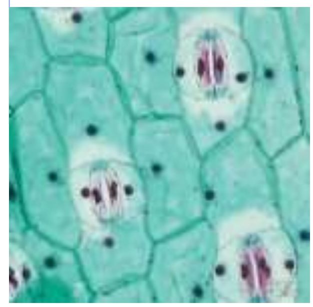
Warm-up

- **Objective:**
  - Describe how the chemical products of the light-trapping reactions couple to the synthesis of carbohydrates.
- **Warm-up:**
  - What is the advantage of the light reaction producing NADPH and ATP on the stroma side of the thylakoid membrane?

Stomates



Photosynthesis:
The Calvin Cycle
Life from Air

Remember what it means to be a plant…

- **Need to produce all organic molecules necessary for growth**
  - carbohydrates, lipids, proteins, nucleic acids
- **Need to store chemical energy (ATP) produced from light reactions**
  - in stable form
  - can be moved around plant
  - saved for a rainy day

Autotrophs

- **Making energy & organic molecules from light energy**
  - photosynthesis

carbon dioxide + water + energy → glucose + oxygen

$6CO_2$ + $6H_2O$ + light energy → $C_6H_{12}O_6$ + $6O_2$

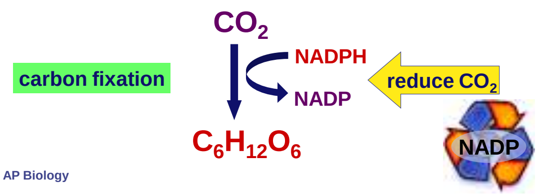
Light reactions

- **Convert solar energy to chemical energy**
  - ATP → energy
  - NADPH → reducing power
- **What can we do now?**

→ → **build stuff** ***!!***

How is that helpful?

- Want to make $C_6H_{12}O_6$
  - synthesis
  - How? From what?
    What raw materials are available?

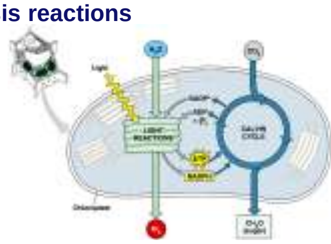


From $CO_2 \rightarrow C_6H_{12}O_6$

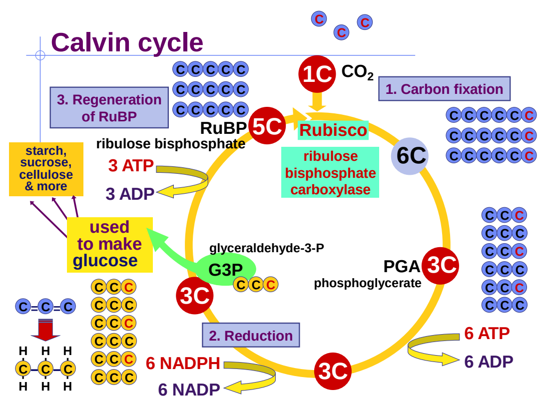
- CO_2 has very little chemical energy
  - fully oxidized
- $C_6H_{12}O_6$ contains a lot of chemical energy
  - reduced
  - endergonic
- Reduction of $CO_2 \rightarrow C_6H_{12}O_6$ proceeds in many small uphill steps
  - each catalyzed by specific enzyme
  - using energy stored in ATP & NADPH

From Light reactions to Calvin cycle

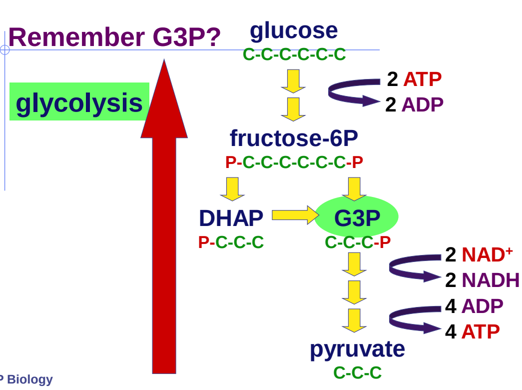
- Calvin cycle
  - chloroplast stroma
- Need products of light reactions to drive synthesis reactions
  - ATP
  - NADPH



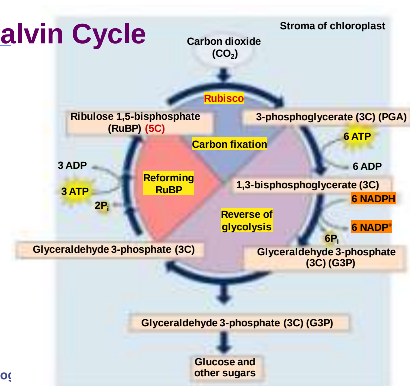
Calvin cycle



Remember G3P?



Calvin Cycle



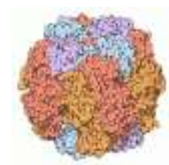
To G-3-P and Beyond!

- Glyceraldehyde-3-P
  - end product of Calvin cycle
  - energy rich 3 carbon sugar
  - "C3 photosynthesis"
- G-3-P = important intermediate

G-3-P → → glucose → → carbohydrates
→ → lipids
→ → amino acids
→ → nucleic acids

Rubisco

- Enzyme which fixes carbon from air
  - ribulose bisphosphate carboxylase
  - the most important enzyme in the world!
    - it makes life out of air!
  - definitely the most abundant enzyme

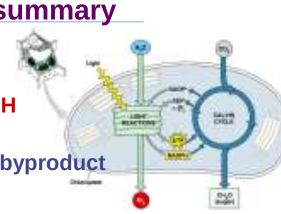


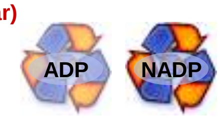
Accounting

- The accounting is complicated
  - 3 turns of Calvin cycle = 1 G3P
  - 3 CO_2 → 1 G3P (3C)
  - 6 turns of Calvin cycle = 1 $C_6H_{12}O_6$ (6C)
  - 6 CO_2 → 1 $C_6H_{12}O_6$ (6C)
  - 18 ATP + 12 NADPH → 1 $C_6H_{12}O_6$
  - any ATP left over from light reactions will be used elsewhere by the cell

Photosynthesis summary

- Light reactions
  - produced ATP
  - produced NADPH
  - consumed H_2O
  - produced O_2 as byproduct
- Calvin cycle
  - consumed CO_2
  - produced G3P (sugar)
  - regenerated ADP
  - regenerated NADP





Summary of photosynthesis

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

- Where did the CO_2 come from?
- Where did the CO_2 go?
- Where did the H_2O come from?
- Where did the H_2O go?
- Where did the energy come from?
- What's the energy used for?
- What will the $C_6H_{12}O_6$ be used for?
- Where did the O_2 come from?
- Where will the O_2 go?
- What else is involved…not listed in this equation?

Supporting a biosphere

- On global scale, photosynthesis is the most important process for the continuation of life on Earth
  - each year photosynthesis synthesizes 160 billion tons of carbohydrate
  - heterotrophs are dependent on plants as food source for fuel & raw materials

The poetic perspective…

- All the solid material of every <u>plant</u> was built by sunlight out of thin air
- All the solid material of every <u>animal</u> was built from plant material

air

sun

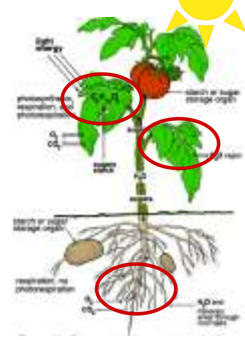
Then all the cats, dogs, rats, people & elephants… are really strands of air woven together by sunlight!

Any Questions??

Photosynthesis:
Variations on the Theme

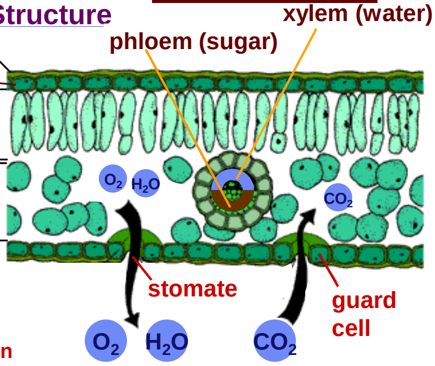
Remember what plants need…

- Photosynthesis
  - light reactions
    - light ← sun
    - H_2O ← ground
  - Calvin cycle
    - CO_2 ← air



What structures have plants evolved to supply these needs?

Leaf Structure

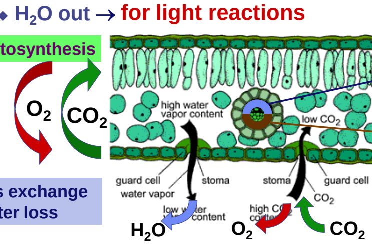


Transpiration

A second inside a leaf…

- Gas exchange & water flow
  - CO_2 in → for Calvin cycle
  - O_2 out → waste from light reactions
  - H_2O out → for light reactions

photosynthesis



gas exchange
water loss

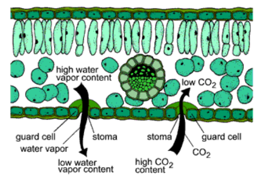
Controlling water loss from leaves

- Hot or dry days
  - stomates close to conserve water
  - guard cells
    - gain H_2O = stomates open
    - lose H_2O = stomates close
  - adaptation to living on land, but…

    creates PROBLEMS!

Closed stomates

- Closed stomates lead to…
  - O_2 builds up → from light reactions
  - CO_2 is depleted → in Calvin cycle
    - causes problems in Calvin Cycle



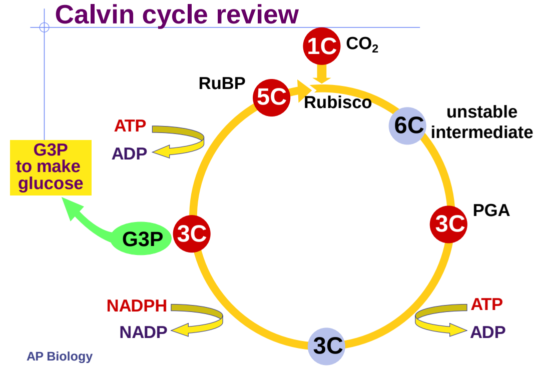
Inefficiency of Rubisco: CO_2 vs O_2

- Rubisco in Calvin cycle
  - carbon fixation enzyme
    - normally bonds C to RuBP
    - reduction of RuBP
    - building sugars

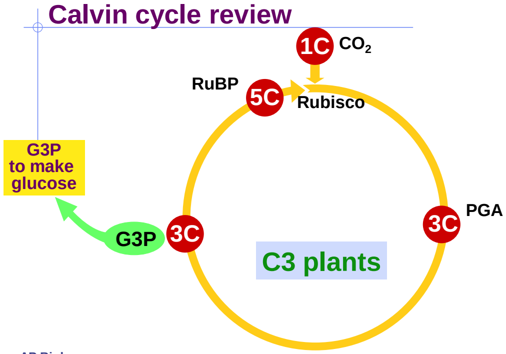
    photosynthesis
  - when O_2 concentration is high
    - Rubisco bonds O to RuBP
    - O_2 is alternative substrate
    - oxidation of RuBP
    - breakdown sugars

    photorespiration

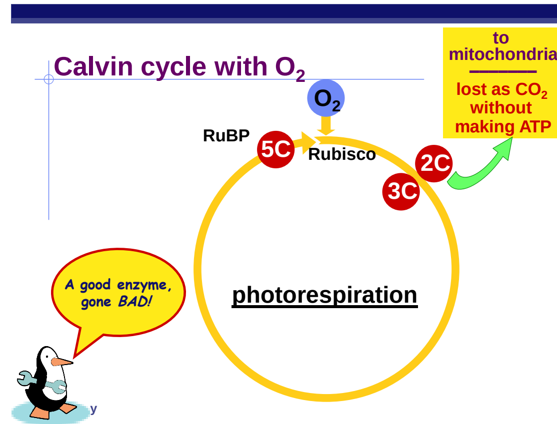
Calvin cycle review



Calvin cycle review



Calvin cycle with O_2



Impact of Photorespiration

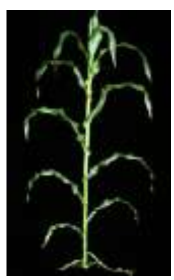
- Oxidation of RuBP
  - short circuit of Calvin cycle
  - <u>loss of carbons to CO_2</u>
    - can lose 50% of carbons fixed by Calvin cycle
  - reduces production of photosynthesis
    - <u>no ATP</u> (energy) produced
    - <u>no $C_6H_{12}O_6$</u> (food) produced
  - if photorespiration could be reduced, plant would become 50% more efficient
    - strong selection pressure to evolve alternative systems

Reducing photorespiration

- Separate carbon fixation from Calvin cycle
  - <u>C4 plants</u>
    - <u>physically separate carbon fixation from actual Calvin cycle</u>
    - different enzyme to capture CO_2
      - <u>PEP carboxylase</u> stores carbon in 4C compounds
    - different leaf structure
  - <u>CAM plants</u>
    - <u>separate carbon fixation from actual Calvin cycle by time of day</u>
    - fix carbon (capture CO_2) during night
      - store carbon in organic acids
    - perform Calvin cycle during day

C4 plants

- A better way to capture CO_2
  - 1st step before Calvin cycle, fix carbon with enzyme <u>PEP carboxylase</u>
    - store as 4C compound
  - <u>adaptation to hot, dry climates</u>
    - have to close stomates a lot
    - different leaf anatomy
  - sugar cane, corn, other grasses…



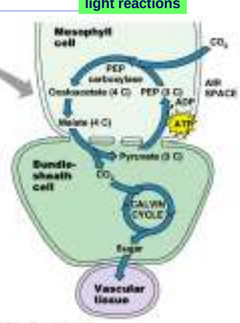
C4 Plants

corn

sugar cane

PEP carboxylase

light reactions → O_2

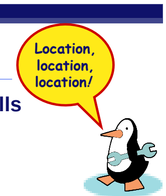


- <u>PEP carboxylase enzyme</u>
  - higher affinity for CO_2 than O_2 (better than Rubisco)
  - fixes CO_2 in 4C compounds
  - <u>regenerates CO_2</u> in inner cells for Rubisco

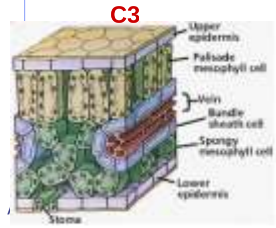
phosphoenolpyruvate (3C) + CO_2 → oxaloacetate (4C)

Comparative anatomy

- Separate reactions in different cells
  - light reactions
  - carbon fixation
  - Calvin cycle



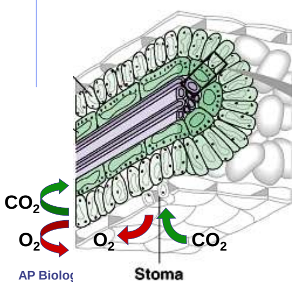
C3



C4

C4 photosynthesis

Physically separated C fixation from Calvin cycle



- Outer cells
  - light reaction & carbon fixation
  - pumps CO_2 to inner cells
  - keeps O_2 away from inner cells
    - away from Rubisco
- Inner cells
  - Calvin cycle
  - glucose to veins

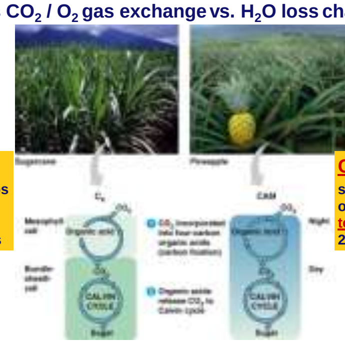
CAM (Crassulacean Acid Metabolism) plants

- Different adaptation to hot, dry climates
  - separate carbon fixation from Calvin cycle by time
    - close stomates during day
    - open stomates during night
  - at night, open stomates & fix carbon in "storage" compounds
    - organic acids: malic acid, isocitric acid
  - in day, close stomates & release CO_2 from "storage" compounds to Calvin cycle
    - increases concentration of CO_2 in cells
  - succulents, some cacti, pineapple

CAM plants

C4 vs CAM Summary

solves CO_2 / O_2 gas exchange vs. H_2O loss challenge



C4 plants
separate 2 steps of C fixation anatomically in 2 different cells

CAM plants
separate 2 steps of C fixation temporally at 2 different times

Why the C3 problem?

- Possibly evolutionary baggage
  - Rubisco evolved in high CO_2 atmosphere
    - there wasn't strong selection against active site of Rubisco accepting both CO_2 & O_2
- Today it makes a difference
  - 21% O_2 vs. 0.03% CO_2
  - photorespiration can drain away 50% of carbon fixed by Calvin cycle on a hot, dry day
  - strong selection pressure to evolve better way to fix carbon & minimize photorespiration

Any Questions??