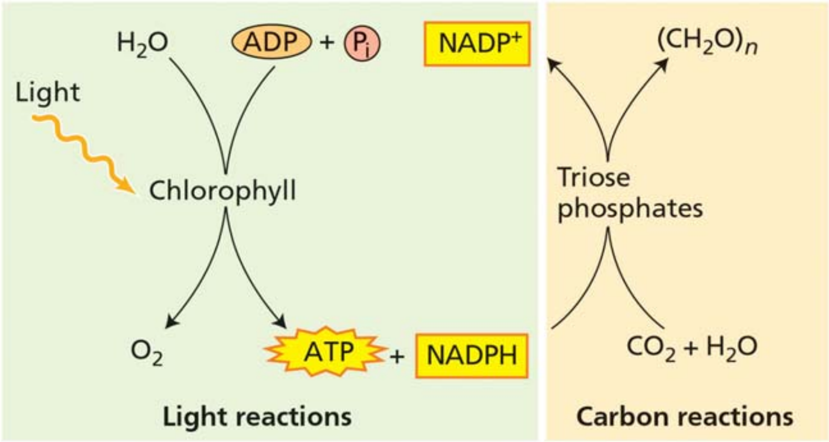
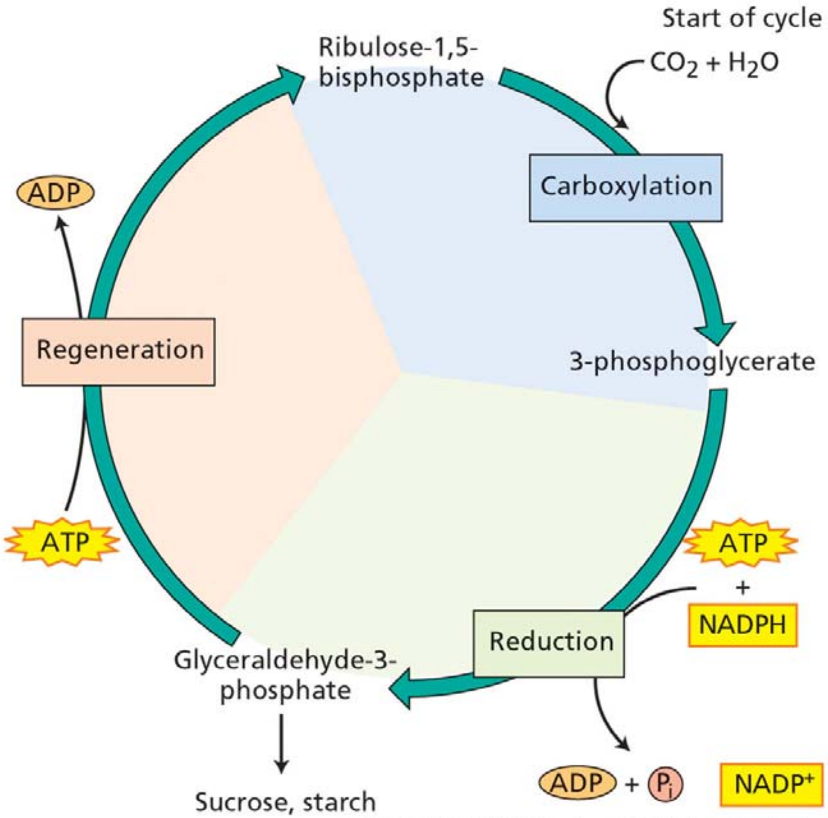
Photosynthesis- Photosynthetic carbon reduction (PCR)

- Overview
- Calvin-Benson cycle (C_3 pathway)
- Regulation
- Photorespiration
- C_4 Photosynthesis
- CAM photosynthesis



Overview

- Three stages:
- CO_2 reduced to triose phosphate
- Uses ATP and NADPH from light reactions
- Occurs in the stroma



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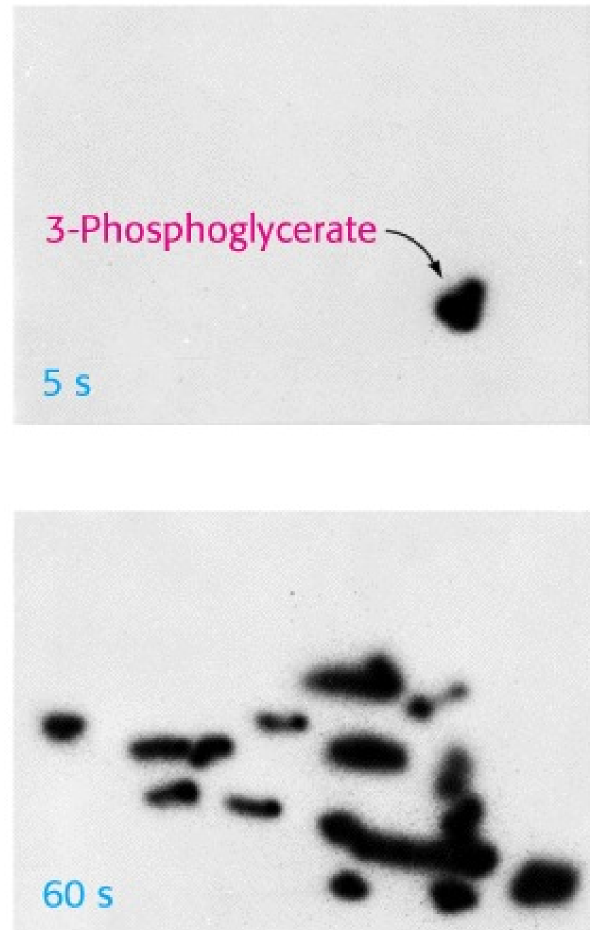
$$CO_2 + H_2O \xrightarrow[+light]{} (CH_2O) + O_2$$

- Light energy converted to chemical energy of ATP and NADPH
- CO_2 is reduced, water is oxidized
- $K_{eq} = 10^{-496}$

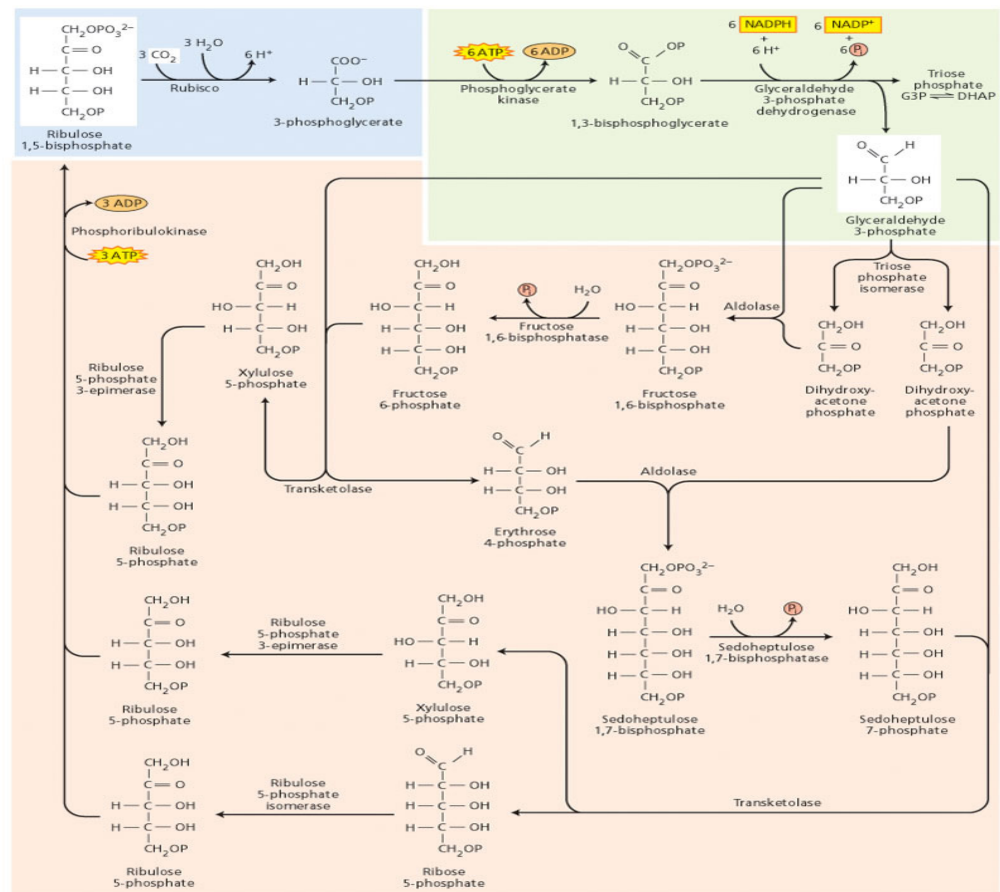
Calvin-Benson cycle (C_3 pathway)

- Discovery
- use of $^{14}CO_2$ and the green alga; Chlorella
- 2 sec exposure
- 1st product a C_3 acid
- Researchers found a 5 carbon acceptor molecule
- Ribulose 1,5-bisphosphate (RuBP)



Stages of Calvin-Benson cycle

- Three stages
- carboxylation
- reduction
- regeneration



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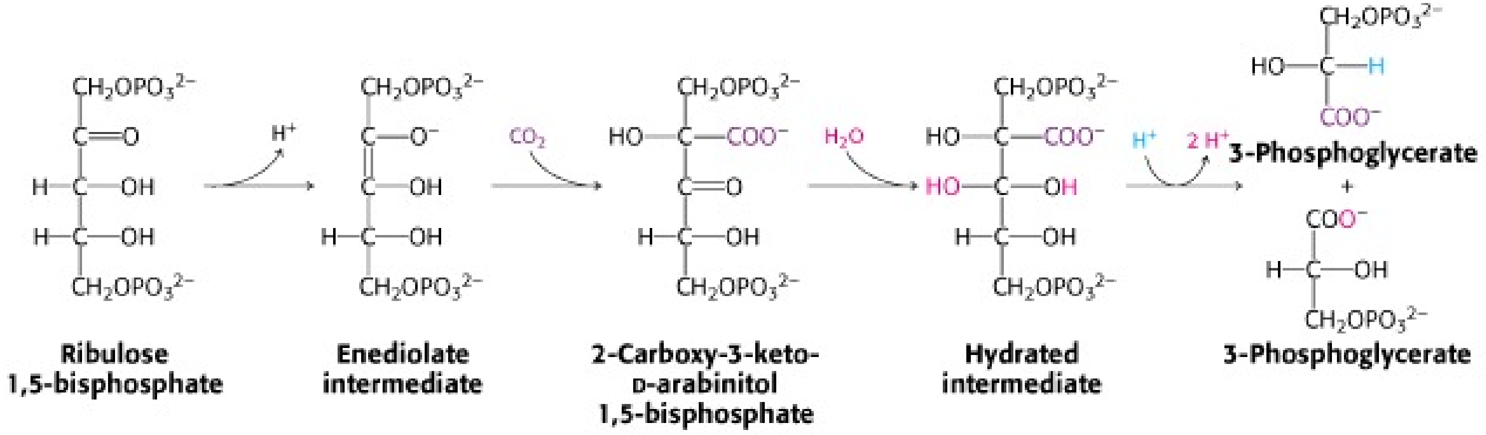
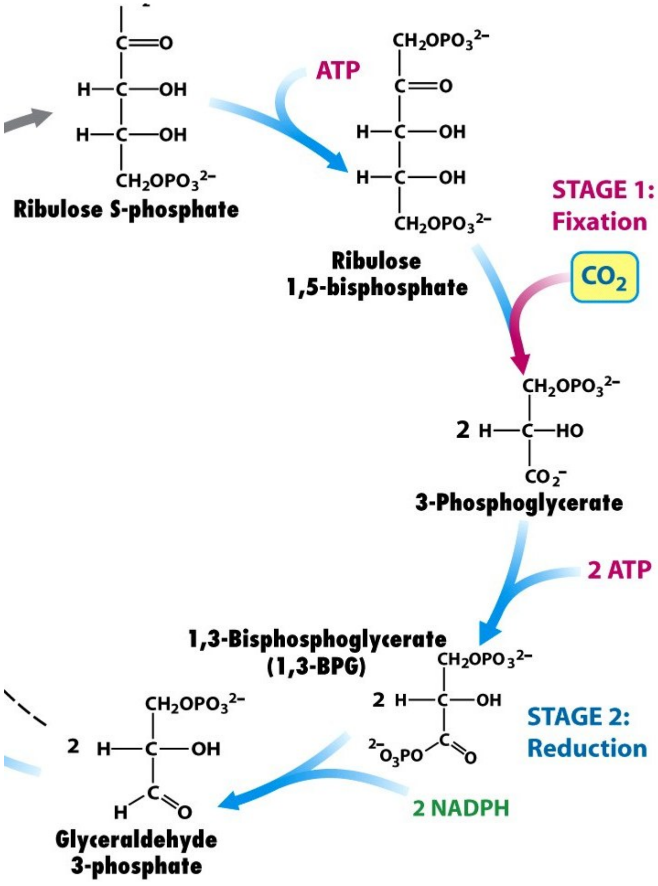
Carboxylation

- **Rubisco (large subunits= 55kd and small sub-unit 13kd), 30% of total leaf protein**
- **coded by chloroplast (lg) and nuclear (small) genes**
- **16 sub-units (8 lg/8small)**
- **spontaneous reaction no energy required, ΔG = -51.9 kJ/mol**
- **Maximal Catalytic rate = 3/s**
- **Km (CO_2)= 12 um**
- **forms 2 (3-PGA)**



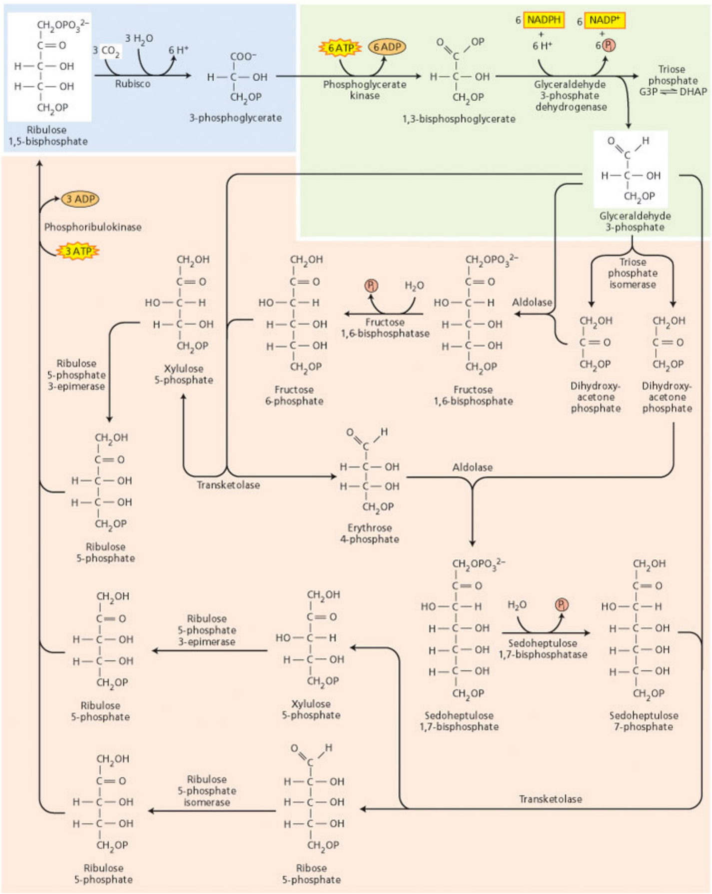
Reduction

- Two steps
- Requires 2 ATP & NADPH
- Forms triose phosphate



Stage 3: Regeneration

- reforms RuBP
- requires 1 ATP
- Overall: 3 ATP/2 NADPH



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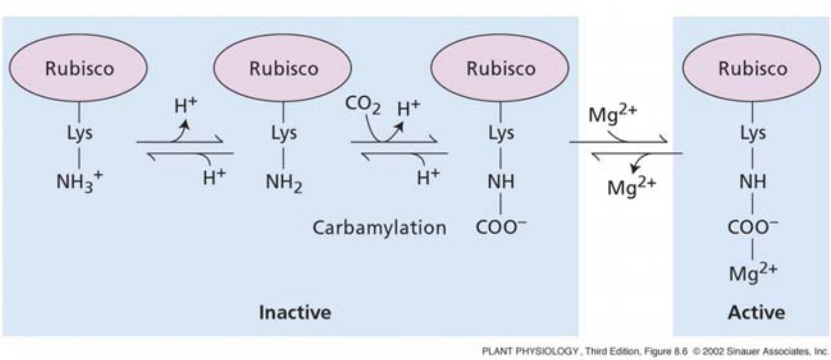
Summary

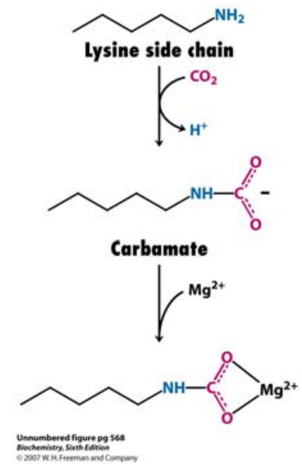
TABLE 8.1
Reactions of the Calvin cycle (Part 1)

Enzyme	Reaction
1. Ribulose-1,5-bisphosphate carboxylase/oxygenase	6 Ribulose-1,5-bisphosphate + 6 CO_2 + 6 H_2O → 12 (3-phosphoglycerate) + 12 H^+
2. 3-Phosphoglycerate kinase	12 (3-Phosphoglycerate) + 12 ATP → 12 (1,3-bisphosphoglycerate) + 12 ADP
3. NADP:glyceraldehyde-3-phosphate dehydrogenase	12 (1,3-Bisphosphoglycerate) + 12 NADPH + 12 H^+ → 12 glyceraldehye-3-phosphate + 12 $NADP^+$ + 12 P_i
4. Triose phosphate isomerase	5 Glyceraldehyde-3-phosphate → 5 dihydroxyacetone-3-phosphate
5. Aldolase	3 Glyceraldehyde-3-phosphate + 3 dihydroxyacetone-3-phosphate → 3 fructose-1,6-bisphosphate
6. Fructose-1,6-bisphosphatase	3 Fructose-1,6-bisphosphate + 3 H_2O → 3 fructose-6-phosphate + 3 P_i
7. Transketolase	2 Fructose-6-phosphate + 2 glyceraldehyde-3-phosphate → 2 erythrose-4-phosphate + 2 xylulose-5-phosphate

Note: P_i stands for inorganic phosphate.

Regulation of Calvin Cycle





- **Rubisco**
- **light activates electron transport**
- **pH stroma goes up from 7 → 8**
- **Mg^{2+} increases in stroma**
- **NADPH allosteric activator**
- **Rubisco Activase catalyzes carbamate formation**
  - **CO_2 required**

Regeneration Enzymes

- Light activated through PS I
- Ferrodoxin-Thioredoxin
- Gly 3-P dehydrogenase
- FBPase
- Sedoheptulose 1,7 Bis phosphotase
- Ribulose 5-P kinase

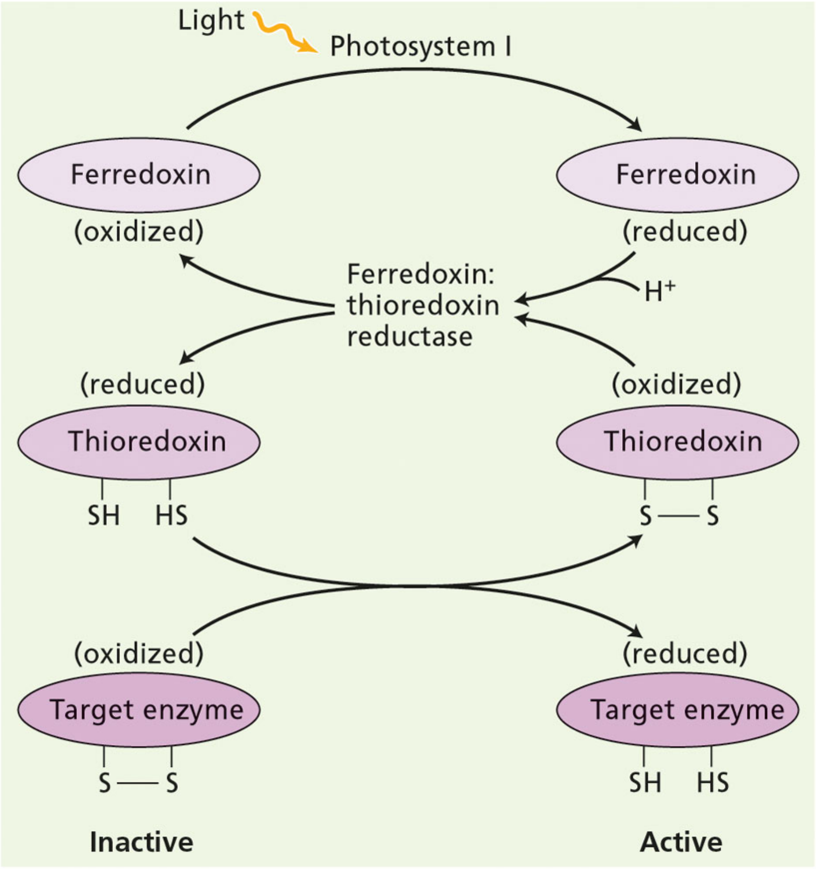
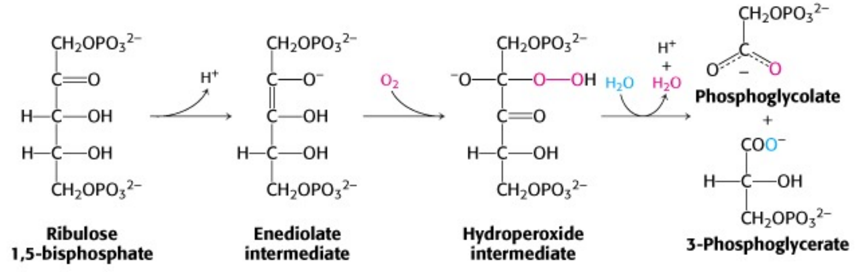


TABLE 20.1 Enzymes regulated by thioredoxin

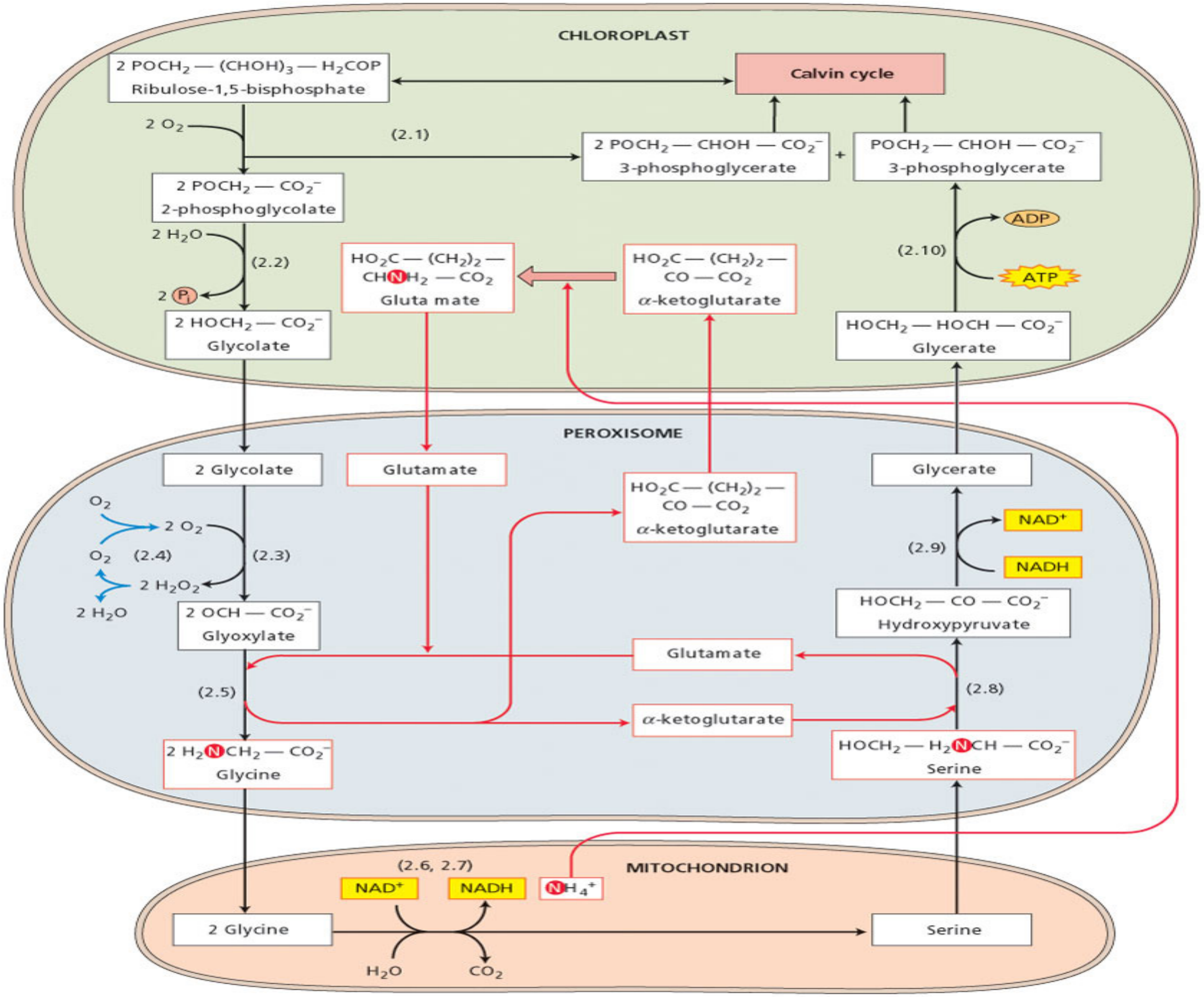
Enzyme	Pathway
Rubisco	Carbon fixation in the Calvin cycle
Fructose 1,6-bisphosphatase	Gluconeogenesis
Glyceraldehyde 3-phosphate dehydrogenase	Calvin cycle, gluconeogenesis, glycolysis
Sedoheptulose bisphosphatase	Calvin cycle
Glucose 6-phosphate dehydrogenase	Pentose phosphate pathway
Phenylalanine ammonia lyase	Lignin synthesis
Ribulose 5′-phosphate kinase	Calvin cycle
$NADP^+$-malate dehydrogenase	C_4 pathway

Photorespiration

- React w/O_2
- Km (O_2) = 250 um
- Atmosphere = 21% O_2
- CO_2 limiting conditions: such as drought, high temperatures
- Three organelles
- chloroplast
- mitochondria
- peroxisome
- loss of fixed CO_2



Photorespiration



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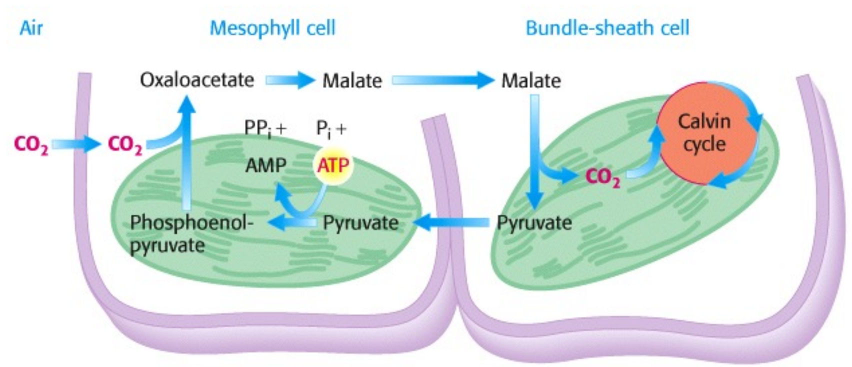
Adaptations to limited CO_2

- C_4 pathway: C_4 acid 1st product
- Discovered by Hatch and Slack in sugar cane
- Shuttle system
- PEP carboyxlase
- Increase CO_2 at site of Calvin cycle
- Under high light/high temperature conditions



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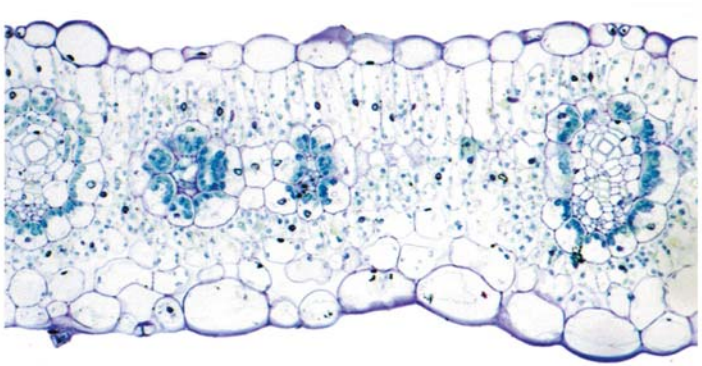

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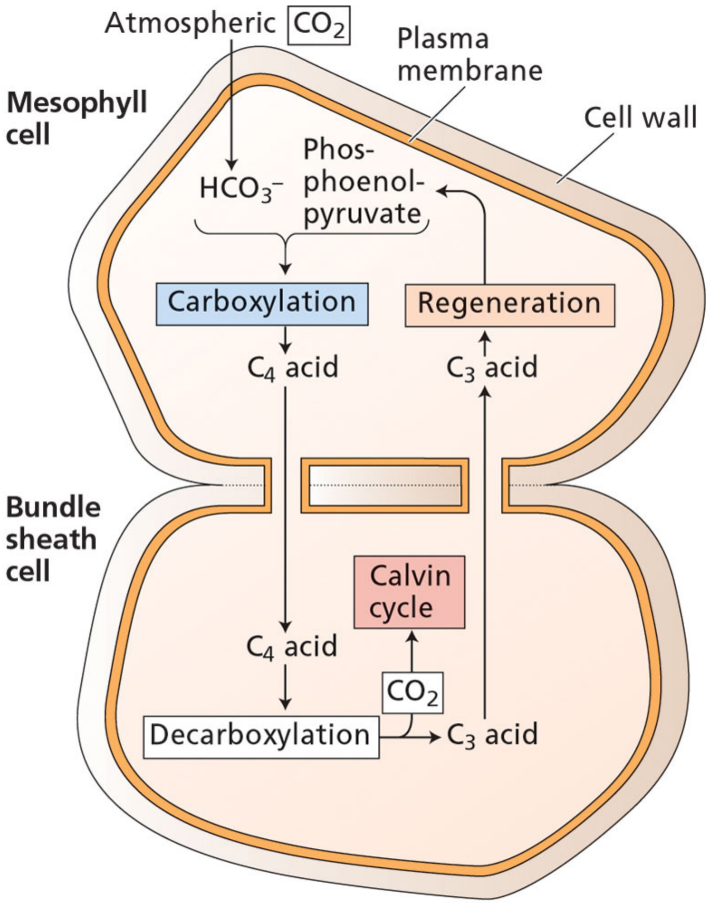
C_4 pathway



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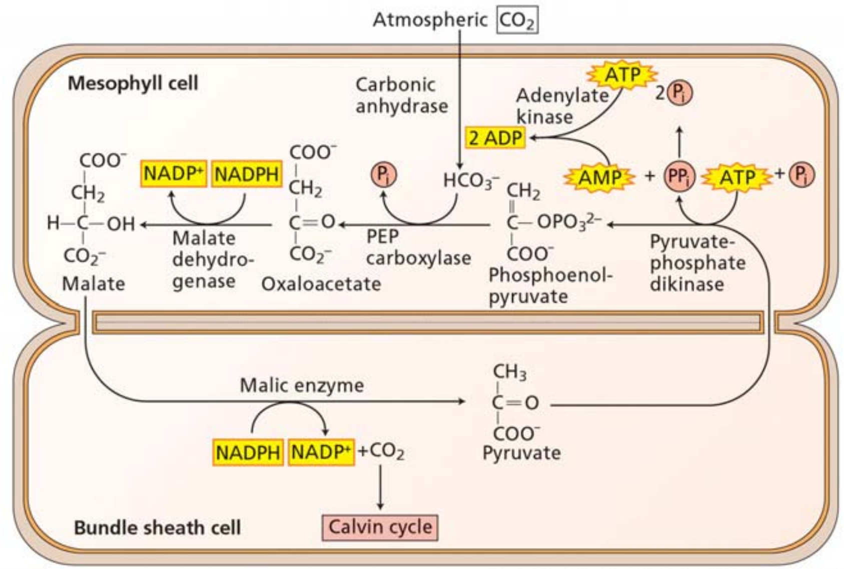

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Reactions

TABLE 8.3
Reactions of the C_4 photosynthetic carbon cycle

Enzyme	Reaction
1. Phosphoenolpyruvate (PEP) carboxylase	Phosphoenolpyruvate + HCO_3^- → oxaloacetate + P_i
2. NADP:malate dehydrogenase	Oxaloacetate + NADPH + H^+ → malate + $NADP^+$
3. Aspartate aminotransferase	Oxaloacetate + glutamate → aspartate + α-ketoglutarate
4. NAD(P) malic enzyme	Malate + $NAD(P)^+$ → pyruvate + CO_2 + NAD(P)H + H^+
5. Phosphoenolpyruvate carboxykinase	Oxaloacetate + ATP → phosphoenolpyruvate + CO_2 + ADP
6. Alanine aminotransferase	Pyruvate + glutamate ↔ alanine + α-ketoglutarate
7. Adenylate kinase	AMP + ATP → 2 ADP
8. Pyruvate–orthophosphate dikinase	Pyruvate + P_i + ATP → phosphoenolpyruvate + AMP + PP_i
9. Pyrophosphatase	PP_i + H_2O → 2 P_i

Note: P_i and PP_i stand for inorganic phosphate and pyrophosphate, respectively.

Energetics

TABLE 8.4
Energetics of the C_4 photosynthetic carbon cycle

Phosphoenolpyruvate + H_2O + NADPH + CO_2 (mesophyll)	→	malate + $NADP^+$ + P_i (mesophyll)
Malate + $NADP^+$	→	pyruvate + NADPH + CO_2 (bundle sheath)
Pyruvate + P_i+ ATP	→	phosphoenolpyruvate + AMP + PP_i (mesophyll)
PP_i + H_2O	→	2 P_i (mesophyll)
AMP + ATP	→	2ADP
Net: CO_2 (mesophyll) + ATP + 2 H_2O	→	CO_2 (bundle sheath) + 2ADP + 2 P_i
Cost of concentrating CO_2 within the bundle sheath cell = 2 ATP per CO_2		

Note: As shown in reaction 1 of Table 8.3, the H_2O and CO_2 shown in the first line of this table actually react with phosphoenolpyruvate as HCO_3^-.
P_i and PP_i stand for inorganic phosphate and pyrophosphate, respectively.

Regulation

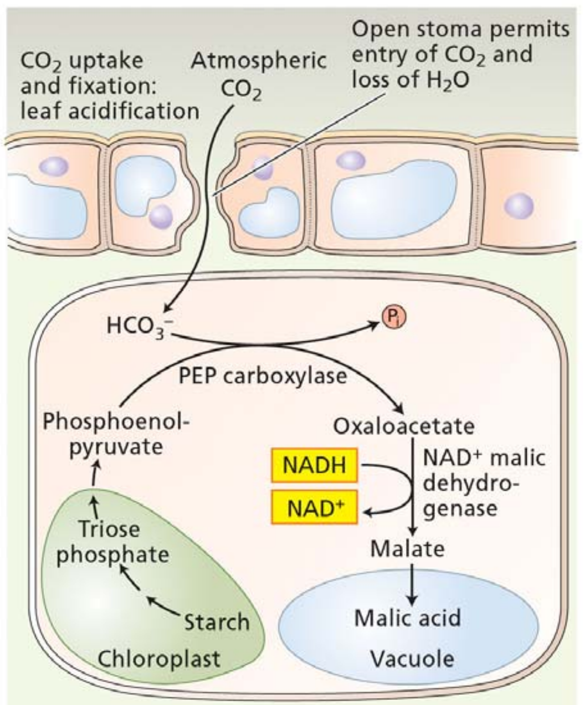
- Thioredoxin: NADP: malate dehydrogenase
- PEP carboxylase: covalent modification by phosphorylation/dephosphorylation; regulated by phosphorylation by PEP carboxylase-kinase to make active
- Pyruvate Pi dikinase: ADP-dependent phosphorylation when light intensity drops

Crassulacean Acid Metabolism

- **Initial CO_2 fixation step which occurs at night.**
- **After the initial carboxylation, malic acid (the first stable product after fixation) is then sequestered into the central vacuole during the night period.**
- **In the following light period, the stomata close and the malic acid returns to the cytoplasm for decarboxylation.**
- **The released CO_2 is then assimilated through the C_3 pathway.**

Pathway

Dark: Stomata opened



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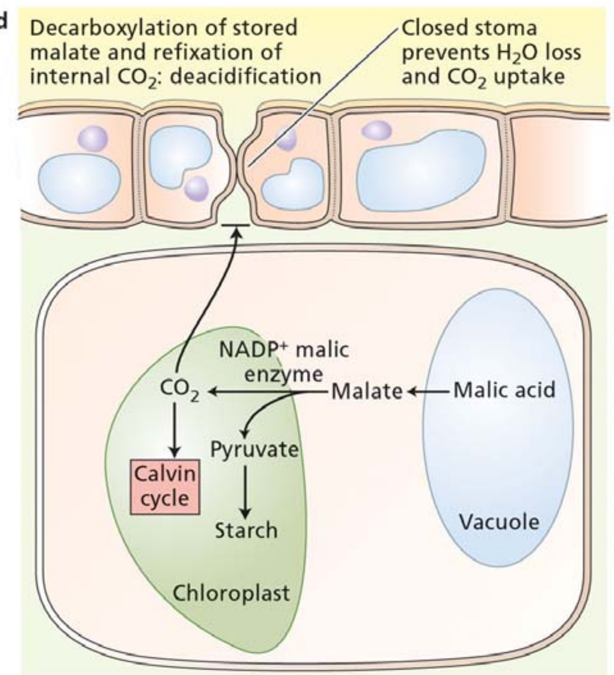
Light: Stomata closed



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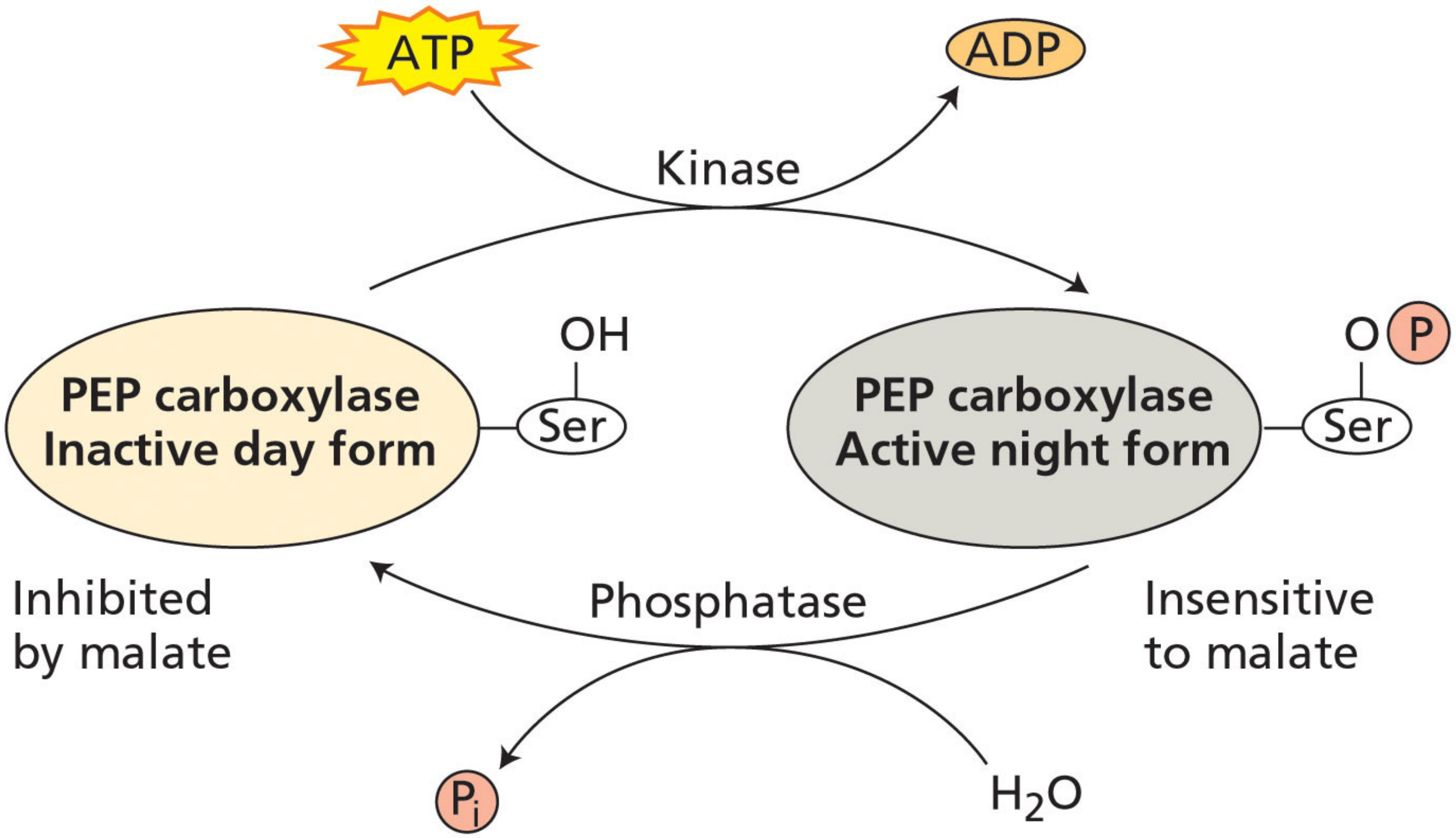
& Regulation


ATP
ADP
Kinase
OH
Ser
PEP carboxylase
Inactive day form
PEP carboxylase
Active night form
O P
Ser
Inhibited
by malate
Phosphatase
Insensitive
to malate
Pi
H2O