Photosynthesis Part II:
The Calvin Cycle, Environmental Conditions,
& Preventing Photorespiration

Photosynthesis: An Overview

- The net overall equation for photosynthesis is:

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

- Photosynthesis occurs in 2 "stages":
  1. The Light Reactions (or Light-Dependent Reactions)
  2. The Calvin Cycle (or Calvin-Benson Cycle or Dark Reactions or Light-Independent Reactions)

Is photosynthesis an ENDERGONIC or EXERGONIC reaction?

Photosynthesis: An Overview

- To follow the energy in photosynthesis,

light → (Light Reactions, thylakoids) → ATP NADPH → (Calvin Cycle, stroma) → Organic compounds (carbs)

light

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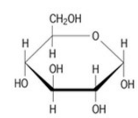
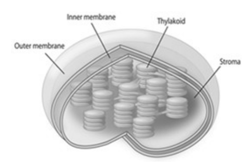
Phase 2: The Calvin Cycle

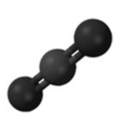
- In the Calvin Cycle, chemical energy (from the light reactions) and CO_2 (from the atmosphere) are used to produce organic compounds (like *glucose*).
- The Calvin Cycle occurs in the *stroma* of chloroplasts.



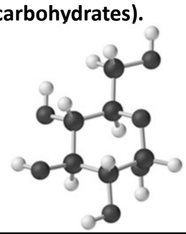


Phase 2: The Calvin Cycle

- The Calvin Cycle involves the process of *carbon fixation.*
  - This is the process of assimilating carbon from a non-organic compound (ie. CO_2) and incorporating it into an organic compound (ie. carbohydrates).

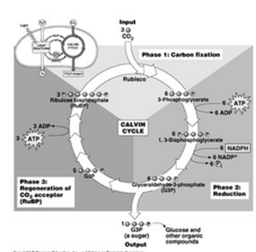


CARBON FIXATION



The Calvin cycle

- 3 molecules of CO2 are 'fixed' into glyceraldehyde 3-phosphate (G3P)
- Phases:
  - 1- Carbon fixation~ each CO2 is attached to RuBP (rubisco enzyme)
  - 2- Reduction~ electrons from NADPH reduces the G3P; ATP used up
  - 3- Regeneration~ G3P rearranged to RuBP; ATP used; cycle continues



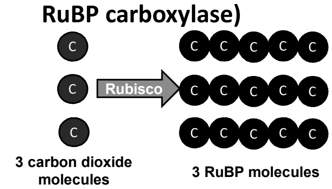
Calvin Cycle, net synthesis

- For each G3P (and for 3 CO2)…….
  Consumption of 9 ATP's & 6 NADPH
  (light reactions regenerate these molecules)
- G3P can then be used by the plant to make glucose and other organic compounds

Phase 2: The Calvin Cycle

Step 1: Carbon Fixation

- **3 molecules of CO_2 (from the atmosphere) are joined to 3 molecules of RuBP (a 5-carbon sugar) by Rubisco (an enzyme also known as RuBP carboxylase)**



This forms 3 molecules which each have 6 carbons (for a total of 18 carbons!)

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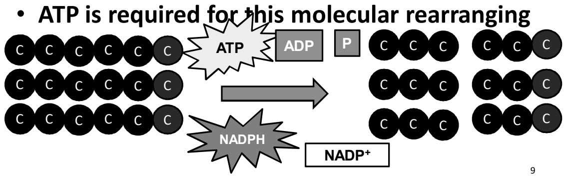
Phase 2: The Calvin Cycle

Step 2: Reduction

Where did the NADPH and ATP come from to do this?

- **The three 6-carbon molecules (very unstable) split in half, forming six 3-carbon molecules.**
- **These molecules are then reduced by gaining electrons from NADPH.**
- **ATP is required for this molecular rearranging**



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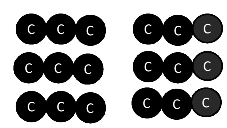
Phase 2: The Calvin Cycle

Where did these 3 extra carbons come from?

- **There are now six 3-carbon molecules, which are known as G3P or PGAL.**
- **Since the Calvin Cycle started with 15 carbons (three 5-carbon molecules) and there are now 18 carbons, we have a net gain of 3 carbons.**
  - **One of these "extra" 3-carbon G3P/PGAL molecules will exit the cycle and be used to form ½ a glucose molecule.**



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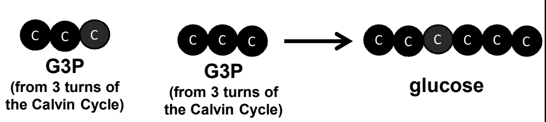
Phase 2: The Calvin Cycle

- **Once the Calvin Cycle "turns" twice (well, actually 6 times), those 2 molecules of G3P (a 3-carbon carbohydrate) will combine to form 1 molecule of glucose (a 6-carbon carbohydrate molecule) OR another organic compound.**



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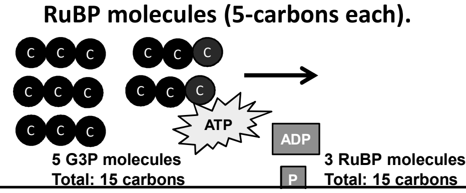
Phase 2: The Calvin Cycle

Step 3: Regeneration of RuBP

Where does the ATP come from to do this?

- **Since this is the Calvin *Cycle*, we must end up back at the beginning.**
- **The remaining 5 G3P molecules (3-carbons each!) get rearranged (using ATP) to form 3 RuBP molecules (5-carbons each).**



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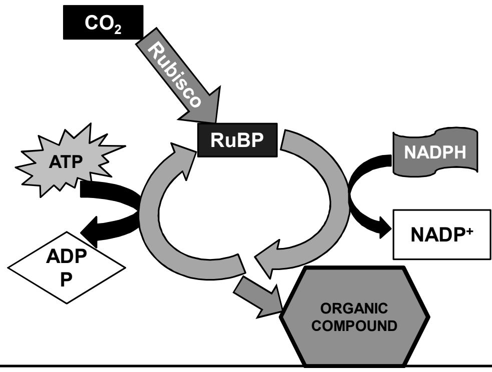
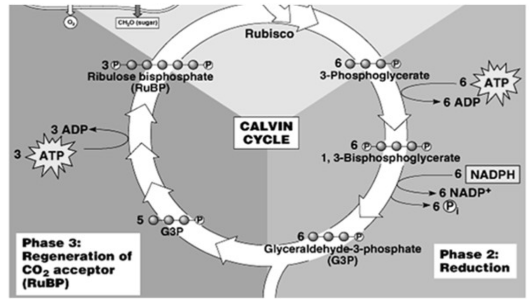
Phase 2: The Calvin Cycle



Phase 2: The Calvin Cycle



Phase 2: The Calvin Cycle

Quick recap:

•In the Calvin Cycle, energy and electrons from the Light Reactions (in the form of ATP and NADPH) and carbon dioxide from the atmosphere are used to produce organic compounds.

•The Calvin Cycle occurs in the stroma inside the chloroplasts (inside the cells…).

•Carbon dioxide, ATP, and NADPH are required (reactants).

•Organic compounds (G3P) are produced (products).

Photosynthesis: A Recap

- **So, as a broad overview of photosynthesis,**
  - **The Light Reactions (Phase 1) capture the energy in sunlight and convert it to chemical energy in the form of ATP and NADPH through the use of photosystems, electron transport chains, and chemiosmosis.**
  - **The Calvin Cycle (Phase 2) uses the energy transformed by the light reactions along with carbon dioxide to produce organic compounds.**

Photosynthesis: A Recap

The photosynthetic equation:

Based on this equation, how could the rate of photosynthesis be measured?

Provides the carbon to produce organic compounds during the Calvin Cycle

The organic compound ultimately produced during the Calvin Cycle

$$6\,H_2O + 6\,CO_2 \xrightarrow{\text{light}} 6\,O_2 + C_6H_{12}O_6$$

Split during the light reactions to replace electrons lost from Photosystem II

Excites electrons during the light reactions

Produced as a byproduct of the splitting of water during the light reactions

Photosynthesis: A Recap

- <u>Photosynthesis Animation</u>

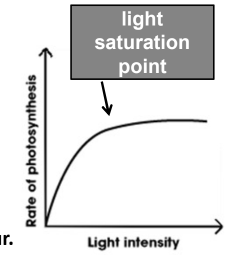
(click on "Animation" after clicking the link)

Environmental Factors & Photosynthesis

- **The *rate* (or speed) of photosynthesis can vary, based on environmental conditions.**
  - **Light intensity**
  - **Temperature**
  - **Oxygen concentration**

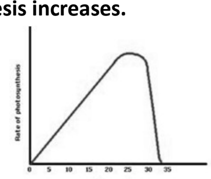
Environmental Factors & Photosynthesis

- **Light intensity**
  - **As light intensity *increases*, so too does the *rate of photosynthesis.***
    - **This occurs due to increased excitation of electrons in the photosystems.**
  - **However, the photosystems will eventually become saturated.**
    - **Above this limiting level, no further increase in photosynthetic rate will occur.**



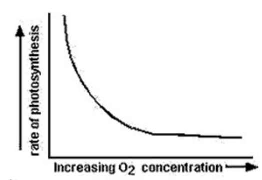
Environmental Factors & Photosynthesis

- **Temperature**
  - **The effect of temperature on the rate of photosynthesis is linked to the action of *enzymes.***
  - **As the temperature increases up to a certain point, the rate of photosynthesis increases.**
    - **Molecules are moving faster & colliding with enzymes more frequently, facilitating chemical reactions.**
  - **However, at temperatures higher than this point, the rate of photosynthesis decreases.**
    - **Enzymes are denatured.**



Environmental Factors & Photosynthesis

- **Oxygen concentration**
  - **As the concentration of oxygen increases, the rate of photosynthesis decreases.**
  - **This occurs due to the phenomenon of *photorespiration.***



Photorespiration

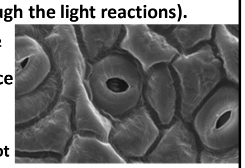
- **Photorespiration occurs when Rubisco (RuBP carboxylase) joins *oxygen* to RuBP in the first step of the Calvin Cycle rather than *carbon dioxide.***
  - **Whichever compound (O_2 or CO_2) is present in higher concentration will be joined by Rubisco to RuBP.**
  - **Photorespiration *prevents* the synthesis of glucose AND utilizes the plant's ATP.**

More CO_2 → Rubisco joins CO_2 to RuBP → Photosynthesis occurs; glucose is produced

More O_2 → Rubisco joins O_2 to RuBP → Photorespiration occurs; glucose is NOT produced

Photorespiration

- **Photorespiration is primarily a problem for plants under water stress.**
  - **When plants are under water stress, their stomata close to prevent water loss through transpiration.**
  - **However, this also limits gas exchange.**
    - **O_2 is still being produced (through the light reactions).**
      - **Thus, the concentration of O_2 is increasing.**
    - **CO_2 is not entering the leaf since the stomata are closed.**
      - **Thus, as the CO_2 is being used up (in the Calvin Cycle) and not replenished, the concentration of CO_2 is decreasing.**



Photorespiration

- As the concentration of O_2 increases and the concentration of CO_2 decreases (due to the closure of the stomata to prevent excessive water loss), photorespiration is favored over photosynthesis.
- Some plant species that live in hot, dry climates (where photorespiration is an especially big problem) have developed mechanisms through natural selection to prevent photorespiration.
  - C_4 plants
  - CAM plants

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Photorespiration

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Photorespiration

- Hot/dry days
- stomata close
- CO2 decrease, O2 increase in leaves
- O2 added to rubisco
- no ATP or food generated
- *Two Solutions…..*

C_4 and CAM Plants

- C_4 plants and CAM plants modify the process of C_3 photosynthesis to prevent photorespiration.
- Overview:
  - C_4 plants perform the Calvin Cycle in a different *location* within the leaf than C_3 plants.
  - CAM plants obtain CO_2 at a different *time* than C_3 plants.
  - Both C_4 and CAM plants separate the initial fixing of CO_2 (carbon fixation) from the using of CO_2 in the Calvin Cycle.

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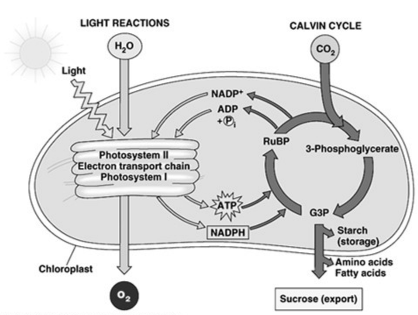
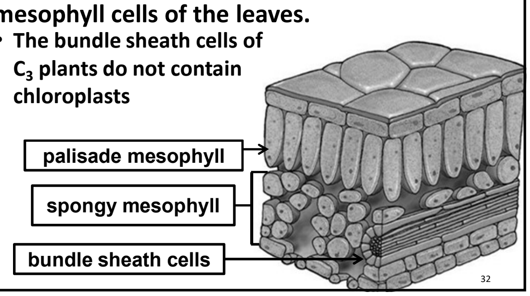
A review of photosynthesis



C_3 Plants

- C_3 plants, which are "normal" plants, perform the light reactions and the Calvin Cycle in the mesophyll cells of the leaves.
  - The bundle sheath cells of C_3 plants do not contain chloroplasts



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