems Capture Solar Power

Although light can be described as "wave-like", it also behaves like "particles". The "particles" are called **photons**. The shorter the wavelength, the MORE ENERGY a photon of light contains.

When a pigment molecule absorbs a photon of light (of the correct wavelength), an electron in the pigment is "boosted" or "exited" to a higher energy level (an **excited state**). The exited electron may be passed on or transferred to a neighboring molecule. Recall that electron-transfer reactions like this are called "**redox**" reactions.

The pigment molecules (chlorophylls *a* and *b*, and the carotenoids) in a leaf are CLUSTERED TOGETHER in assemblies of 200-300 molecules. Together, these pigments act as an **antenna** to capture light energy. When one of these pigments absorbs a photon of light, an excited electron is generated that is passed from pigment molecule to pigment molecule until it reaches a special chlorophyll *a* molecule (the **reaction center**) in the antenna assembly. The reaction center is associated with another molecule called the **primary electron acceptor** that will act as the FIRST electron-carrier in an electron-transport chain.

The COMBINATION of the antenna molecules, reaction center, and primary electron acceptor is called a **photosystem**. There are actually TWO kinds of photosystems in the thylakoid membrane:

Photosystem II-- has a reaction center called **P680** (a chlorophyll *a* molecule that preferentially absorbs light of 680 nm wavelength).

Photosystem I-- has a reaction center called **P700** (a chlorophyll *a* molecule that preferentially absorbs light of 700 nm wavelength).

These two photosystems are LINKED TOGETHER in the light reactions.

Unit 7.8 – In the Light Reactions, Electron Transport Chains Generate ATP, NADPH, and O_2

THE FUNCTION OF THE LIGHT REACTIONS:

> **To produce ATP and NADPH** that will be used in the Calvin Cycle ("dark reactions") to drive synthesis of glucose.
>
> **Water is split** to yield both **electrons** and **hydrogen** atoms (H) that will be carried by the "electron-shuttle" NADPH. Oxygen (O_2) is produced as water is split.

PRODUCTS of the light reactions: ATP, NADPH, O_2

Steps in the light reactions:

1) Light is absorbed at **Photosystem II** and funneled to P680 reaction center.
2) Water is split, and electrons are boosted ("exited") by absorbed energy
3) Excited electrons pass from P680 to primary electron acceptor

4) Electrons pass through a FIRST **electron transport chain—ATP is generated** by chemiosmotic phosphorylation
5) Electrons enter **photosystem I**, where they receive ANOTHER BOOST from light absorbed at 700 reaction center.
6) Electrons pass down a SECOND **electron transport chain**, to $NADP^+$, **reducing** it to NADPH.

Thus, TWO electron-transport chains are involved in the light reactions.

Unit 7.9 – Chemiosmosis Powers ATP Synthesis in the Light Reactions

As we saw in Chapter 6, in cellular respiration, some ATP synthesis occurs by "substrate-level phosphorylation", and but most occurs by "chemiosmotic phosphorylation" .

Recall that chemiosmotic phosphorylation differs from substrate-level phosphorylation in that chemiosmotic phosphorylation involves the hydrogen ion **concentration gradient** generated by the **electron-transport chain**. In photosynthesis, the ATP is generated ENTIRELY by chemiosmotic phosphorylation. Because the energy to drive chemiosmotic phosphorylation in photosynthesis is provided by LIGHT, the process is called **photophosphorylation**.

The processes of chemiosmotic ATP synthesis in cellular respiration and in the light reactions of photosynthesis are very similar and share these common features:
1) Electrons flow from a high-energy state to a low-energy state as they are passed from one electron-carrier in the chain to the next.
2) Electron-carriers in the chain pump hydrogen ions (H^+) across membrane to generate a **concentration gradient**.
3) H^+ ions seeking to return back across the membrane are channeled through a special enzyme "port" (**ATP synthase**), that adds a phosphate group to ADP to generate ATP.

However, the processes of chemiosmotic ATP synthesis in cellular respiration and photosynthesis differ in two important respects:
1) In respiration, the final electron acceptor in the electron-transport chain is OXYGEN. In photosynthesis, the final electron acceptor in the electron-transport chain is **$NADP^+$**.
2) In respiration, H^+ ions are pumped across the inner mitochondrial membrane. In photosynthesis, H^+ ions are pumped across the **thylakoid** membrane, into the **thylakoid compartment**.

Unit 7.10 – ATP and NADPH Power Sugar Synthesis in the Calvin Cycle

Inputs = CO_2, + ATP and NADPH (from light reactions!)
Products = GLUCOSE ($C_6H_{12}O_6$)!! + ADP^+ + $NADP^+$

An important **intermediate** in the Calvin Cycle is a 3-carbon molecule called glyceraldehyde-3-phosphate or **G3P** that is used not only for the production of glucose, but can be used by plants as a BUILDING BLOCK for other organic molecules as well.