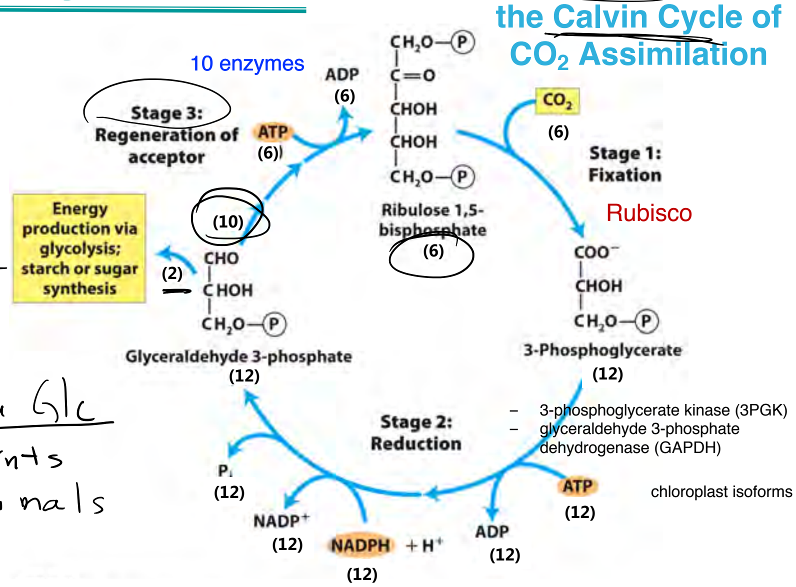
Photosynthesis

The Three Stages of the Calvin Cycle of CO_2 Assimilation



1 Glc ←

Make Glc
- Plants
- Animals

*Ribulose 1,5-bisphosphate carboxylase/oxygenase (also RuBisCo)

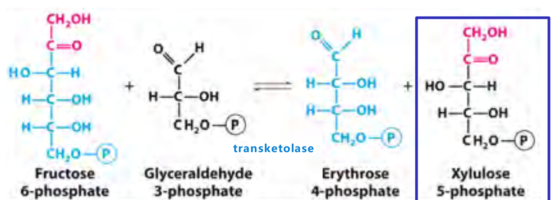
Photosynthesis

Third Stage of Calvin Cycle

Stage 3: Regeneration of Ru 1,5-P_2

10→use 6 GA3P

4 GA3P → 2 Fru 6-P



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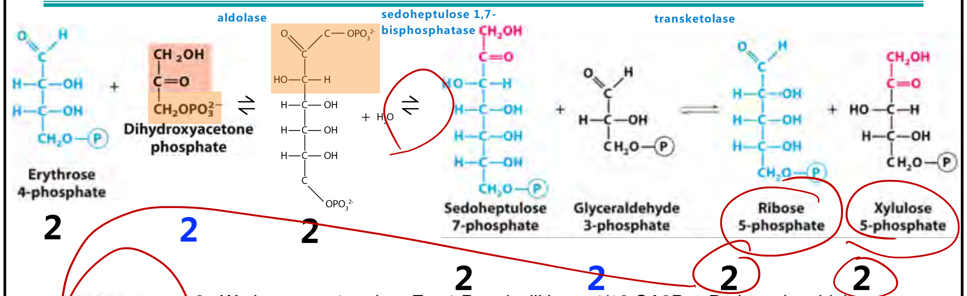
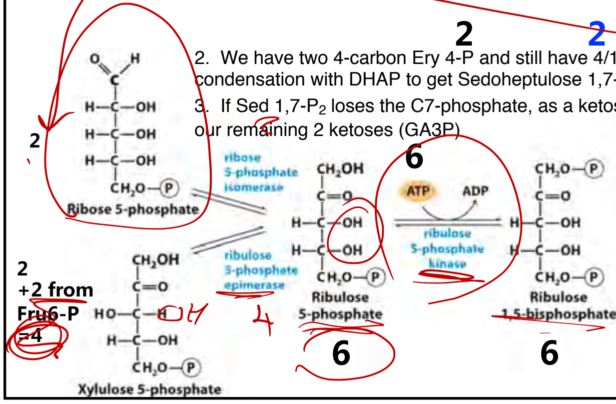
Stage 3 Photosynthesis



2. We have two 4-carbon Ery 4-P and still have 4/12 GA3Ps. Do it again; aldol condensation with DHAP to get Sedoheptulose 1,7-bisphosphate (Sed 1,7-P_2).

3. If Sed 1,7-P_2 loses the C7-phosphate, as a ketose, we can pull 2 carbons off and put on our remaining 2 ketoses (GA3P)



Sedoheptulose 1,7-bisphosphate dephosphorylated to sedoheptulose 7-phosphate (S7P) via *sedoheptulose 1,7-bisphosphatase*

- This enzyme is unique to plants.

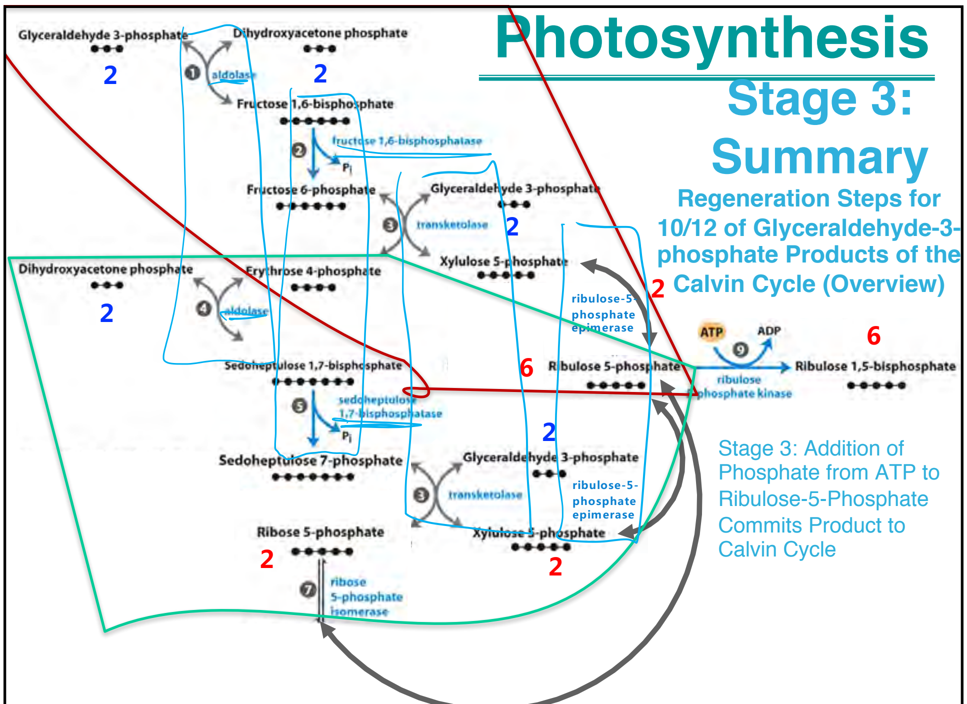
Finally, RuP phosphorylated to ribulose 1,5-bisphosphate by *phosphoribulokinase*

- This enzyme is also unique to plants and regulated by NADPH

Photosynthesis

Stage 3: Summary

Regeneration Steps for 10/12 of Glyceraldehyde-3-phosphate Products of the Calvin Cycle (Overview)



Stage 3: Addition of Phosphate from ATP to Ribulose-5-Phosphate Commits Product to Calvin Cycle

Photosynthesis

Stoichiometry and Energetics of CO_2 Assimilation in the Calvin Cycle & NET Reaction for Photosynthesis:

$6\ CO_2 + 12\ NADPH + 12\ H^+ + 12\ H_2O + 18\ ATP \rightarrow 1\ C_6H_{12}O_6 + 2\ H^+ + 12\ NADP^+ + 18\ ADP + 18\ P_i + 18\ H^+$

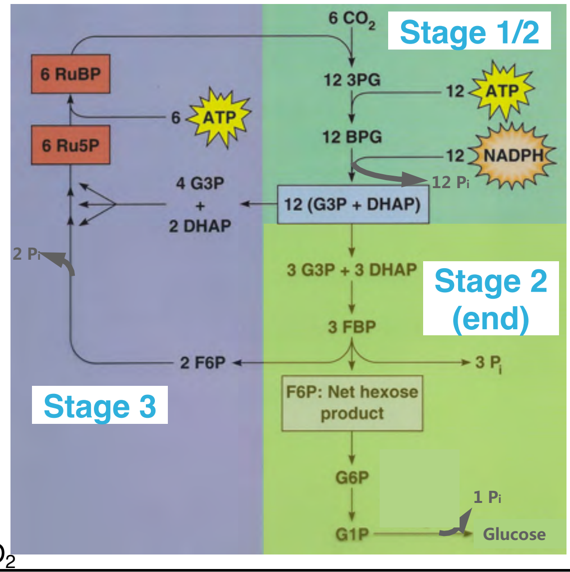
This is 3:2 ATP:NADPH! (from 8 photons)
For every NADPH, 4 photons needed
∴ need 12x4=48 photons to make 1 Glc

Stage 1/2
6Ru5P→12GA3P
$\Delta G^{\circ\prime}$ = –56 kcal/mol

Stage 2 (end)
2GA3P→1Glc
$\Delta G^{\circ\prime}$ = –10 kcal/mol

Stage 3
10GA3P→ 6Ru5P
$\Delta G^{\circ\prime}$ = –38 kJ/mol

NET: –104/6 = –17.3 per CO_2

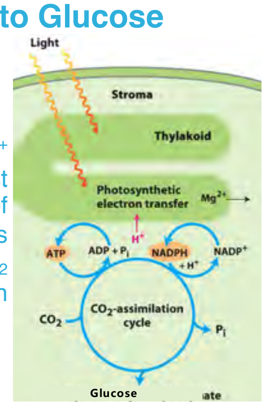


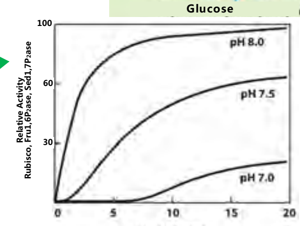
Photosynthesis

Photosynthesis: Control by Light and CO_2 to Glucose

- The assembly of one molecule of glucose requires the capture of roughly 48 photons.
  - H^+ move from the stroma to the thylakoid
  - creates alkaline conditions in the stroma
- Accompanied by Mg^{2+} transport from thylakoid to stroma
- Enzyme for photosynthesis and CO_2 assimilation more active in the alkaline & high [Mg^{2+}] conditions of the stroma
- This is a source of coordinated regulation by several enzymes:
  - Target enzymes regulated by NADPH, Mg^{2+}, and pH, or all three are:
    - Rubisco
    - fructose 1,6-bisphosphatase
    - seduloheptose 1,7-bisphosphatase
    - glyceraldehyde 3-phosphate dehydrogenase
    - ribulose 5-phosphate kinase (phosphoribulokinase)

How H^+ and Mg^{2+} Movement Assist in Activation of Photosynthesis and CO_2 Assimilation





How are these regulated by NADPH?

Photosynthesis

Photosynthesis: Control from Light and CO_2 to Glucose

Target enzymes regulated by Fd:NADPH:

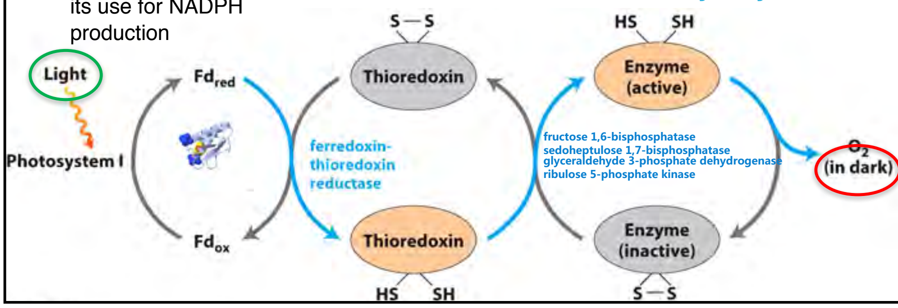
- fructose 1,6-bisphosphatase
- seduloheptose 1,7-bisphosphatase
- glyceraldehyde 3-phosphate dehydrogenase
- ribulose 5-phosphate kinase (phosphoribulokinase)
- Rubisco activase

If oxidized (Cys residues in Cys-Cys disulfide form) → enzymes are inactive.

In light, photosystem I sends e^- to *ferredoxin,* which sends them to **thioredoxin**, which donates them to disulfide bonds to reduce them to free Cys.

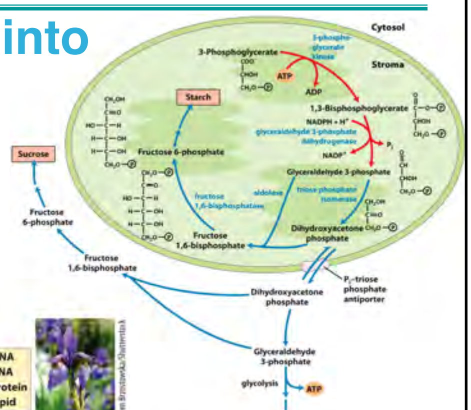
Excess reduced F_d is only available after its use for NADPH production

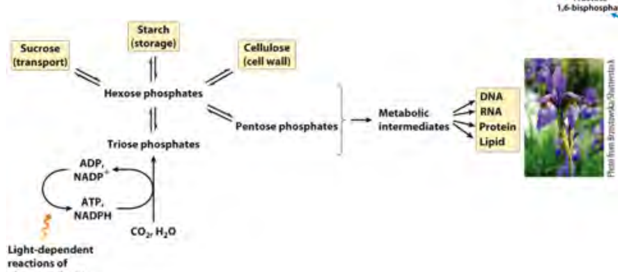
Light Activation of FOUR Calvin Cycle Enzymes via Electron-Driven Reduction of Cys-Cys Crosslinks



Photosynthesis

Assimilation of CO_2 into Biomass





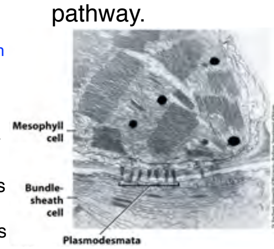
- Plant cells: use 3-C intermediates for further synthesis
  - Glyceraldehyde 3-phosphate (G3P) is the most important one.
  - made from CO_2, H_2O, plus ATP and NADPH from photosynthesis

Photosynthesis

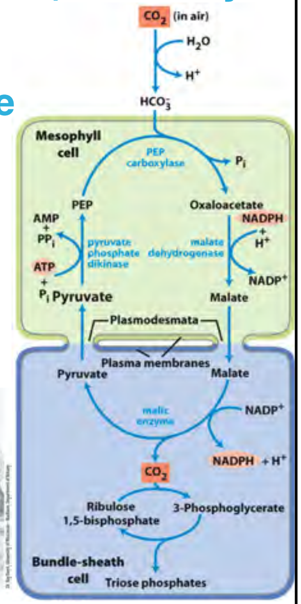
C_4 versus C_3 Plants; Benefits of C_4 Plants: Heat and Drought Resistance

- Most crop plants are C_3 (fix CO_2 into **3-C** product).
  - for example: wheat, barley, potatoes
- *C_4 plants have an earlier step (before rubisco).*
  - bypass the C-3 fixation step by fix CO_2 into a **4-C** compound (oxaloacetate)
  - have high growth rate in hotter climates, low water loss, special leaves
    - for example: sugar cane, corn/maize
- Physical separation of reactions:
  - CO_2 is captured into ***oxaloacetate*** in mesophyll cells of the leaf.
  - Oxaloacetate then passes into bundle-sheath cells where CO_2 is released for Rubisco
- The C_4 pathway has a higher energy cost, but also has increased efficiency in heat.
  - As temperature increases, rubisco affinity for CO_2 decreases and more photorespiration
- Another pathway to avoid photorespiration was first discovered in *Crassulacae (**C**rassulacean **A**cid **M**etabolism (CAM))* in high, dry conditions
  - for example: pineapple, cacti
  - Stomata open during cooler and moister night for CO_2 absorption, C4 fixation; malate **stored in vacuoles.**
  - In daytime, stomata are closed, minimize loss of water vapor during heat of the day
  - Also, $[O_2]$ is low; only then malate releases CO_2 for CO_2 fixation by rubisco

C_4 plants spatially separate CO_2 fixation from rubisco activity, resulting in less reaction of rubisco with oxygen and avoidance of the costly glycolate pathway.

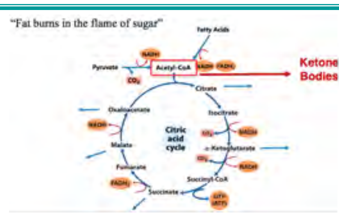


C_4 Pathway



Photosynthesis

Recall in animals:

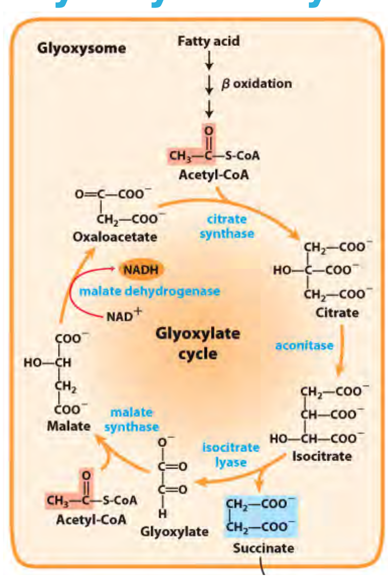


Kornberg Cycle

Plants Use Fats and Proteins for Carbohydrate Synthesis:

- Instead of burning isocitrate it short circuits TCA directly to succinate
- The result is the glyoxylate bi-product
- Re-cycle this by making malate from some more acetyl CoA in a similar reaction as citrate synthase

GlyOXylate Cycle



Photosynthesis: Carbon Fixation Summary

We learned that:

- ATP and NADPH from photosynthesis are needed in order to assimilate CO_2 into carbohydrates by Rubisco
- This key enzyme of the Calvin cycle fixes carbon dioxide as well as oxygen.
- assimilations of six CO_2 molecules via the Calvin cycle lead to the formation of one molecule of glucose for use in anabolic reactions
- enzymes of Calvin Cycle have common regulation mechanisms via pH, Mg^{2+}, and/or NADPH (F_d)
- low selectivity of rubisco causes a wasteful incorporation of molecular oxygen in C_3 plants. C_4 and CAM plants have evolved separate methods for reducing this waste.
- plants can convert acetyl-CoA into carbohydrates via the Kornberg Cycle (glyoxylate cycle)