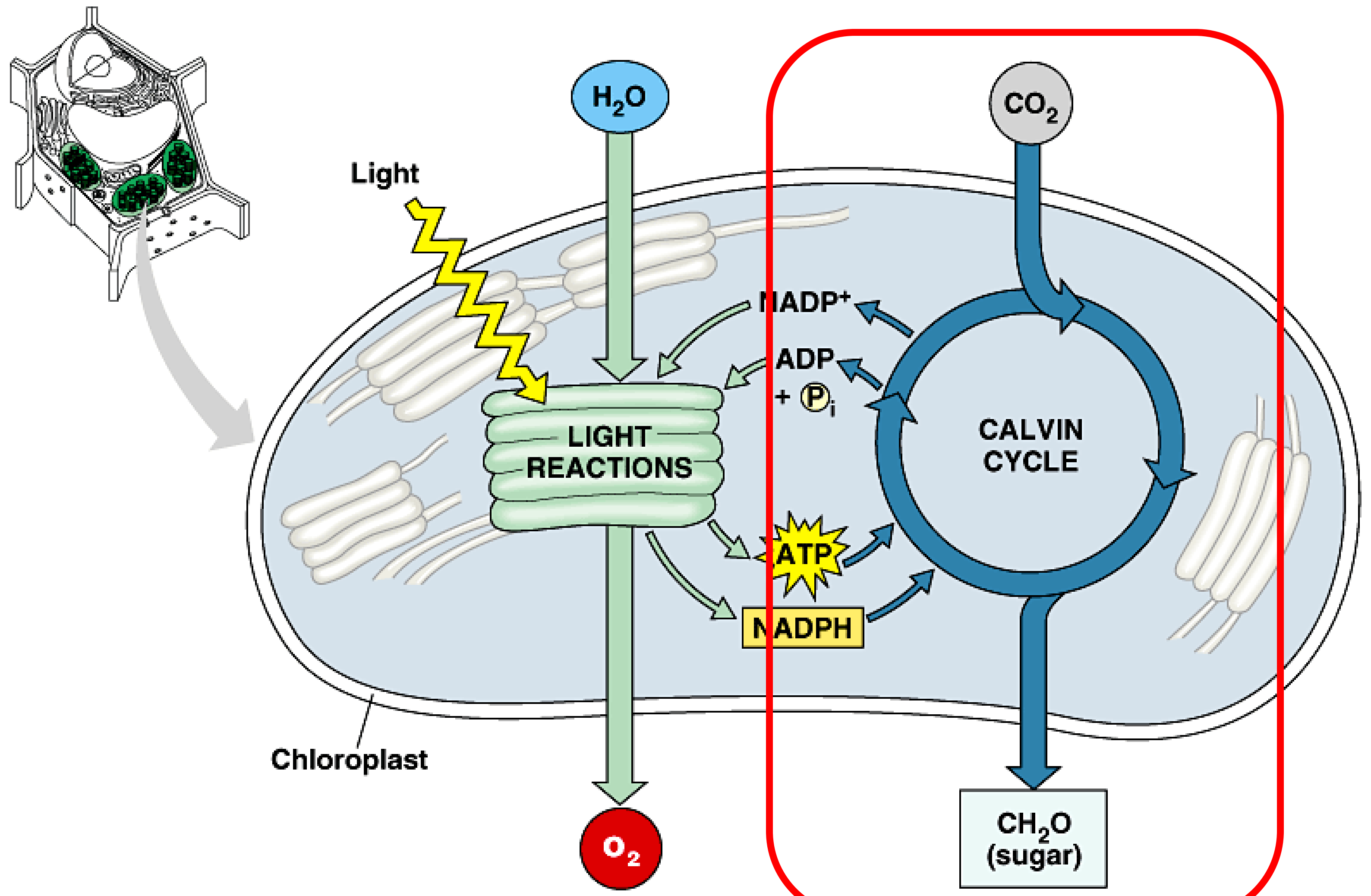
PHOTOSYNTHESIS PART 2

Calvin Cycle

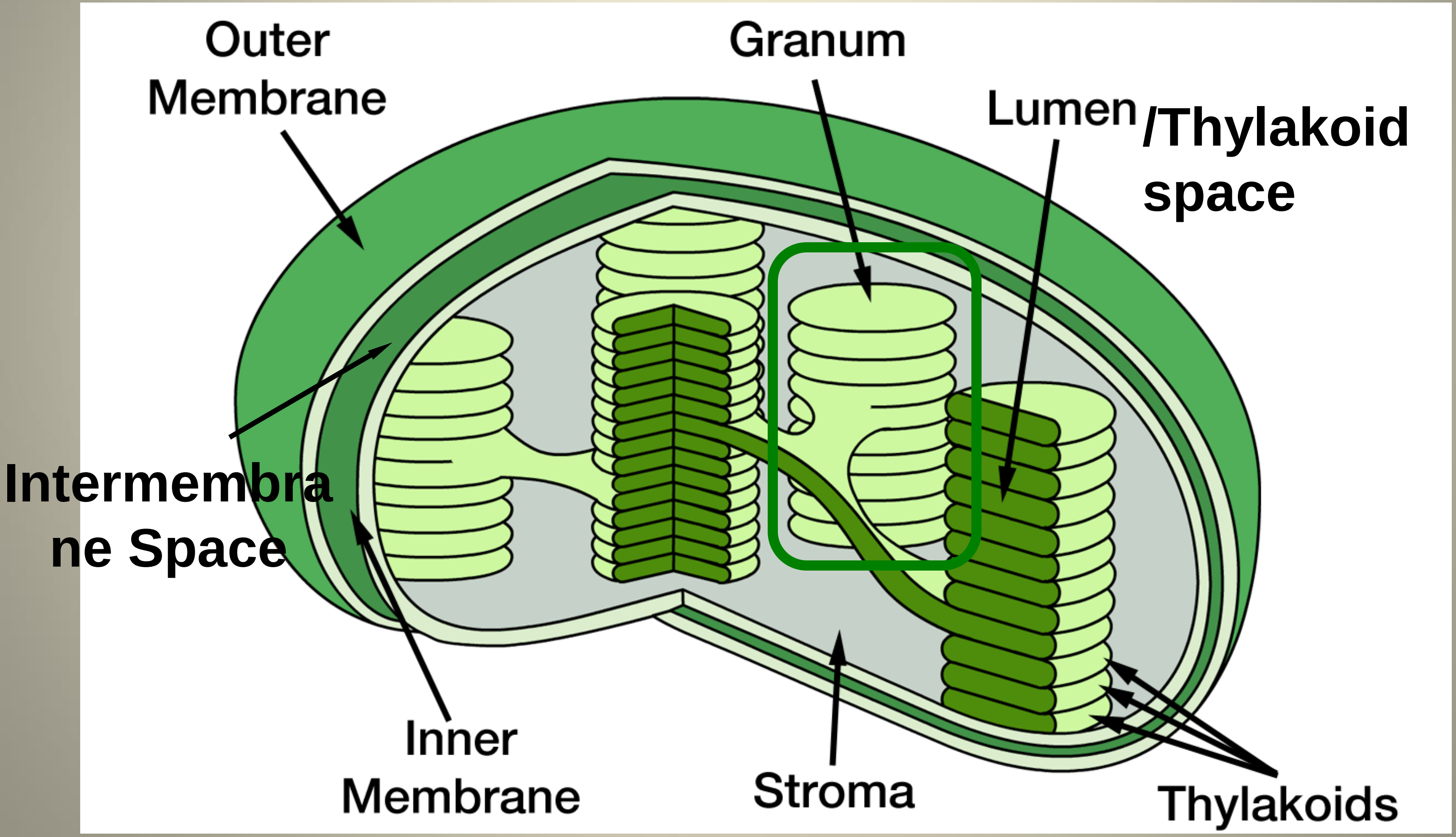
Adaptations

Factors Affecting Rate

Calvin Cycle



Calvin cycle occurs in the stroma

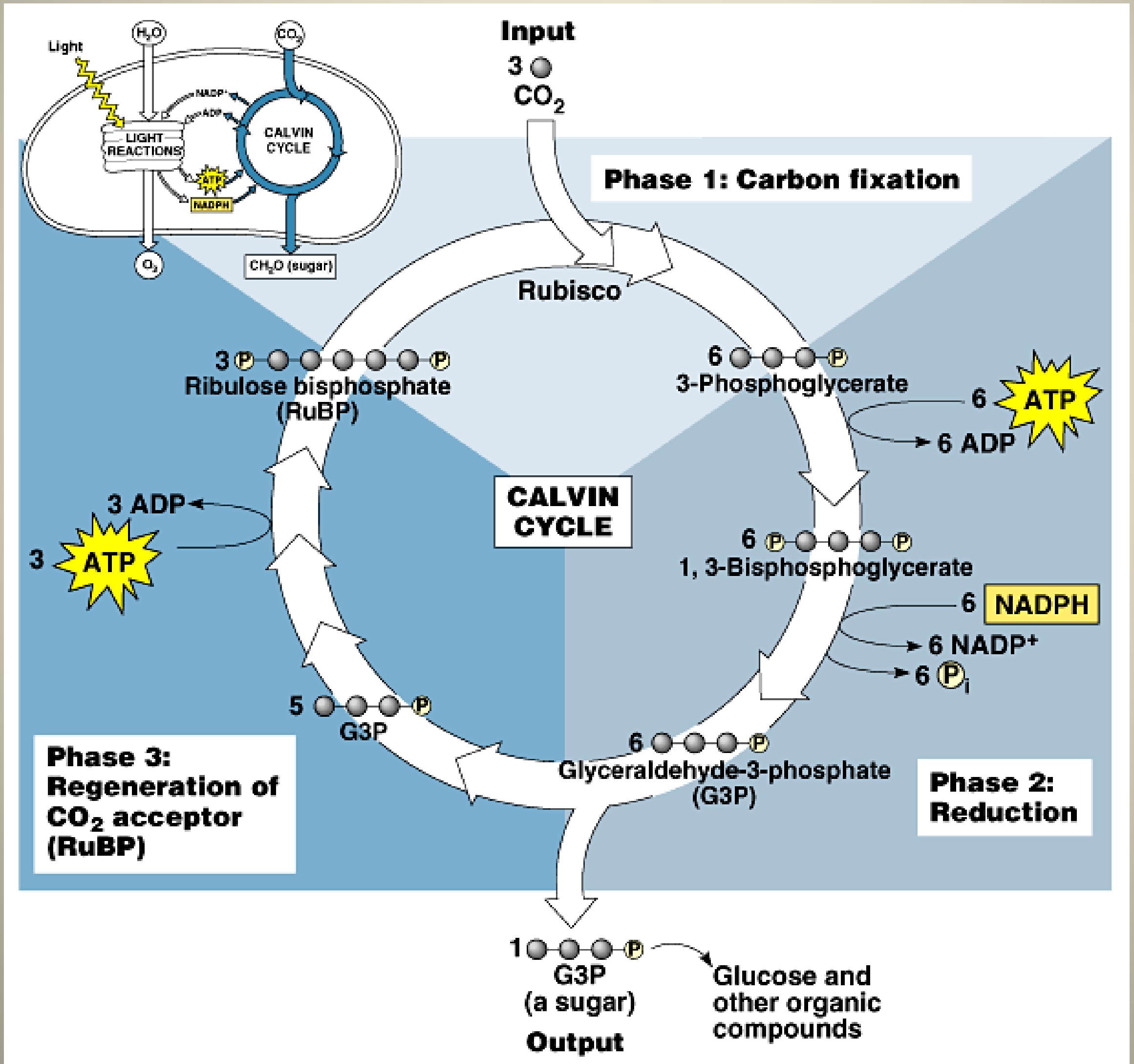


Calvin Cycle Overview

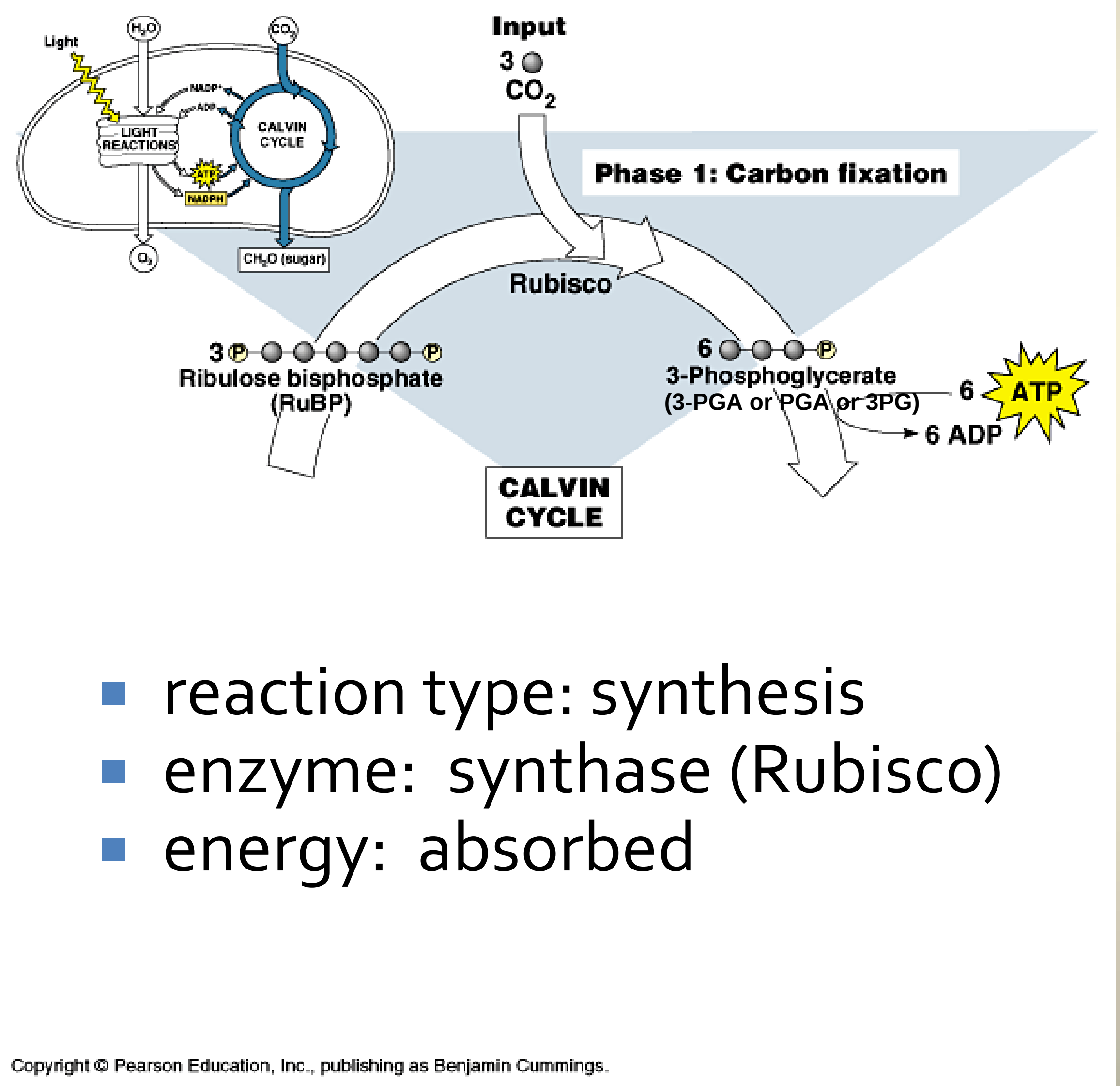
Cyclical process with 3 phases:

- Carbon fixation: incorporation of CO_2
- Reduction: utilization of energy molecules to form organic compound
- Renegeration: regenerates molecules for another cycle

Calvin Cycle Overview



Phase 1: Carbon Fixation



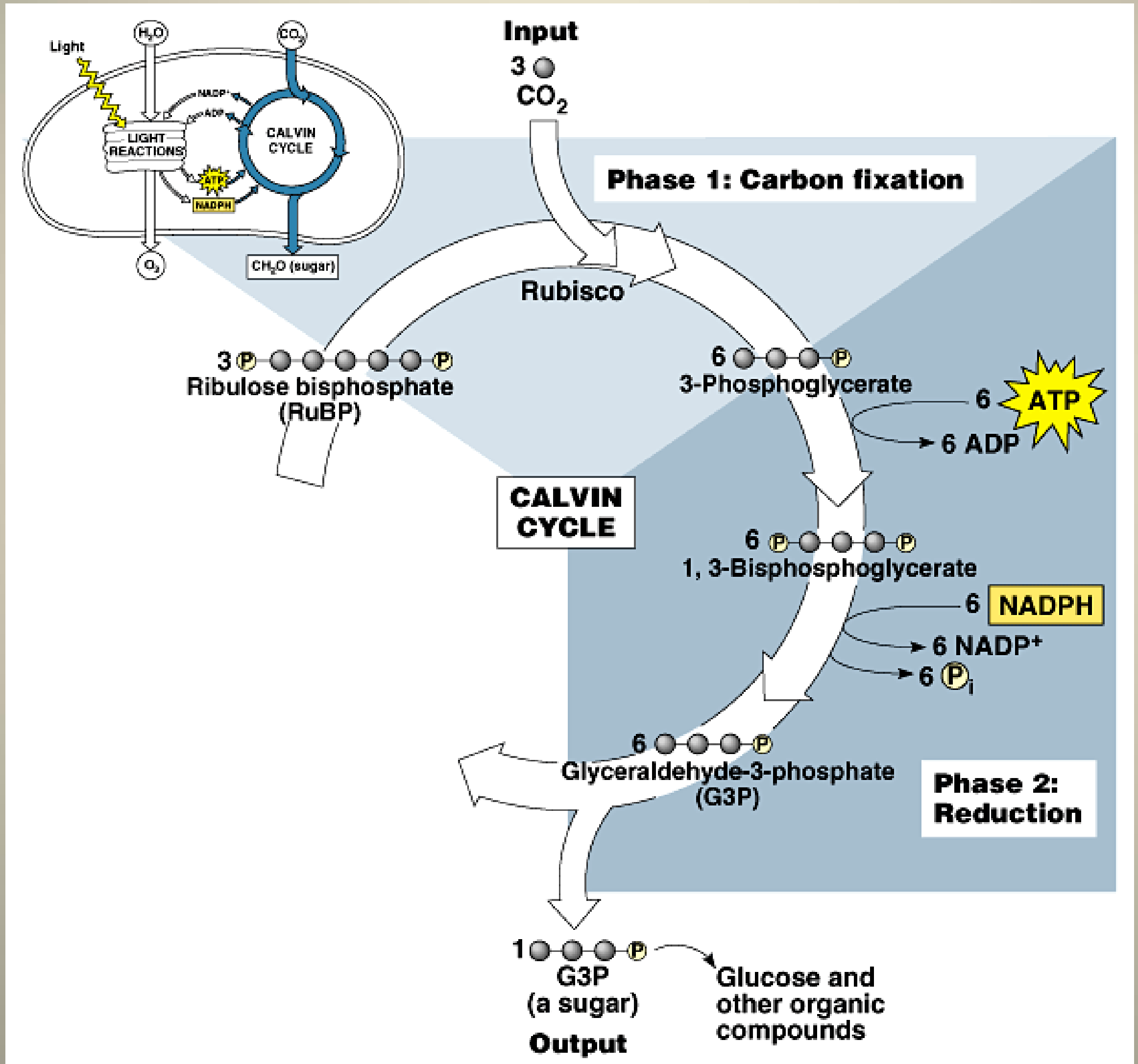
- reaction type: synthesis
- enzyme: synthase (Rubisco)
- energy: absorbed

- CO_2 (1c) + 1,5-RuBP (5c) = short lived 6C intermediate
- 6C molecule split into two 3C molecule known as 3-PGA/PGA/3PG
- Above reaction occurs 3x

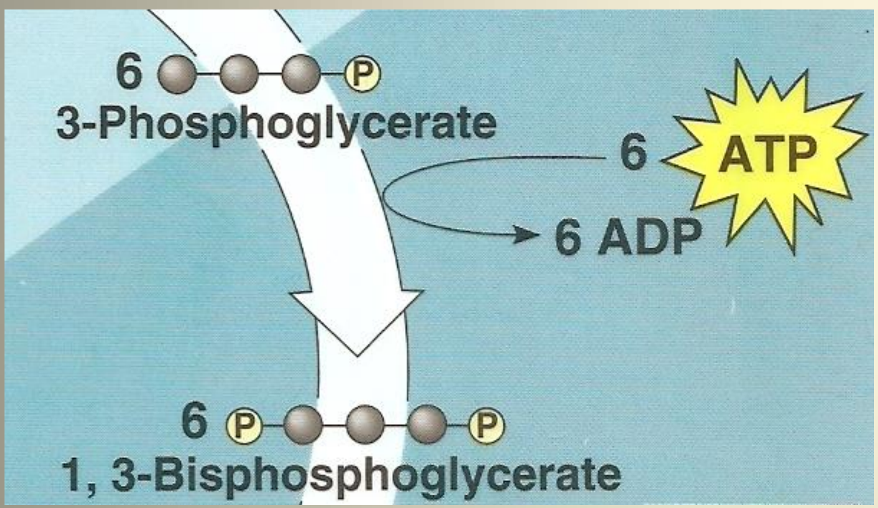
Rubisco

- ribulose bisphosphate carboxylase / oxygenase
- large, slow reacting enzyme
  - most enzymes process 1000 reactions / second
  - rubisco processes 3 reactions / second
- plants need large amounts of rubisco for Calvin cycle
  - half the protein in a leaf
  - most abundant protein on Earth

Phase 2: Reduction



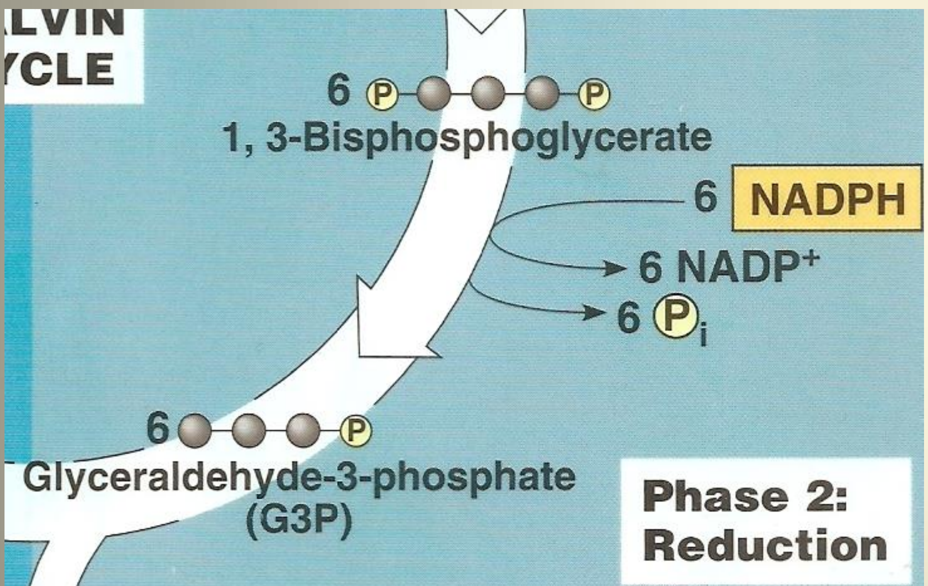
Calvin Cycle: Energy Utilization



- ATP phosphorylates each 3-carbon molecule

- reaction type: phosphorylation
- enzyme: kinase
- energy: absorbed

Calvin Cycle: Energy Utilization

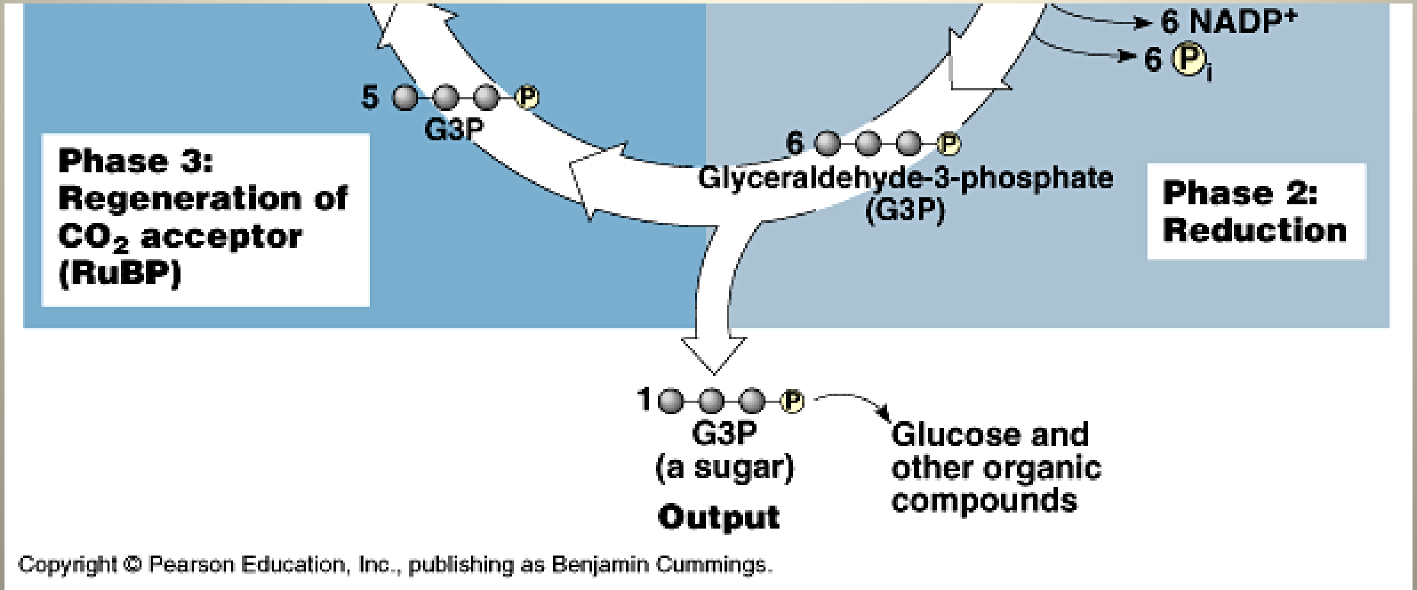


- NADPH used to synthesize G3P

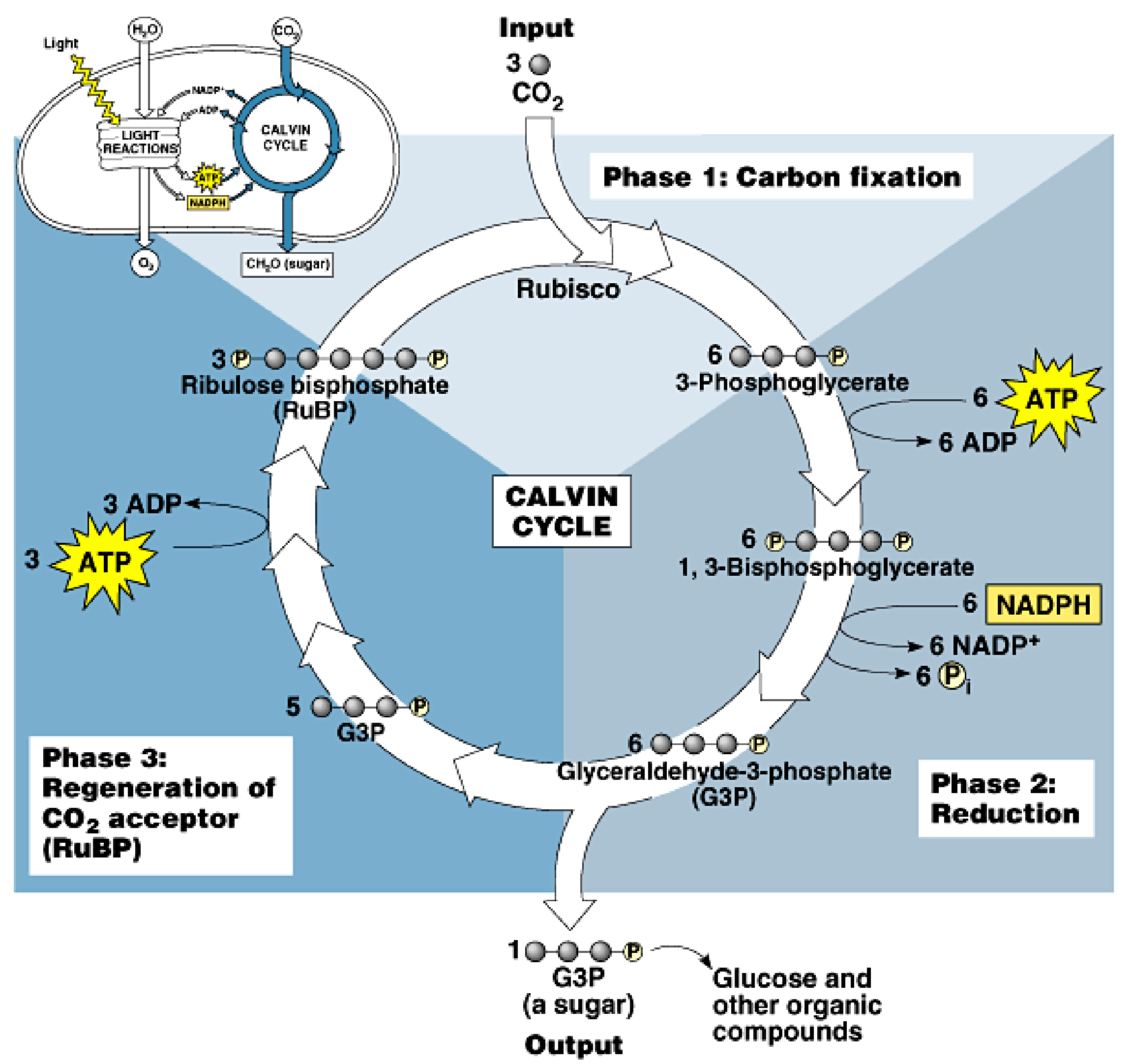
- reaction type: redox
- enzyme: dehydrogenase
- energy: absorbed

Phase 3: Regeneration

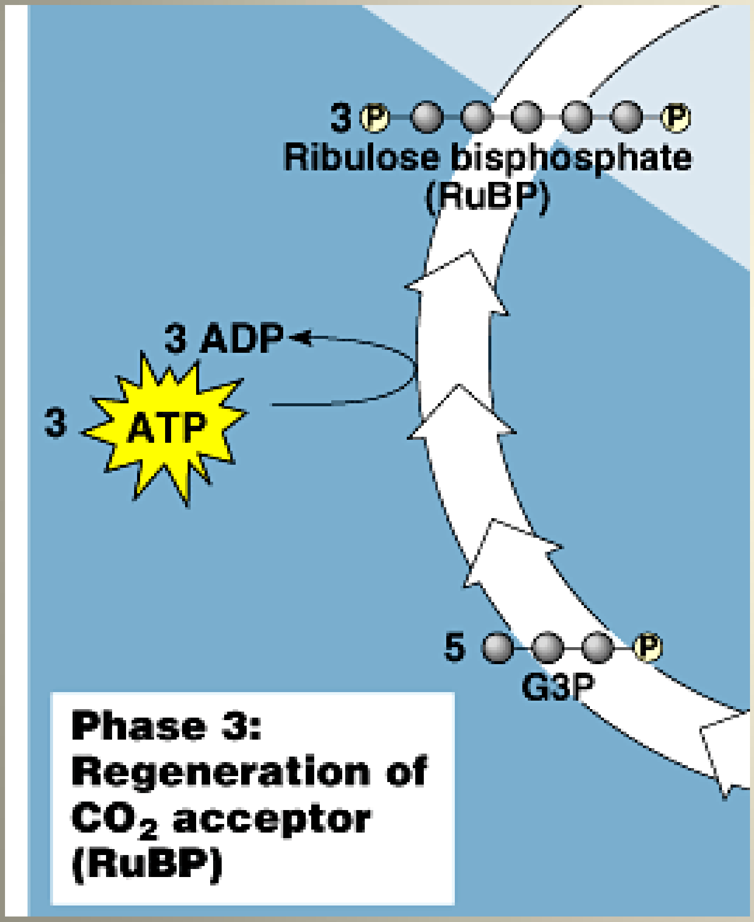
- Of the 6 G3P produced 1 of them exits the cycle to eventually become glucose and other types of organic compounds
- The other 5 G3P continue in the cycle to help regenerate the starting substances



Phase 3: Regeneration

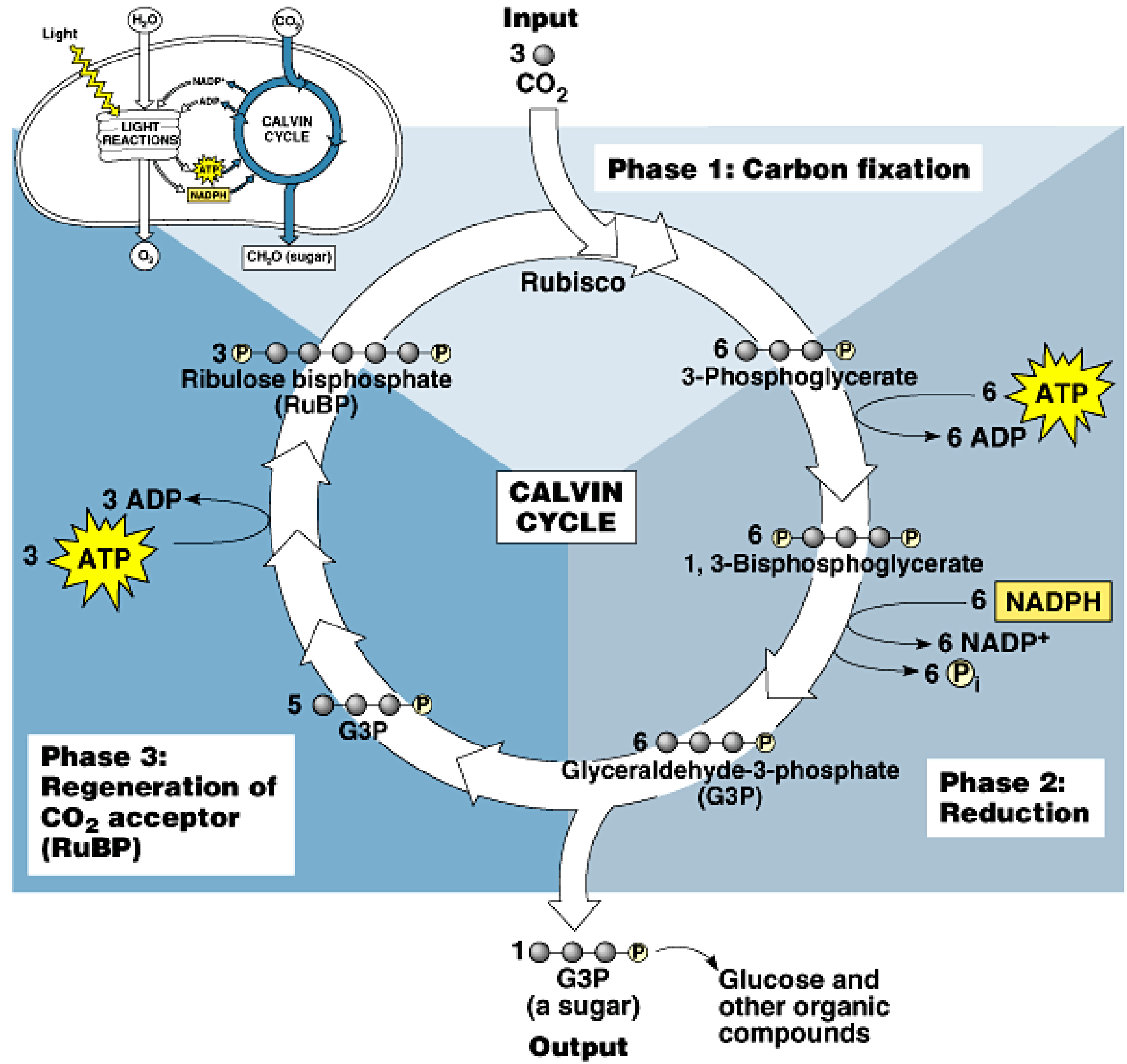


Calvin Cycle: Regenerate Molecules



- G3P resynthesized to 1,5-RuBP
- 5 x 3C (G3P) → 3 x 5C (RuBP)
- 15 C in total
- Uses ATP

- reaction type: synthesis
- enzyme: synthase
- energy: absorbed



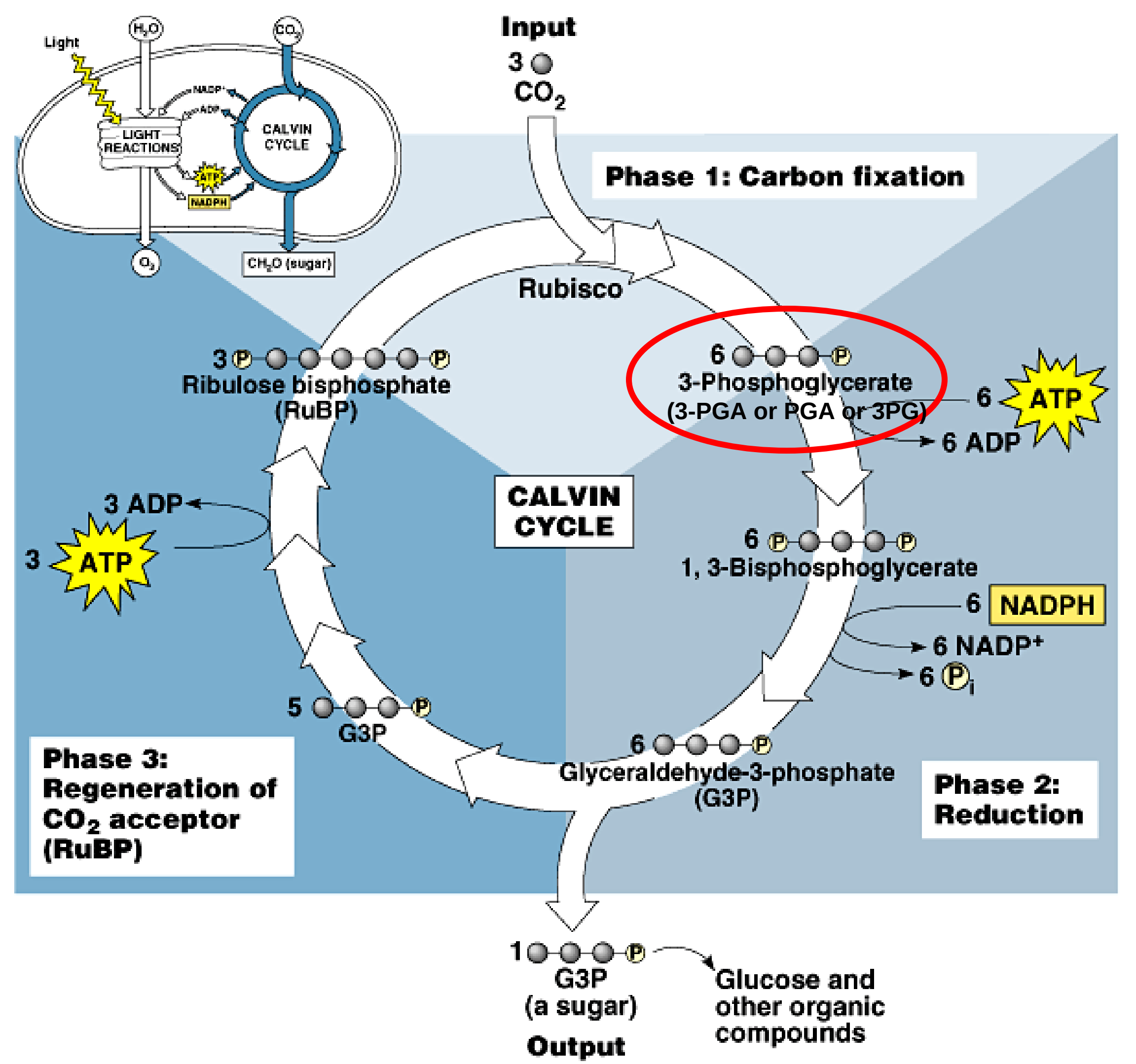
Light
H_2O
CO_2
LIGHT REACTIONS
CALVIN CYCLE
NADP+
ADP
ATP
NADPH
O_2
CH_2O (sugar)
Input
3 CO_2
Phase 1: Carbon fixation
Rubisco
3 Ribulose bisphosphate (RuBP)
6 3-Phosphoglycerate
6 ATP
6 ADP
CALVIN CYCLE
3 ADP
3 ATP
6 1, 3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
5 G3P
6 Glyceraldehyde-3-phosphate (G3P)
Phase 3: Regeneration of CO_2 acceptor (RuBP)
Phase 2: Reduction
1 G3P (a sugar)
Output
Glucose and other organic compounds

Adaptations to Limitations

- Photorespiration limitations:
  - C_3 plant
- Adaptations to hot, arid conditions:
  - C_4 plants
  - CAM plants

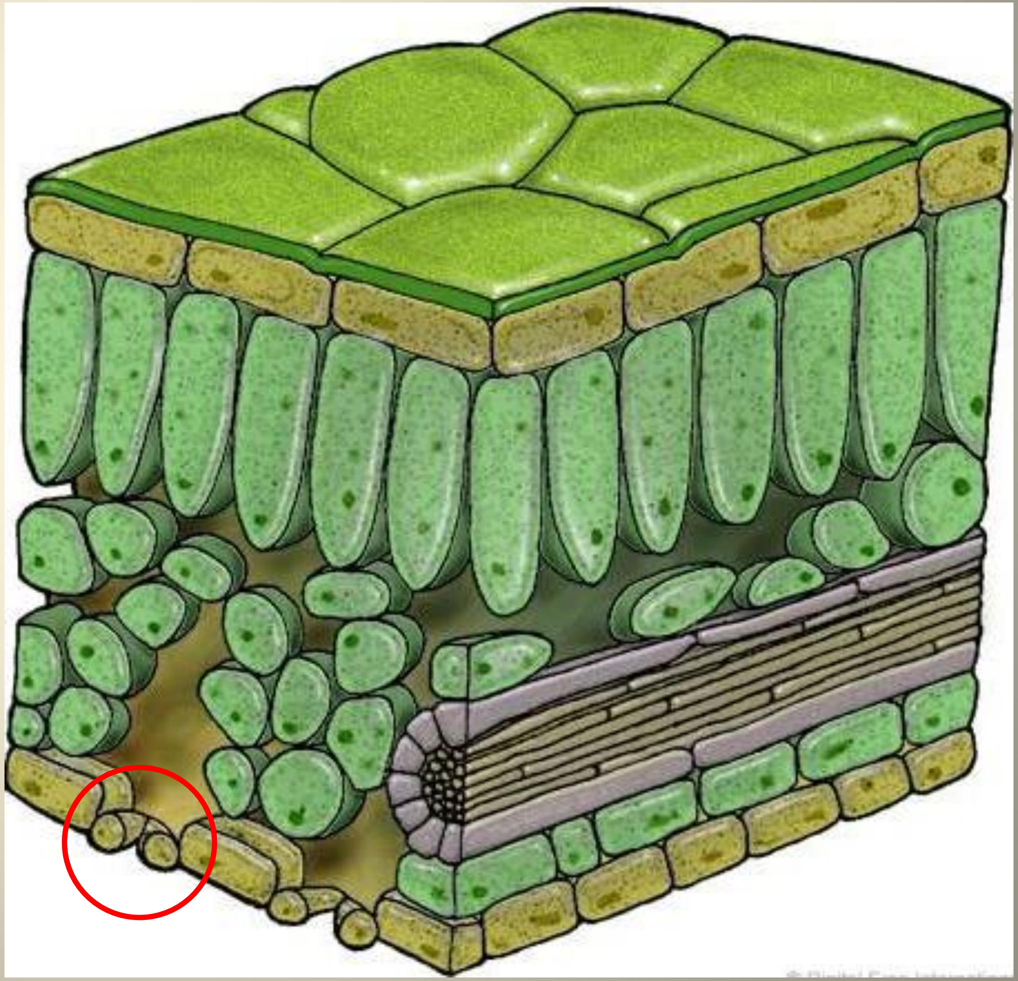
C3 Plants

- Plants whose first organic product of carbon fixation is a 3-carbon compound
- C3 plants undergo photosynthesis as described



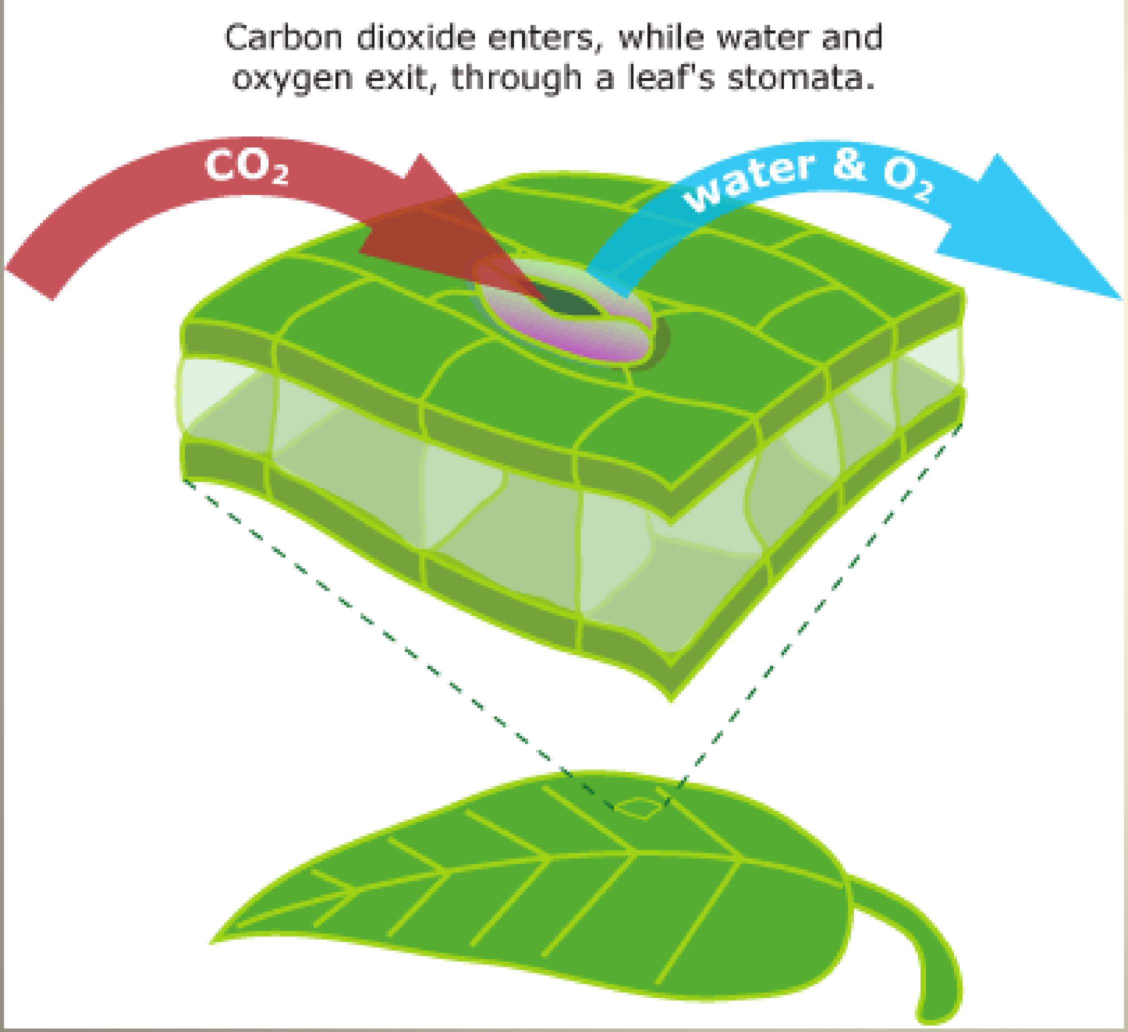
C_3 Plants

- Stomata are open during the day / closed at night
- What happens to stomata in hot, arid conditions?



Stomata

C_3 Plant Limitations

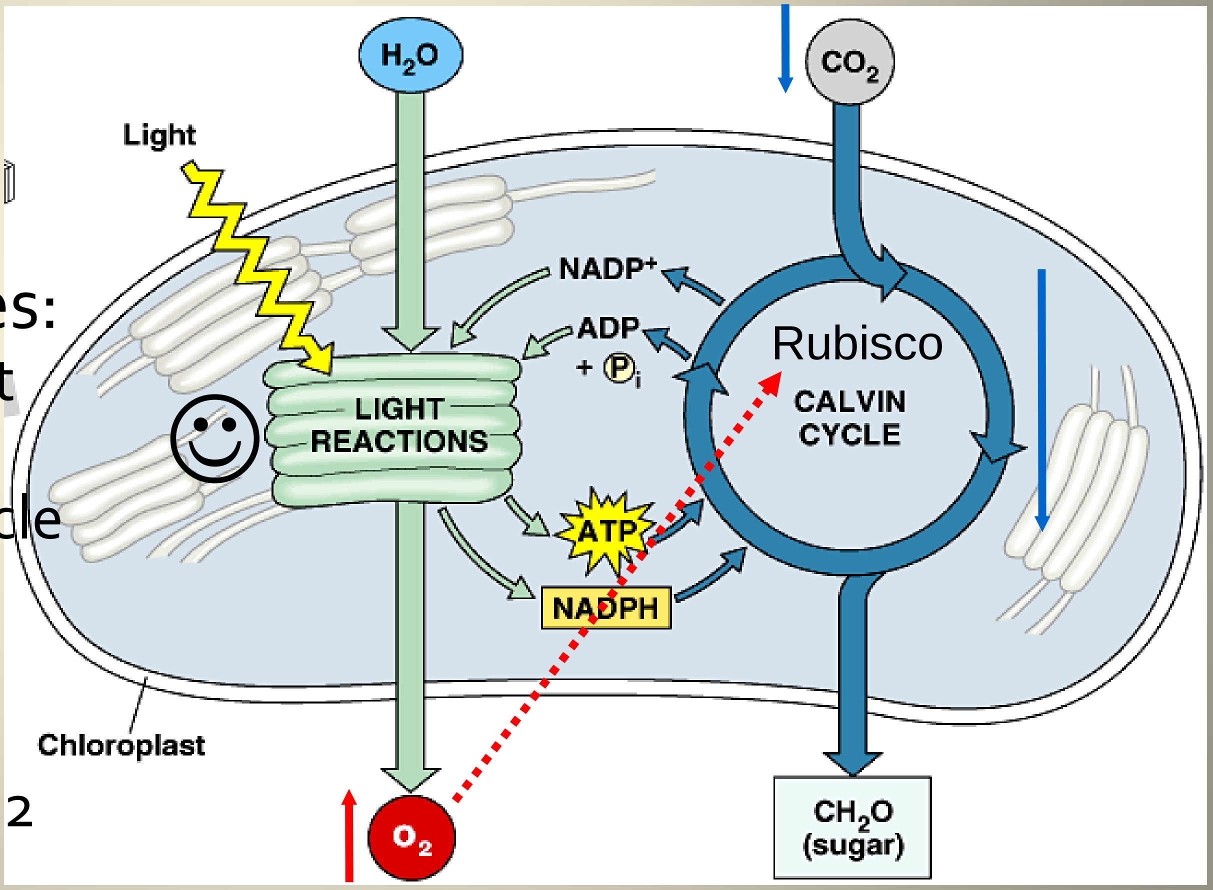


- In hot, arid conditions, plants close the stomata to prevent water loss
- What affect does that have on CO2 and O2 concentration?

http://evolution.berkeley.edu/evolibrary/images/interviews/stoma_diagram.gif

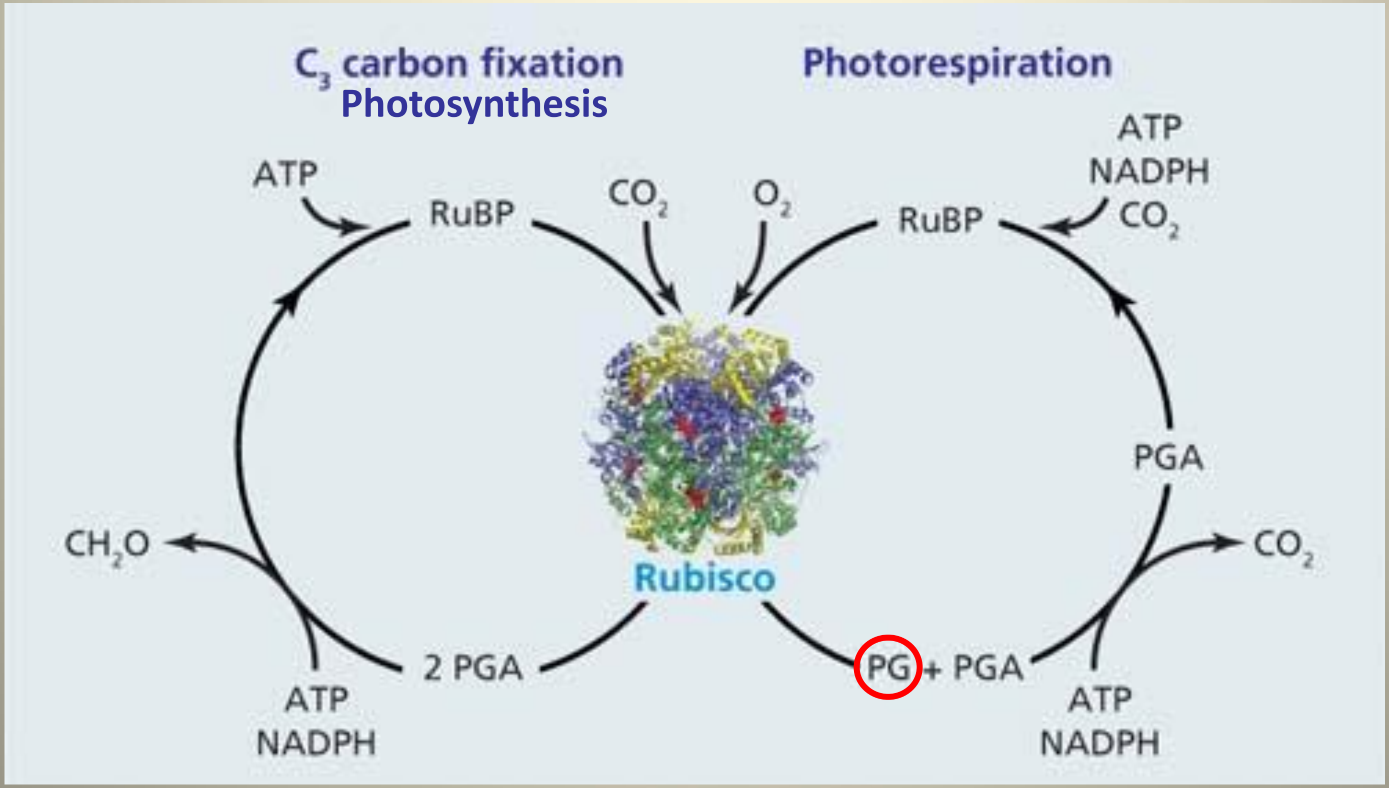
C_3 Plant Limitations

- Effect of closed stomata on gases:
  - CO_2 decreases
  - O_2 increases
- Effect on processes:
  - No change to light reactions
  - Slow/no Calvin cycle
  - No glucose produced
- Effect on Rubisco
  - rubisco binds to O_2 rather than CO_2

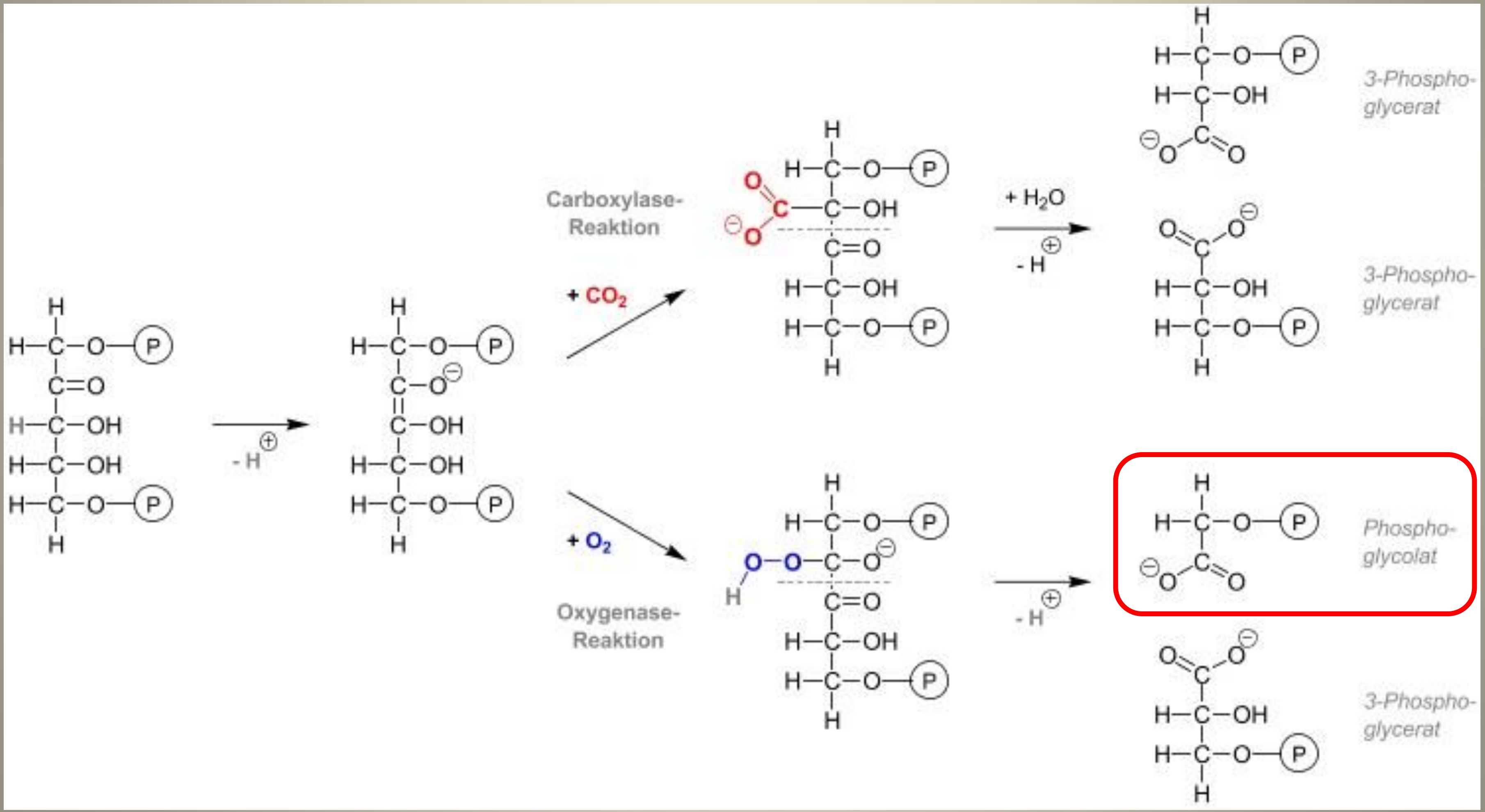


Rubisco

- 2 possible substrates: CO_2 or O_2
- Carboxylase: binds CO_2 yields 2x PGA
- Oxygenase: binds O_2 yields 1x PGA and PG



Rubisco Reaction



Phosphoglycollate (PG)

- cannot be converted directly into sugars
- is a wasteful loss of carbon
- to retrieve the carbon from it, plants must use an energy-expensive process called photorespiration

Photorespiration (aka photo-oxidation)

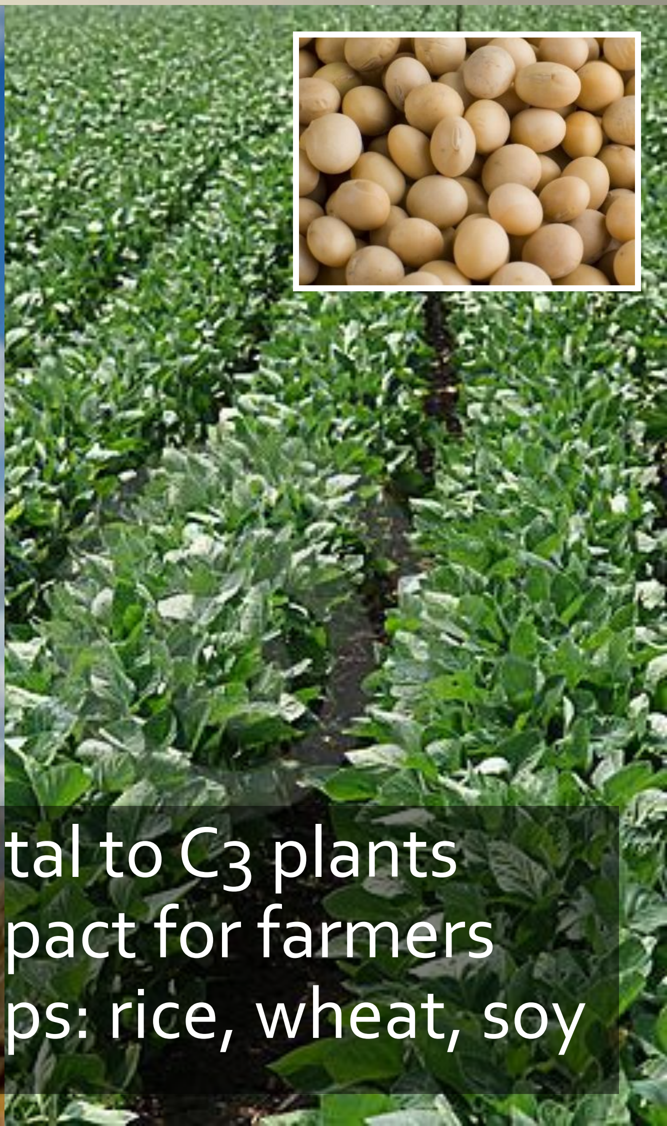
- "photo": occurs in the light
  - unlike photosynthesis, produces no organic fuel (no Calvin cycle)
- "respiration": consumes oxygen (by rubisco)
  - unlike cellular respiration, generates no ATP
- wastes energy and reducing power
- results in the production of dangerous reactive oxygen species (**H_2O_2**) in the **peroxisome**

Why does photorespiration exist?

- Evolutionary baggage:
  - Metabolic relic from earlier time when atmosphere had less O_2 and more CO_2
  - With so much CO_2, rubisco's inability to exclude O_2 had little impact on photosynthesis
- Modern times:
  - Rubisco's affinity for O_2 has a negative impact on crop yields

C_3 Plants: Agricultural Crops





- Hot arid dry conditions are detrimental to C_3 plants
- These conditions have a negative impact for farmers and consumers of C_3 agricultural crops: rice, wheat, soy

Evolutionary Efficiency

- Atmospheric O_2 is 500x higher than CO_2
- Yet rubisco fixes on average 4 CO_2 for every O_2

Photosynthetic Adaptations

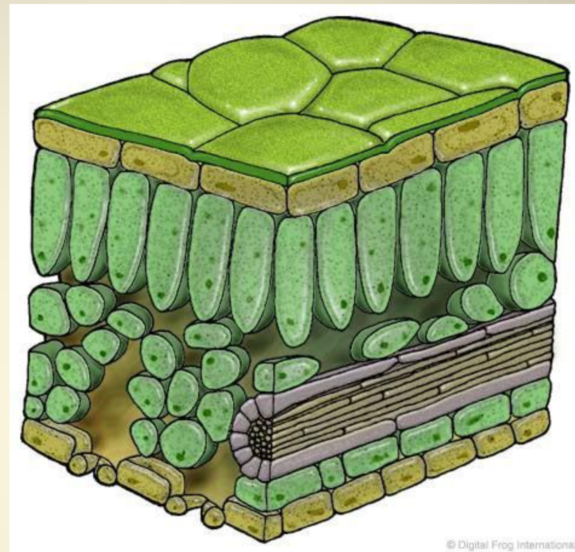
- 2 other plant types have adapted photosynthesis to dry, arid conditions:
  - C_4 plants – spatial (structural) separation
  - CAM plants – temporal (behavioural) separation

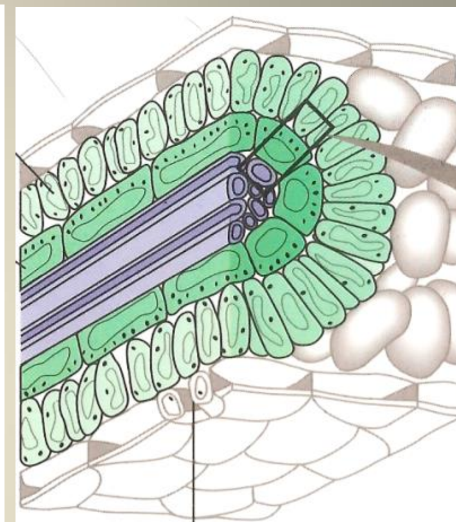
C_4 Plants

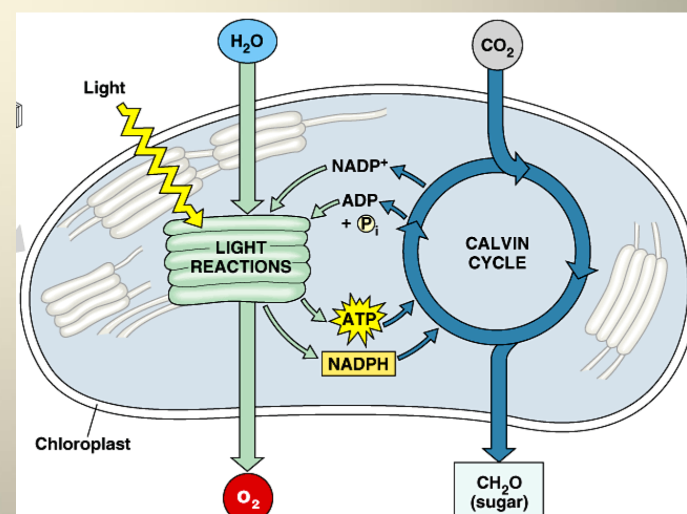
- Preface the Calvin cycle with an alternate mode of carbon fixation that produces a 4-carbon compound as their first organic product
- Agricultural C_4 crops: sugar cane, corn

C_4 Plant Adaptation

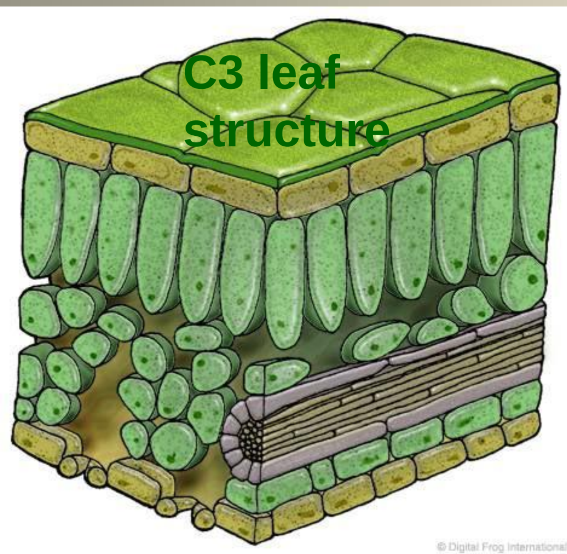
- Recall:
  - Which leaf cells are primarily responsible for the light reactions of photosynthesis?
  - What is the by-product of the light reactions?
  - How is Rubisco affected by the by-product?
- What if we moved Rubisco somewhere else?

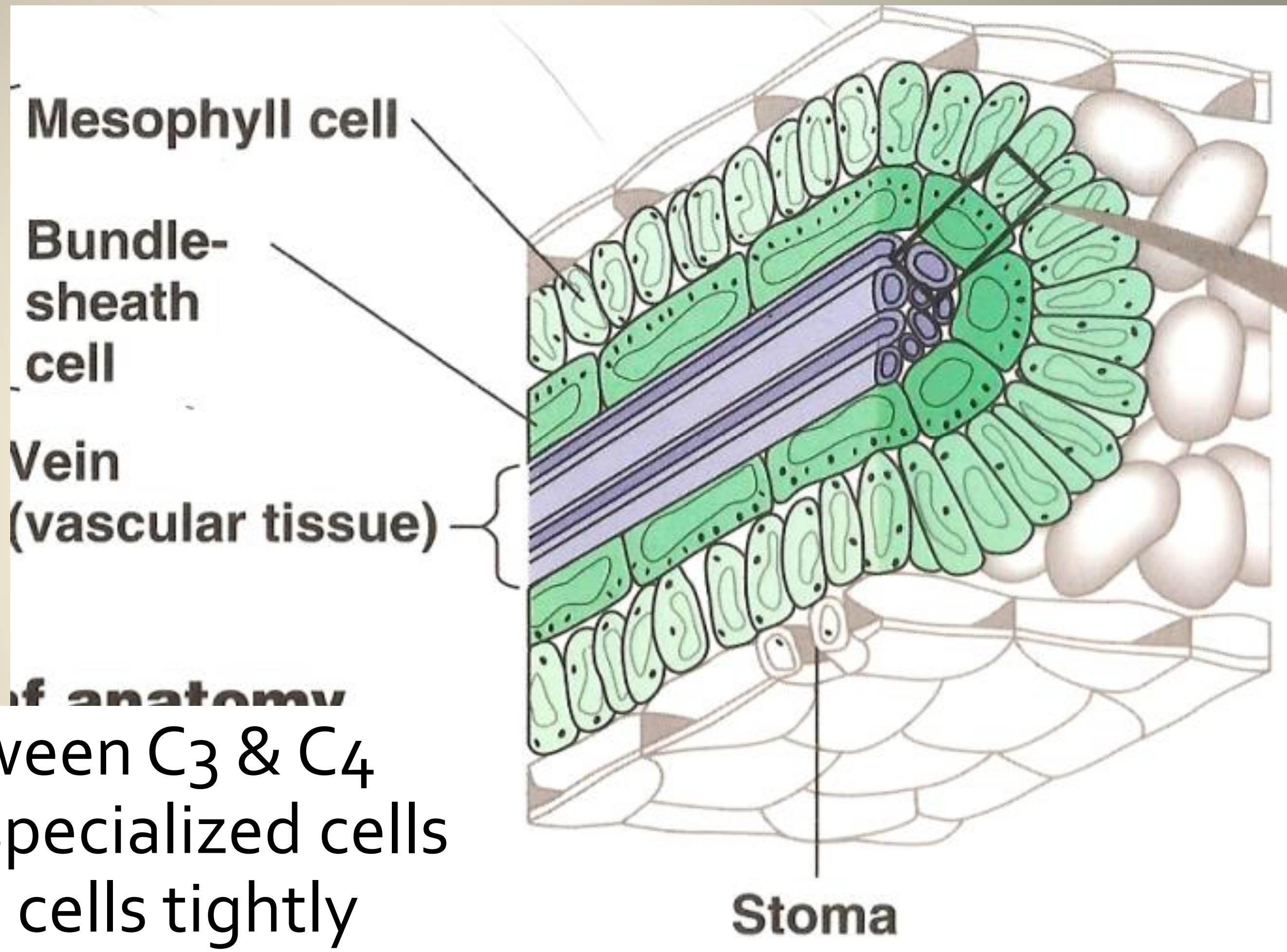






C_4 Plant: Leaf Structure



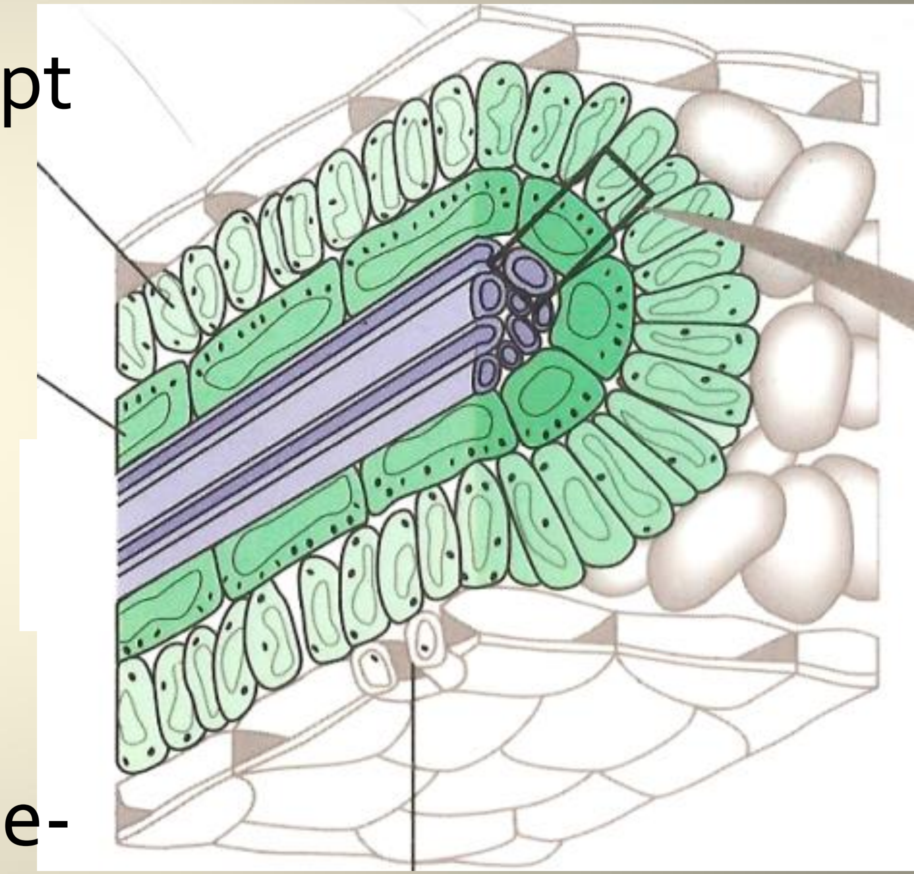


- Difference between C_3 & C_4 leaf structure: specialized cells
- **Bundle-sheath** cells tightly packed next to mesophyll cells and around vascular bundle

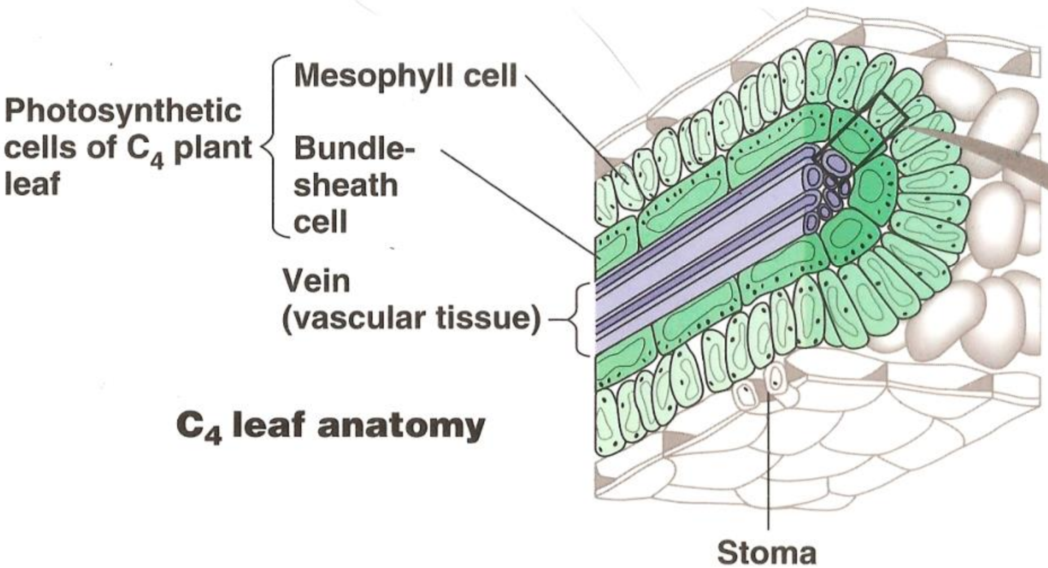
C4 Plant Adaptation

- Light reactions (O_2) kept separate in palisade mesophyll cells
- Calvin cycle (rubisco) confined to bundle-sheath cells

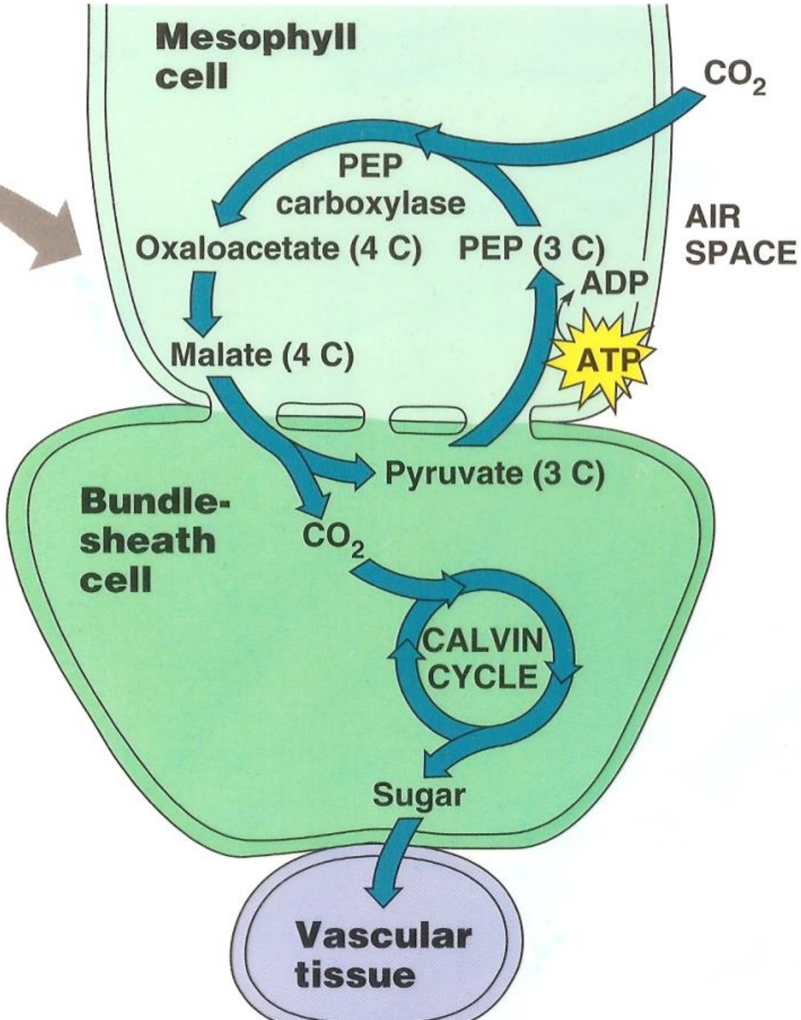
- Q: But then how does CO_2 get into the bundle-sheath cells?



C_4 Plant Adaptation

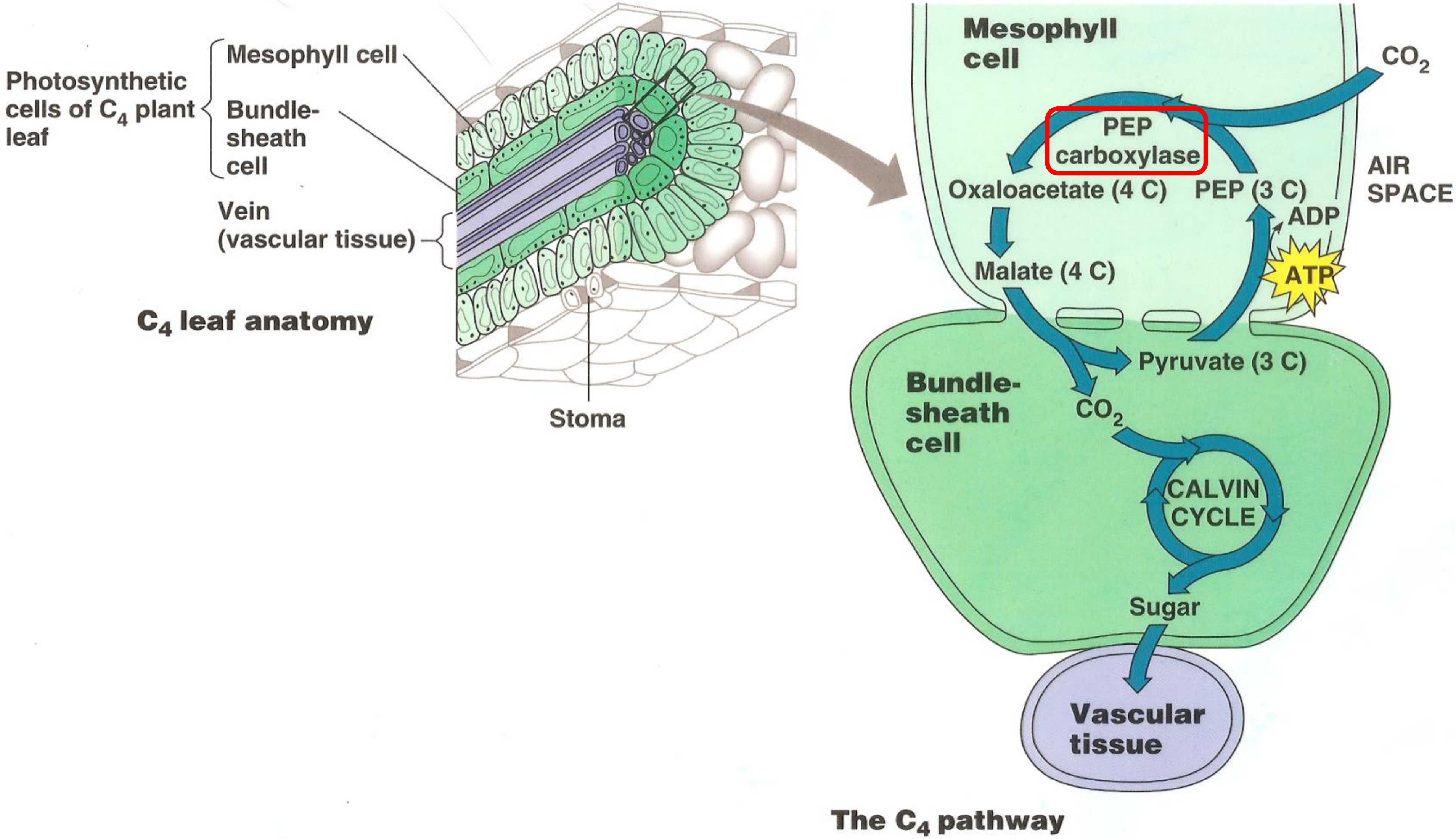


C_4 leaf anatomy



The C_4 pathway

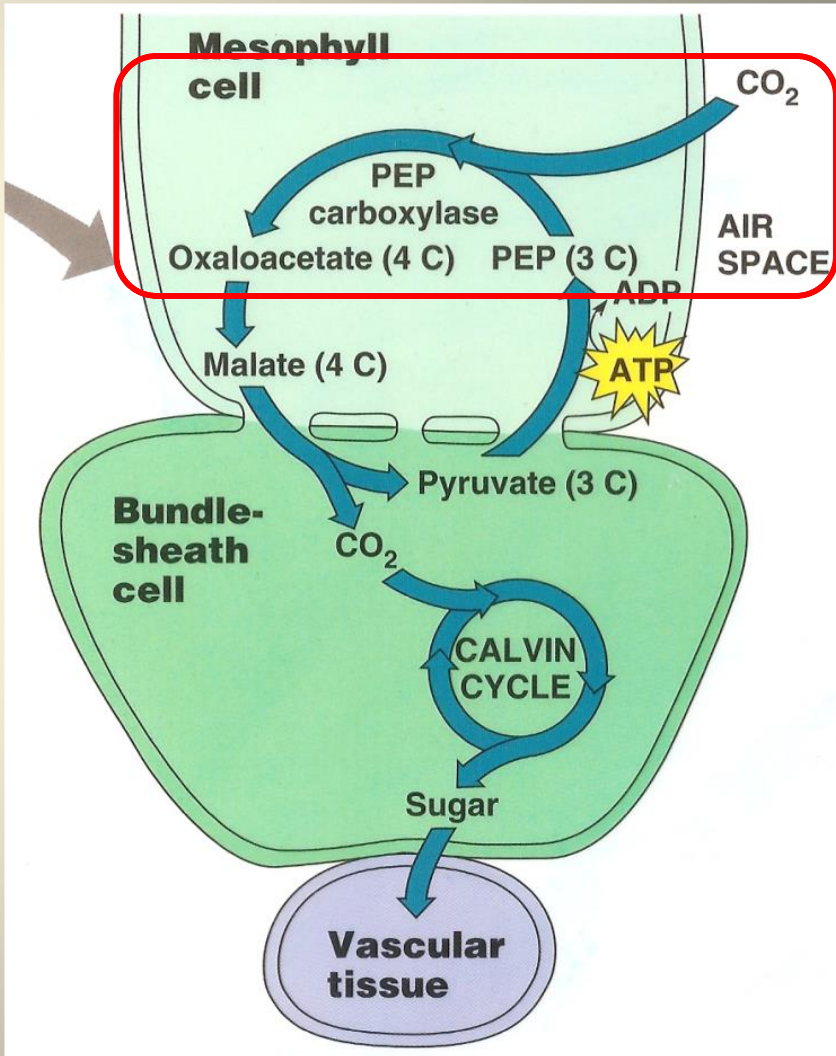
C_4 Plant Adaptation



C_4 Plant Adaptation

Mechanism:

- Step 1: CO_2 added to a phosphoenolpyruvate (PEP) (3C) to form a oxaloacetate (OAA) (4C), then to malate
- CO_2 + PEP → OAA → malate

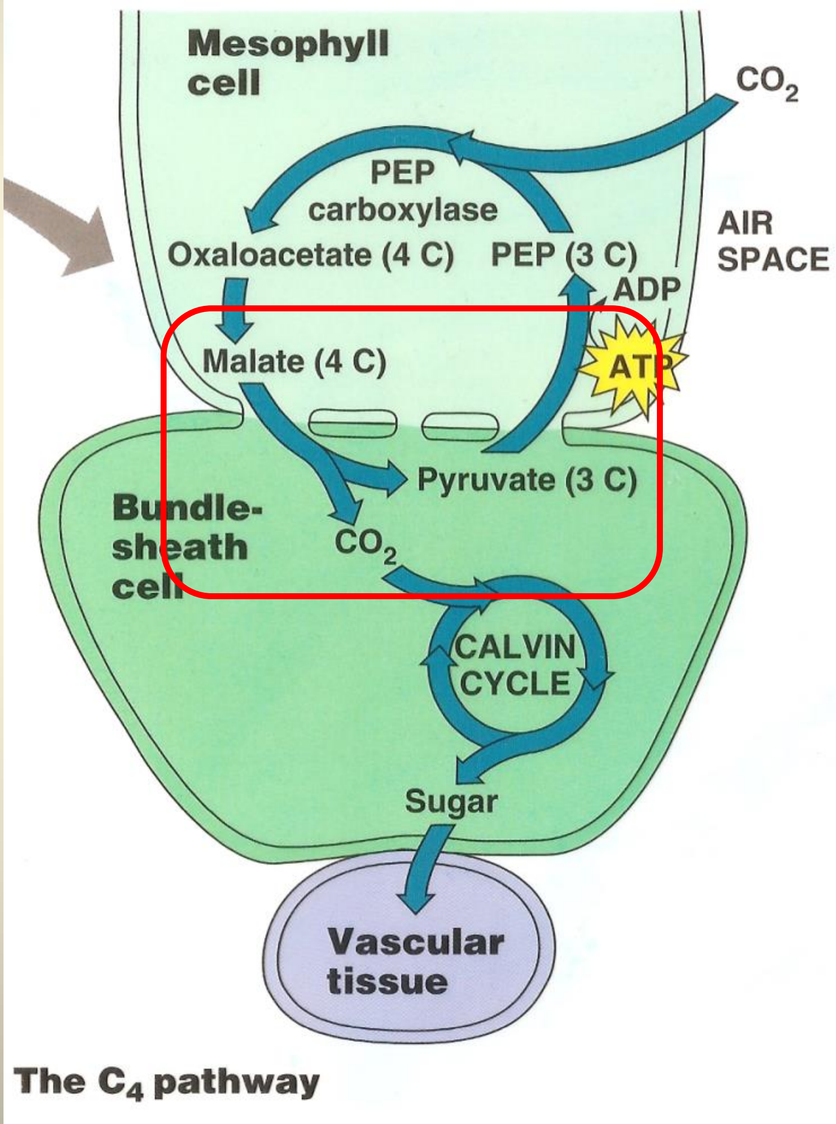


The C_4 pathway

C_4 Plant Adaptation

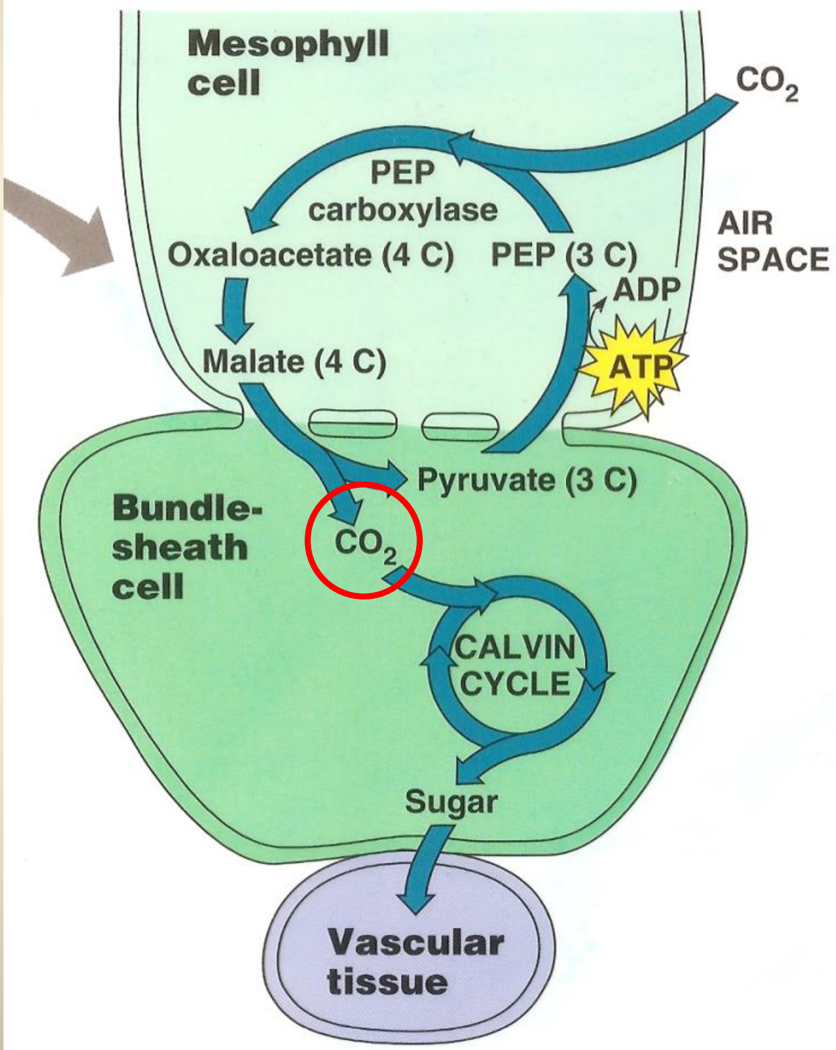
Mechanism:

- Step 2: 4C compound is exported to bundle-sheath cells where it releases CO2 and a 3C pyruvate
- Step 3a: CO2 is assimilated into the Calvin cycle by rubisco
- Step 3b: Pyruvate returns to the mesophyll cell to be converted back to PEP (3C)



C_4 Plant Adaptation

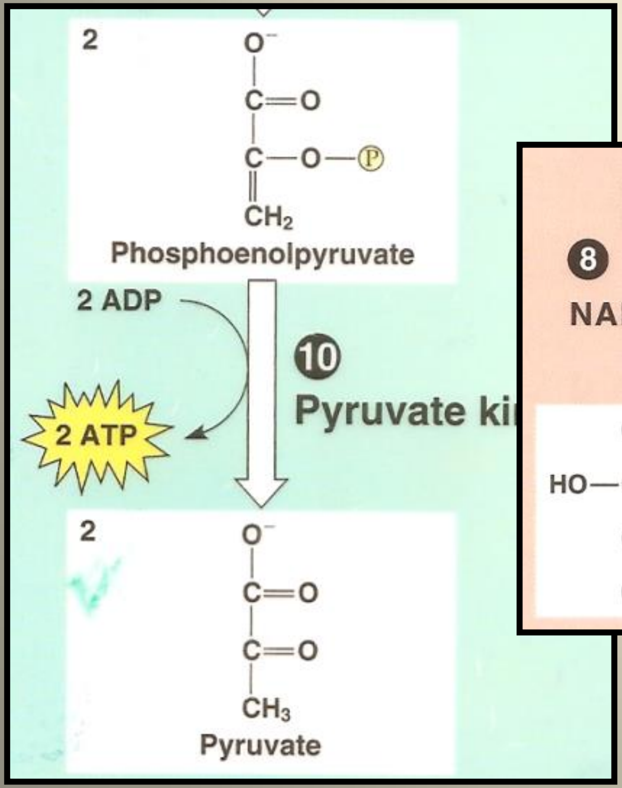
- Mesophyll cells act as a CO_2 pump
- Keeps concentration of CO_2 in bundle-sheath cells high (10-120x higher than normal) so that rubisco can bind CO_2
- But adaptation costs energy

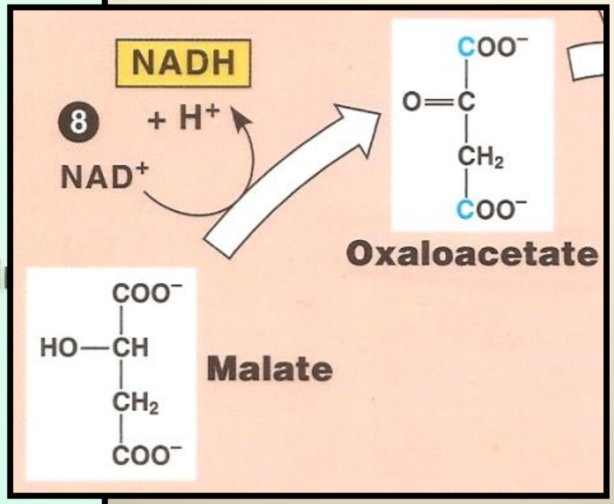


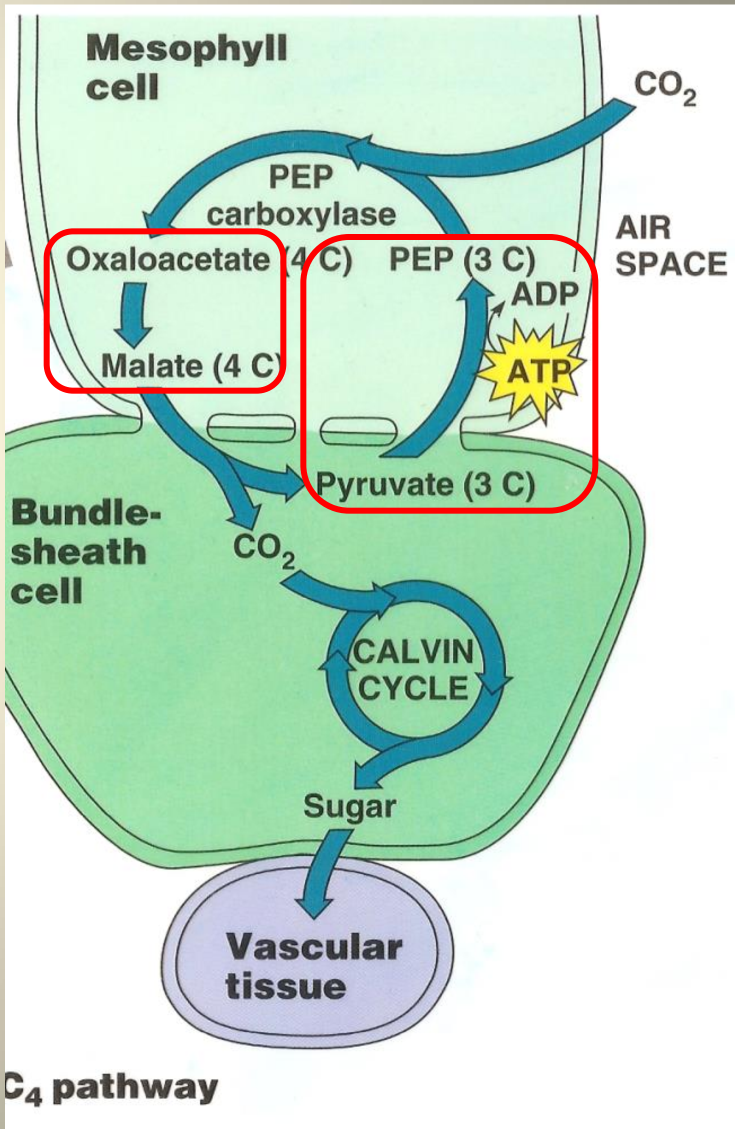
The C_4 pathway

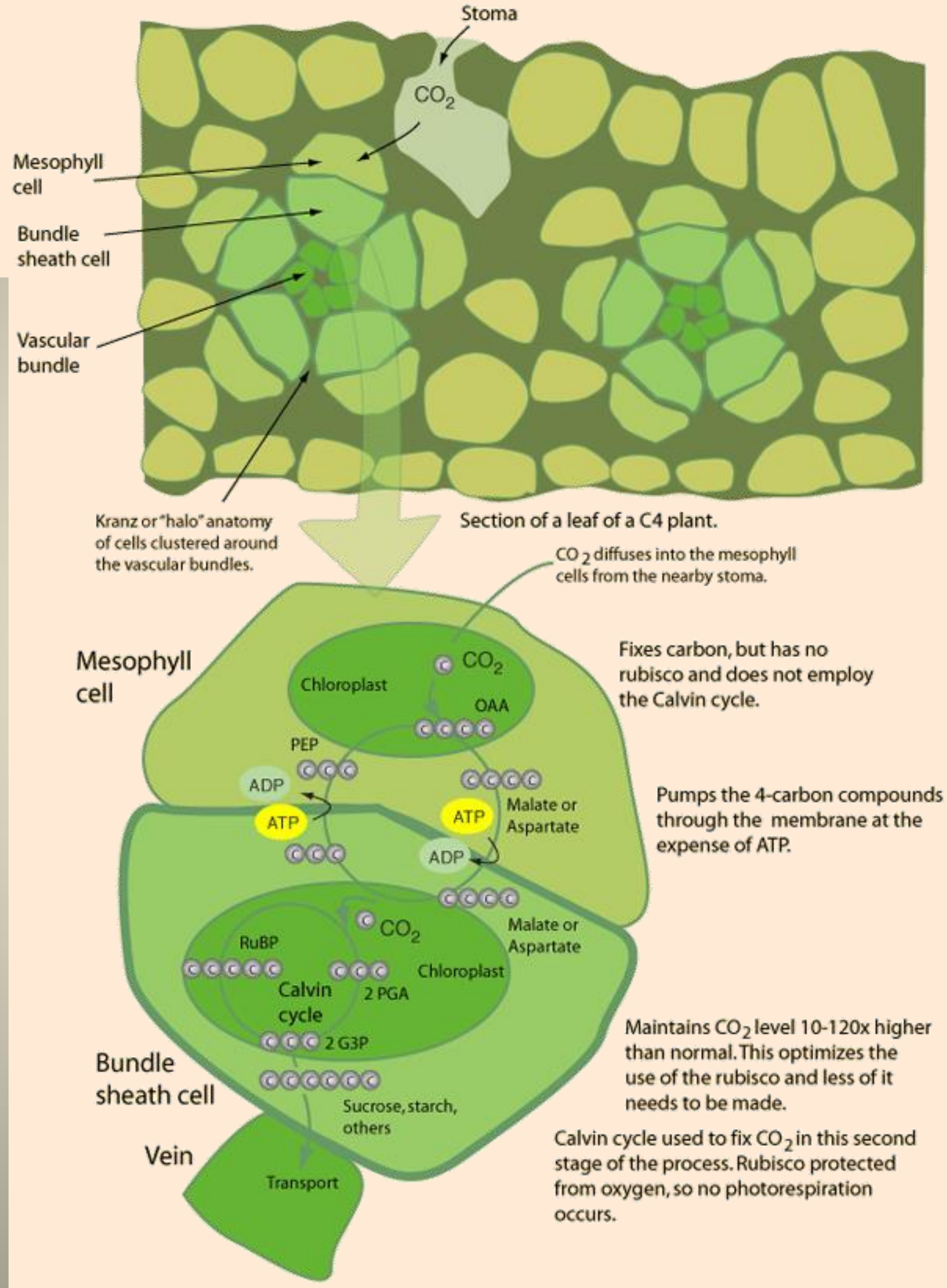
C_4 Plant Adaptation

- Can you identify where the reactions (below) come from?
- Hint: cellular respiration



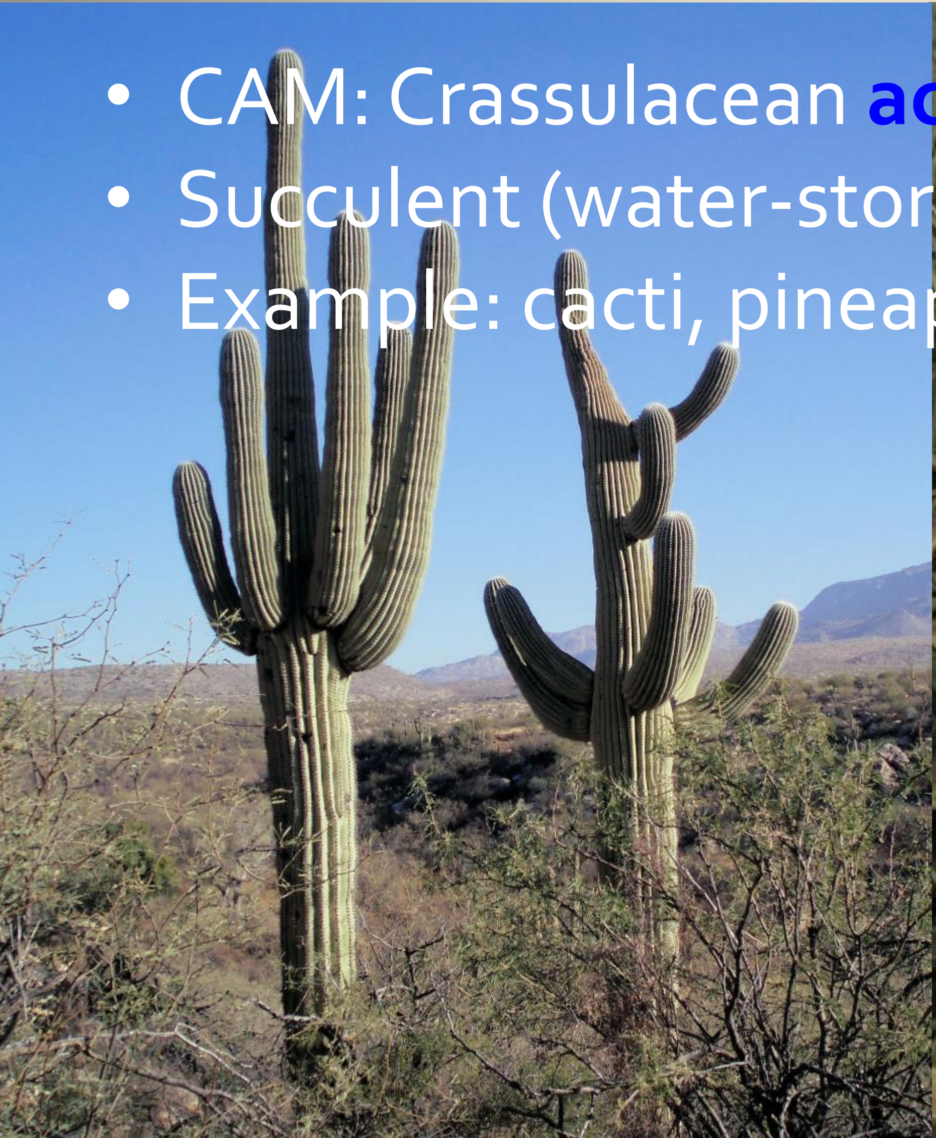





Stoma
CO_2
Mesophyll cell
Bundle sheath cell
Vascular bundle
Kranz or "halo" anatomy of cells clustered around the vascular bundles.
Section of a leaf of a C4 plant.
CO_2 diffuses into the mesophyll cells from the nearby stoma.
Mesophyll cell
Chloroplast
CO_2
OAA
PEP
ADP
ATP
Malate or Aspartate
ATP
ADP
Fixes carbon, but has no rubisco and does not employ the Calvin cycle.
Pumps the 4-carbon compounds through the membrane at the expense of ATP.
Malate or Aspartate
CO_2
RuBP
Calvin cycle
2 PGA
Chloroplast
2 G3P
Bundle sheath cell
Sucrose, starch, others
Vein
Transport
Maintains CO_2 level 10-120x higher than normal. This optimizes the use of the rubisco and less of it needs to be made.
Calvin cycle used to fix CO_2 in this second stage of the process. Rubisco protected from oxygen, so no photorespiration occurs.

CAM Plants

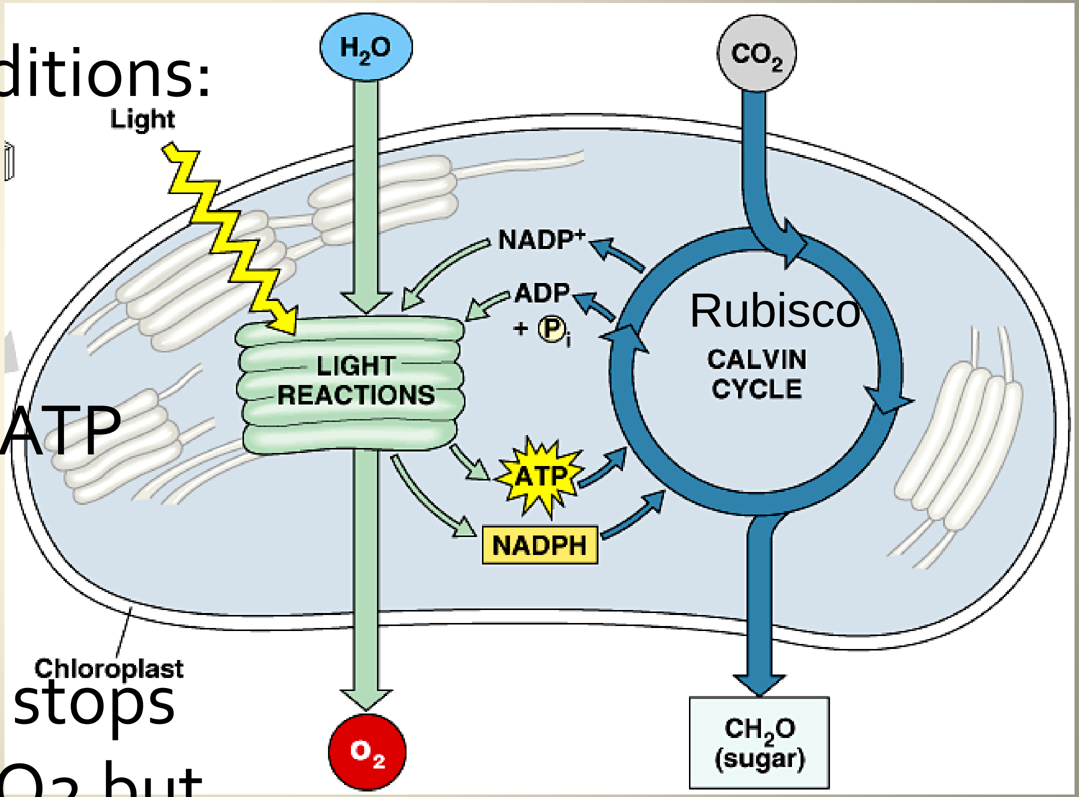
- CAM: Crassulacean **acid** metabolism
- Succulent (water-storing) plants
- Example: cacti, pineapples



CAM Plant Adaptation

Daytime in hot arid conditions:

- Stomata closed
- Conserve water
- no CO_2 uptake
- Light reactions make ATP and NADPH and O_2

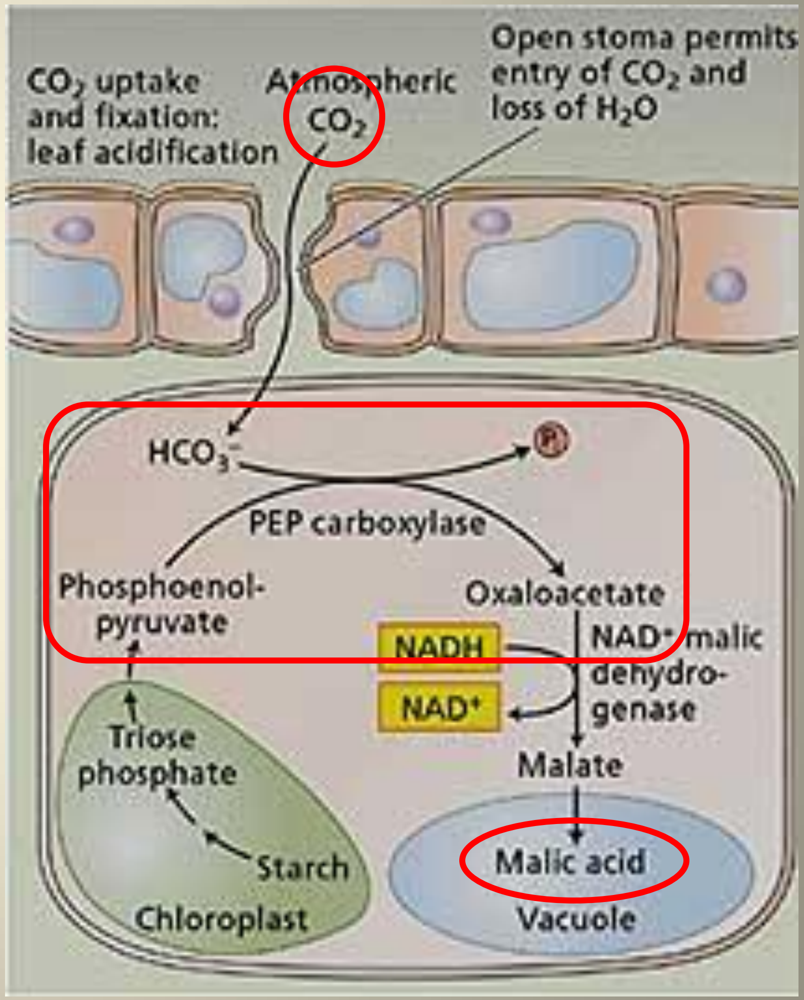


- Normally Calvin cycle stops due to low CO_2, high O_2 but in CAM…

CAM Plant Adaptation

Nighttime:

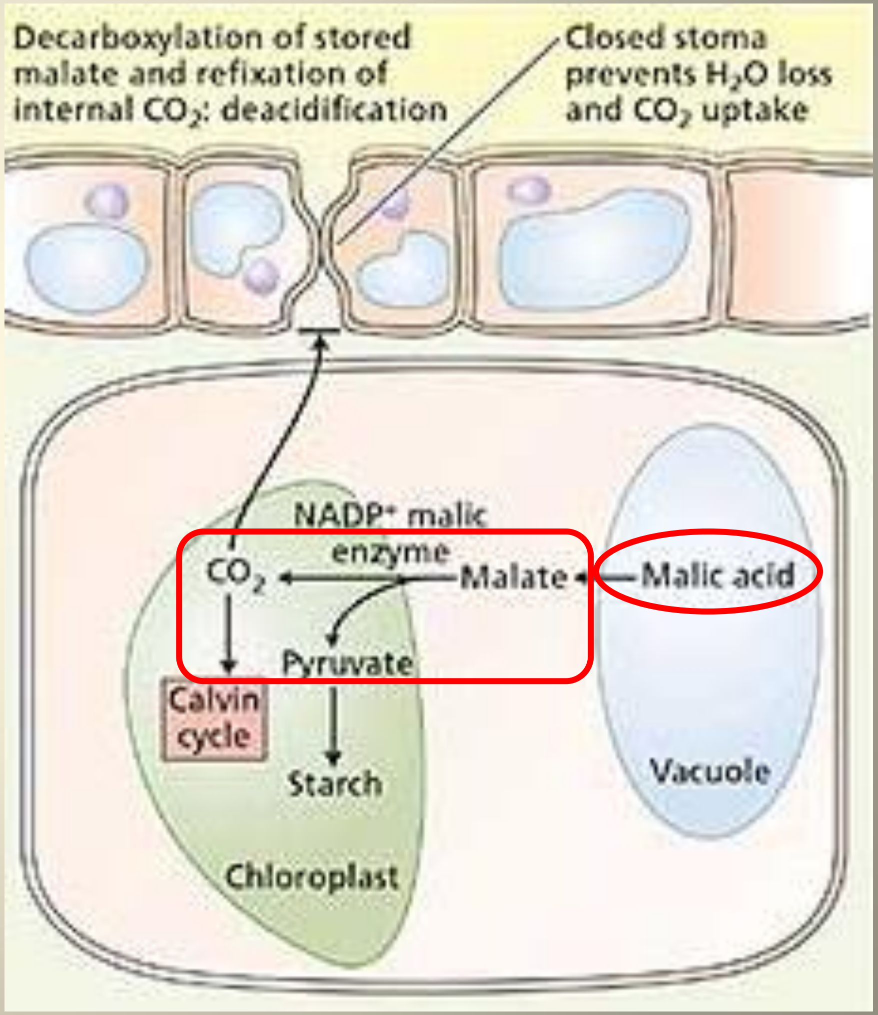
- Cooler
- Stomata open
- CO_2 enter
- Enzyme PEP carboxylase:
  - Recall: high affinity for CO_2
  - CO_2 + PEP (3C) → OAA (4C)
- Further converted to an organic **acid** (malate / malic acid) which is stored in vacuoles of mesophyll cells



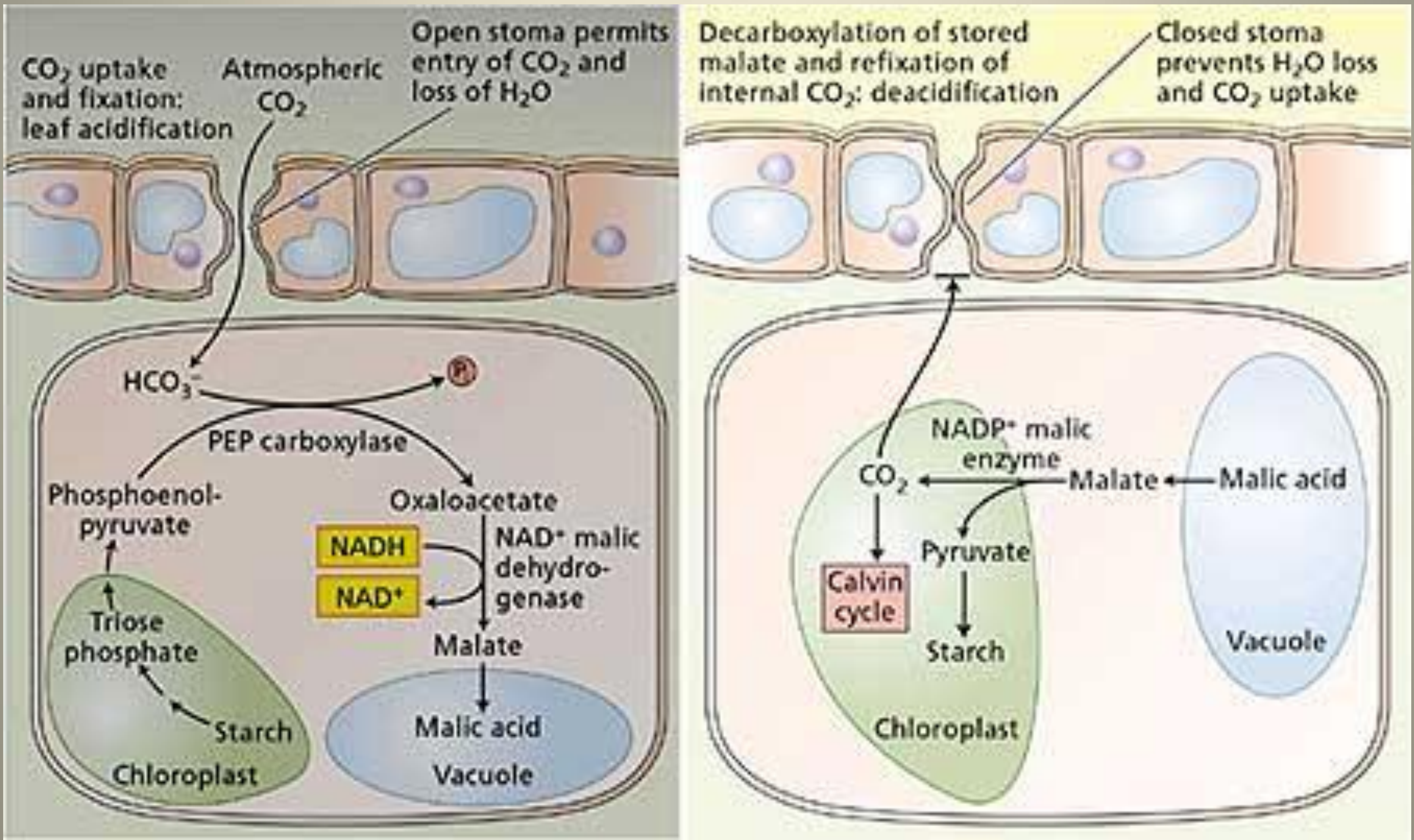
CAM Plant Adaptation

Daytime:

- CO_2 in malic acid stored in vacuoles from the night is released to run the Calvin cycle
  - Malate (4C) → pyruvate (3C) + CO_2
- Light reactions also occurring so the ATP & NADPH made will help run the Calvin cycle

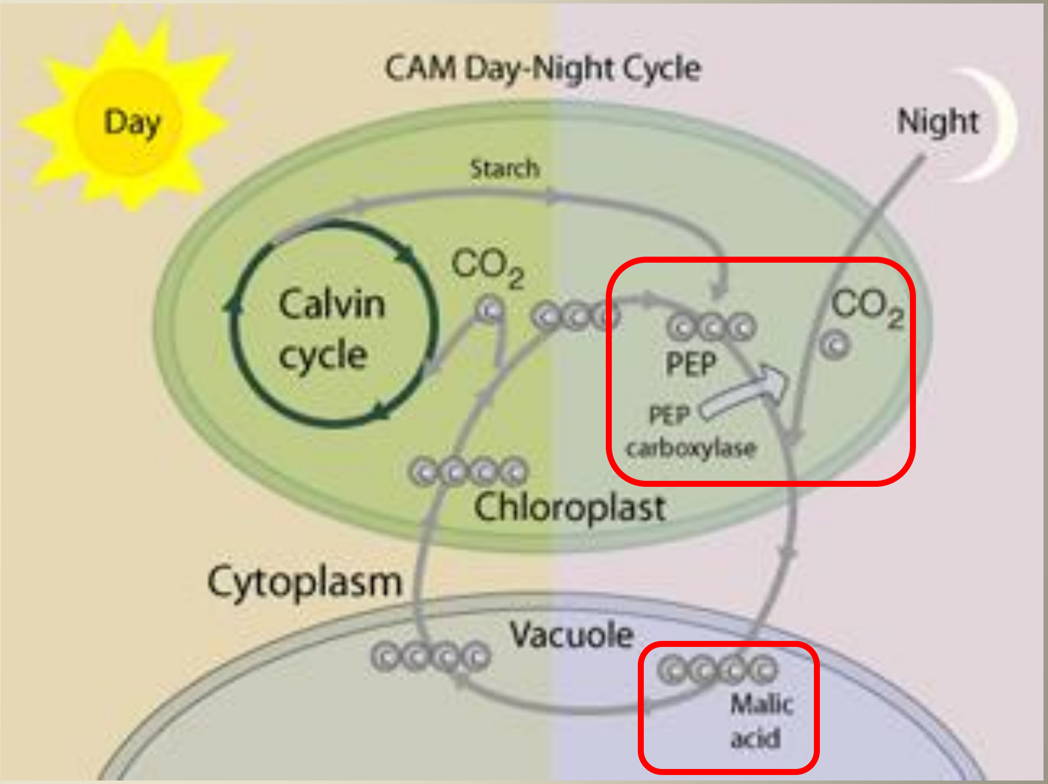


CAM Plant Adaptation



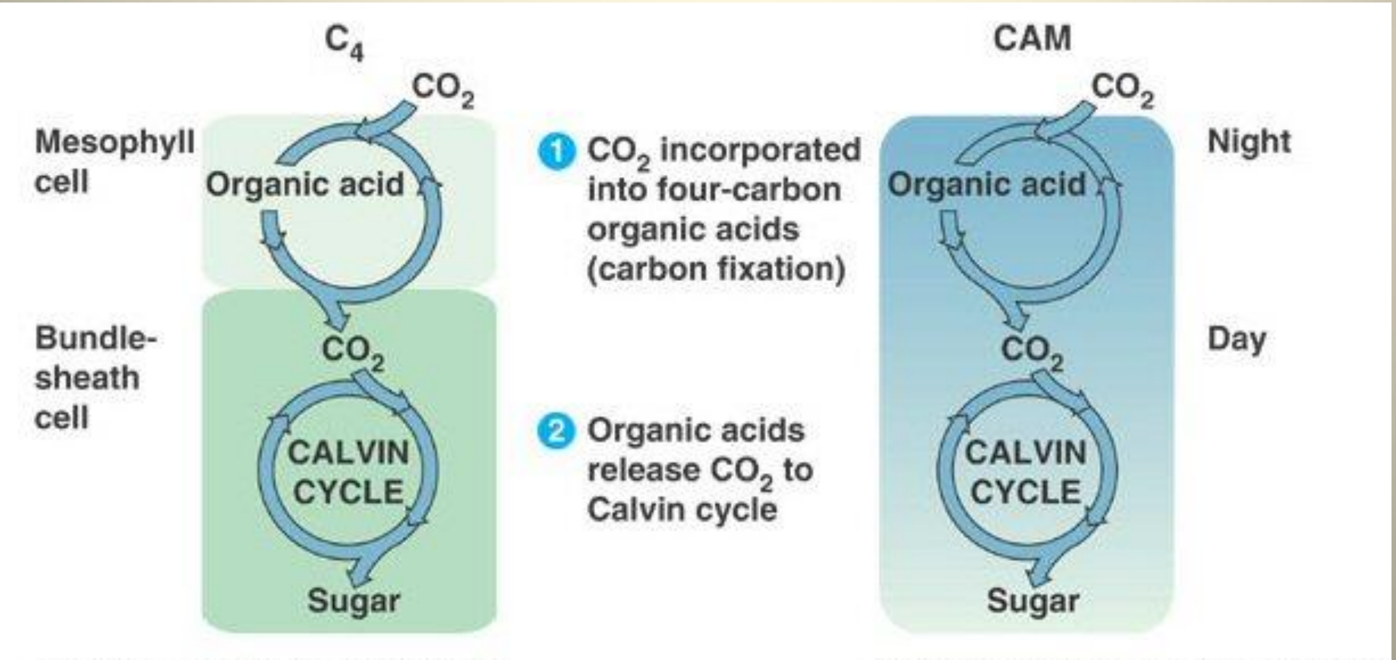
CAM Plant Adaptation

- Nighttime: CO_2 incorporation into organic acids, stored in vacuole
- Daytime: Calvin cycle with energy from light reaction and CO_2 from night storage



C4 and CAM Plants

- CO2 is incorporated into organic intermediates which is then released into the Calvin cycle generating an environment that is high in CO2 so that Rubisco isn't binding O2
- C4: initial carbon fixation separated structurally
- CAM: initial carbon fixation separated temporally



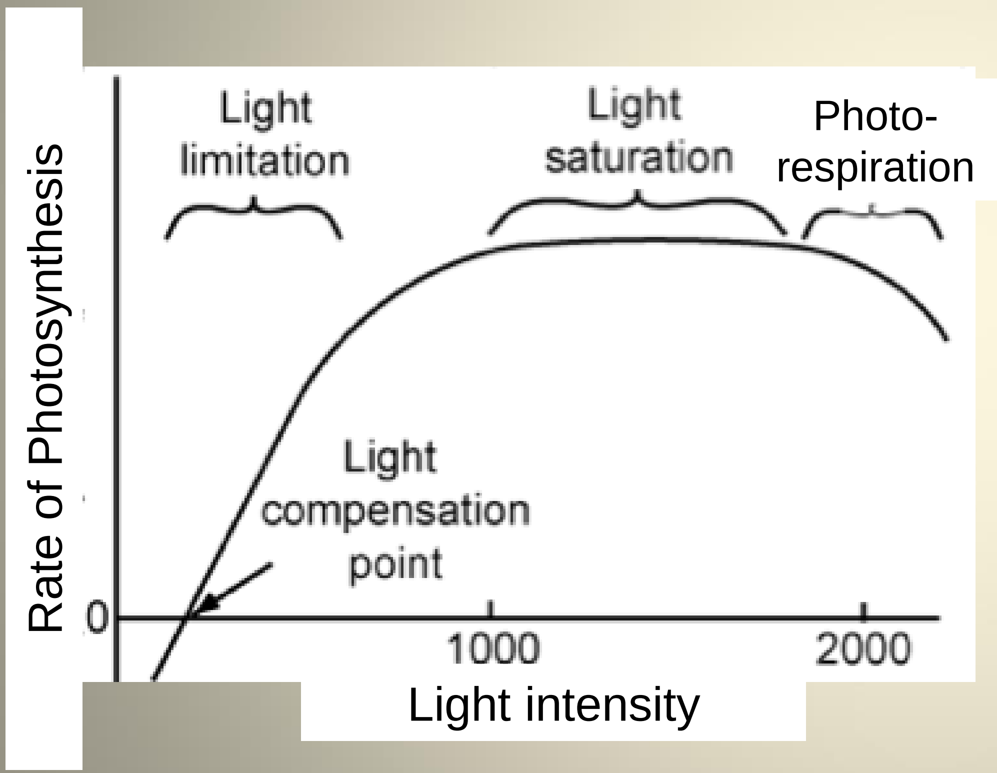
(a) Spatial separation of steps

(b) Temporal separation of steps

Factors Affecting Photosynthesis

- Light intensity
- Carbon dioxide concentration
- Temperature

Light Intensity



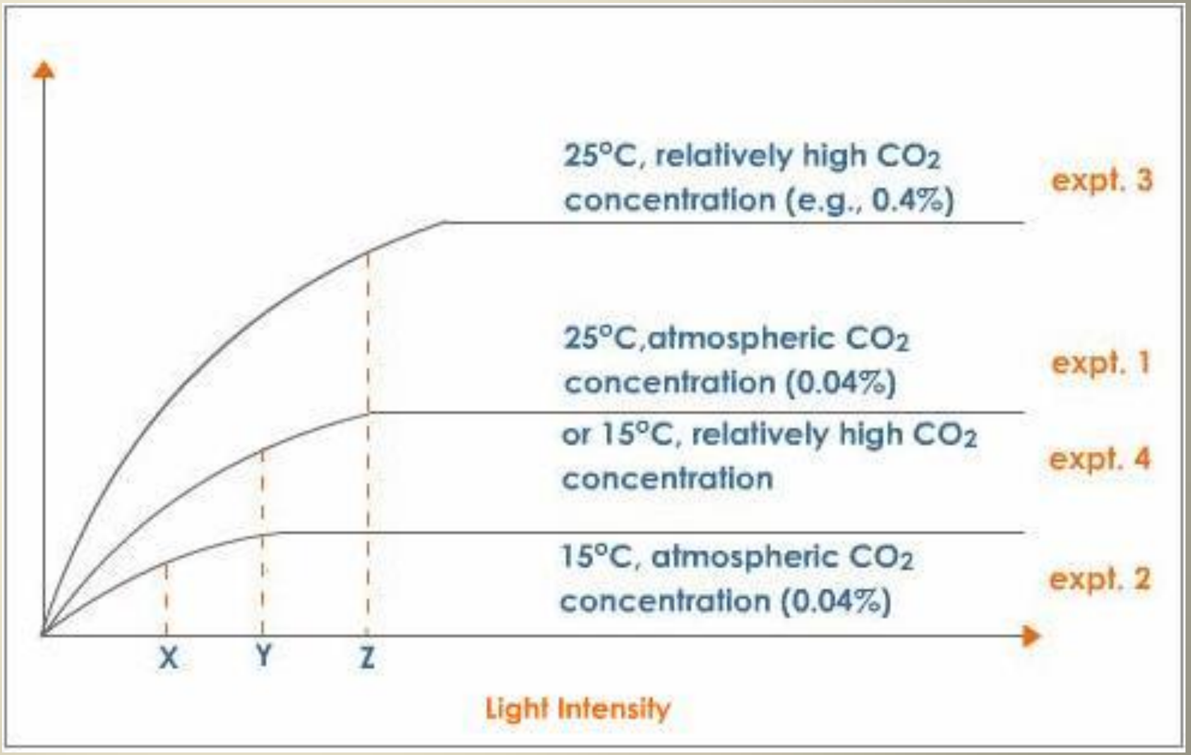
- Low-mid intensity: linear response
- Higher intensity: saturation due to other limiting factors in photosynthesis
- Highest intensity: photorespiration
- light compensation point: minimum light intensity at which the leaf shows a net gain of carbon

http://www2.geog.ucl.ac.uk/~plewis/geogg124/_images/chapin1.png

Light Intensity

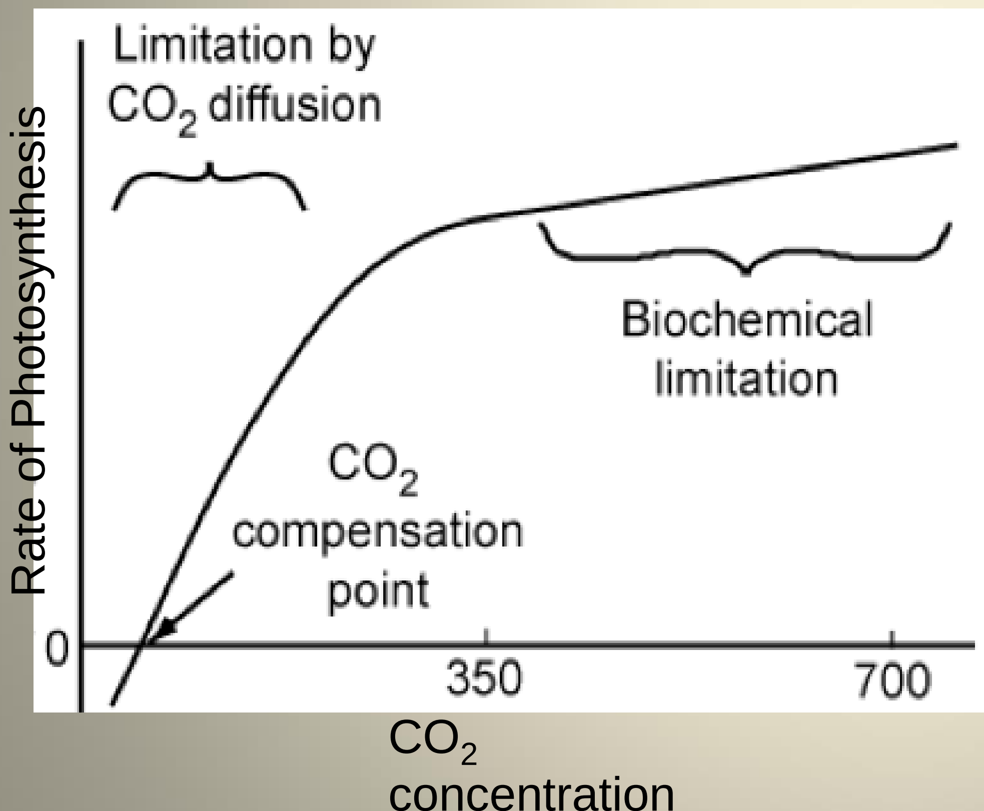
factors contributing to saturation

- Rate at which photosynthesis is saturated is increased with temperature and CO_2 levels



http://image.tutorvista.com/content/nutrition/light-intensity.jpeg

CO_2 Concentrations



- Low concentration: CO_2 diffusion limits rate
- High concentration: saturation due to other limiting factors in photosynthesis

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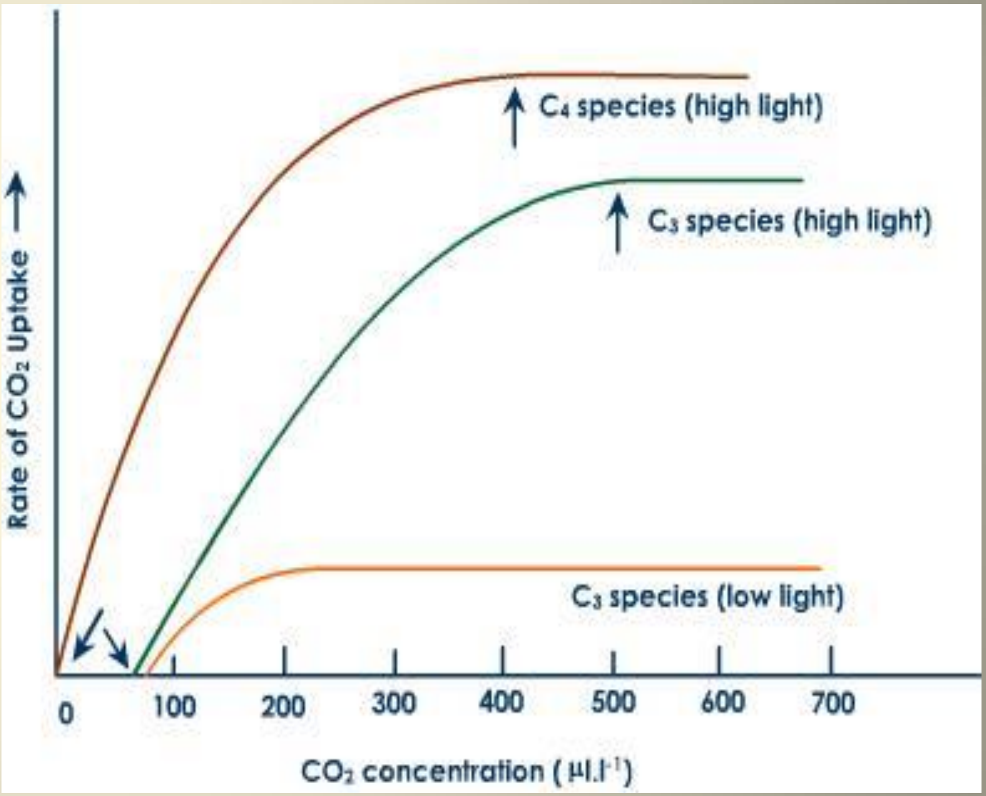
CO_2 Concentrations

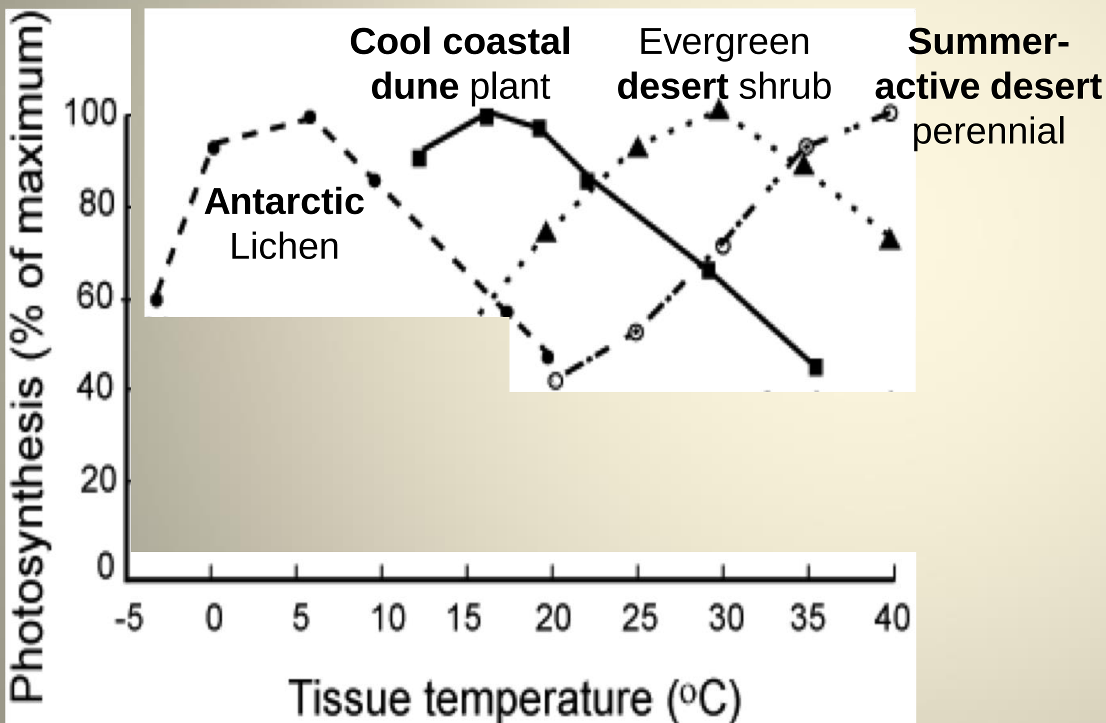
factors contributing to saturation

- Rate at which photosynthesis is saturated is increased with light intensity



http://images.tutorvista.com/content/photosynthesis/carbondioxide-concentration-c3-c4-species.jpeg

Temperature



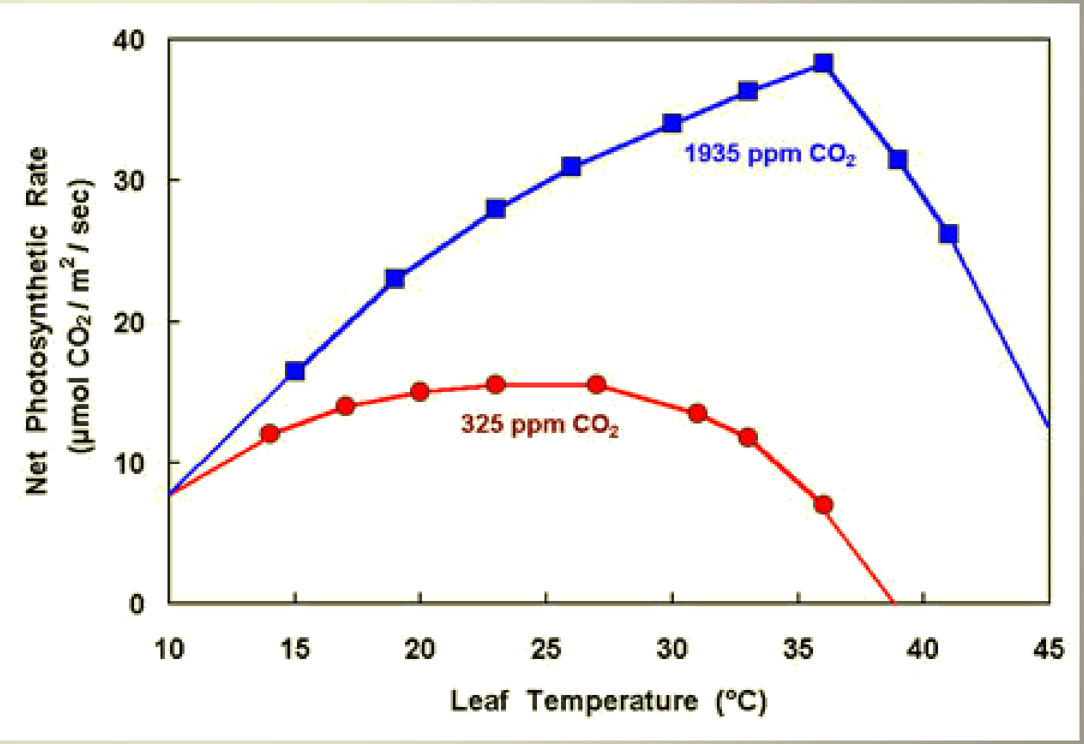
- Each type of plant has a temperature range where photosynthesis is optimal

http://www2.geog.ucl.ac.uk/~plewis/geogg124/_images/chapin6.png

Temperature

factors contributing to maximum rate of photosynthesis

- Increased CO2 levels increases the maximal rate of photosynthesis



http://www.co2science.org/education/reports/extinction/figures/fig1.jpg

Photosynthesis Rate Factors

Factor	Effect on	Rate of photosynthesis
Light intensity	Light reactions	Increase to a plateau (saturation) since Calvin cycle cannot keep up with light reactions
CO_2 levels	Calvin cycle	Increase to a plateau since light reactions can not keep up with Calvin cycle
Temperature		Maximum rate can be increased by increasing CO_2