Photosynthesis =

Sunlight

↓

Energy

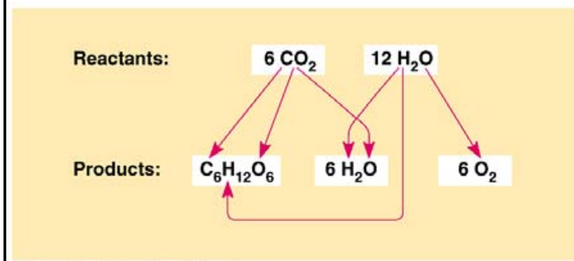
↓

$CO_2 + H_2O$

↓

Sugars (carbohydrates = $[C\ H_2O\ ]_n$

Figure 10.3 Tracking atoms through photosynthesis

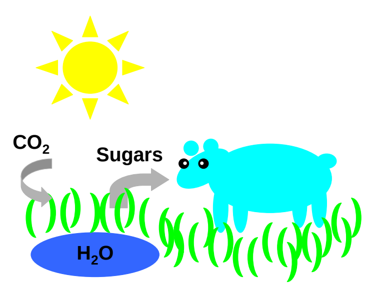


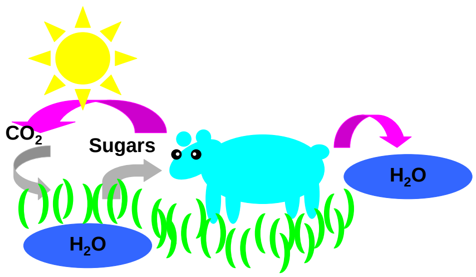
Three big concepts

- Photosynthetic organisms are autotrophs – specifically, photoautotrophs
- Non-photosynthetic organisms are heterotrophs
- Photosynthesis and cellular respiration are complimentary processes

Figure 10.1 Photoautotrophs

Figure 10.0 Sunbeams





Two stages of photosynthesis

- Light reactions = conversion of light energy to chemical energy
- "Dark" reactions = Calvin cycle = light-independent reactions = photosynthetic carbon reduction pathway = conversion of carbon dioxide into sugars

Figure 10.x1 Melvin Calvin

During the light reactions:

- Chemical energy is stored in covalent bonds of adenosine triphosphate, ATP
- Chemical energy is stored as "reducing power" in reduced nicotinamide adenine nucleotide diphsophate (NADPH)

Figure 10.4 An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle (Layer 1)

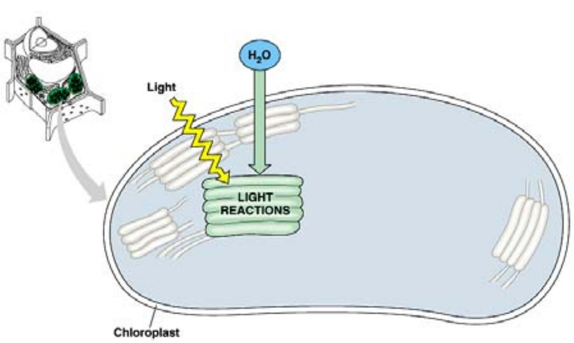
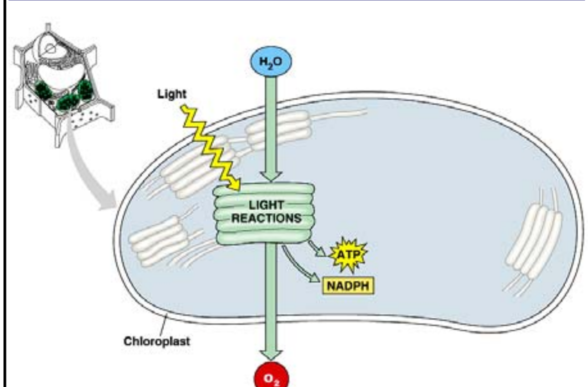


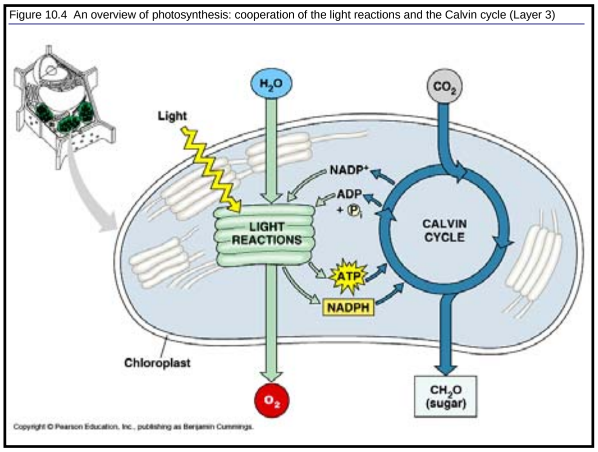
Figure 10.4 An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle (Layer 2)



During the dark reactions:

- Chemical energy stored in covalent bonds in ATP is released;
- Energy from ATP and electrons from NADPH are used to form covalent bonds between carbon dioxide and water molecules during sugar formation

Figure 10.4 An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle (Layer 3)



Organization of light reactions

- Occur in thylakoid membranes of chloroplasts
- Light energy is absorbed by pigments that are attached to proteins embedded in the thylakoid membranes

Figure 10.2 Focusing in on the location of photosynthesis in a plant

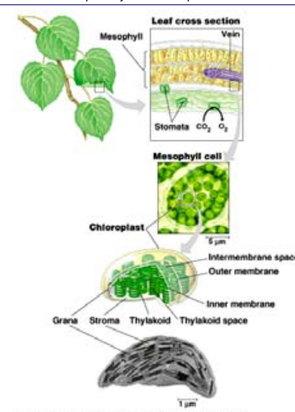
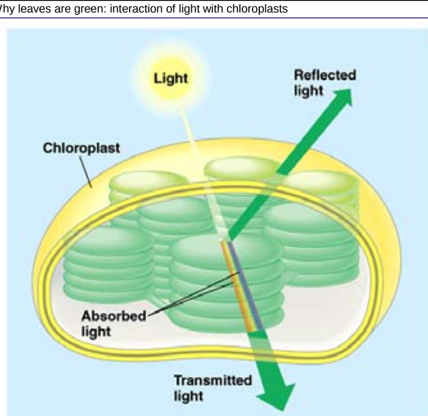


Figure 10.6 Why leaves are green: interaction of light with chloroplasts



The major light-absorbing pigment is chlorophyll

- Two major forms: chlorophyll a (Chla) and chlorophyll b (Chlb)
- Both forms absorb red and blue light but not green, yellow, etc.
- Other pigments (e.g. carotenoids) = accessory pigments absorb other colors (wavelengths) of light

Figure 10.9 Location and structure of chlorophyll molecules in plants

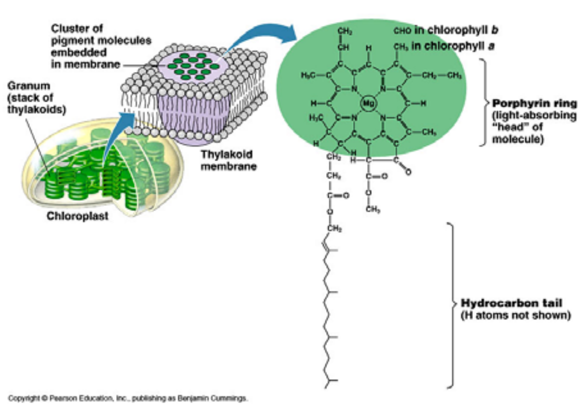


Figure 10.09x Chlorophyll

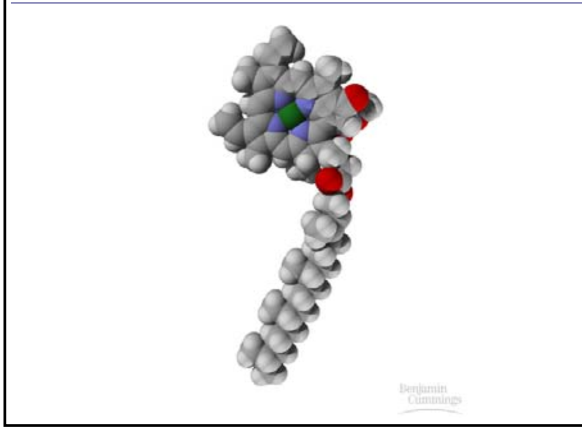


Figure 10.5 The electromagnetic spectrum

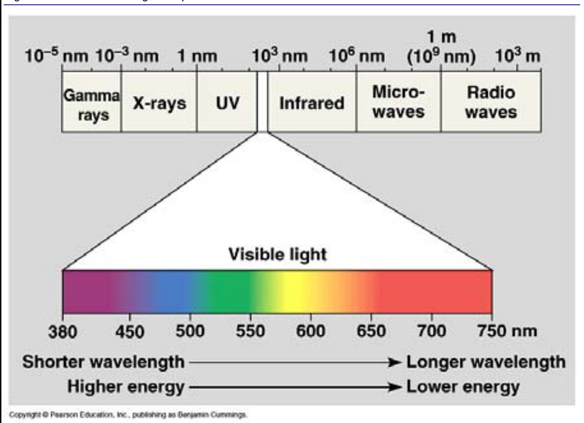


Figure 10.7 Determining an absorption spectrum

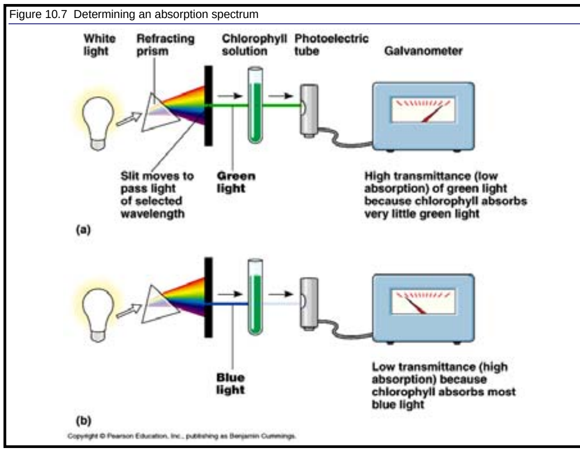
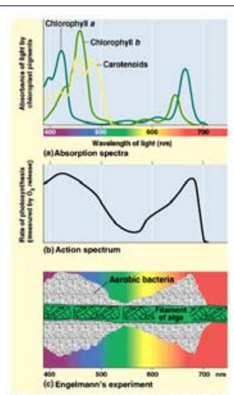


Figure 10.8 Evidence that chloroplast pigments participate in photosynthesis: absorption and action spectra for photosynthesis in an alga



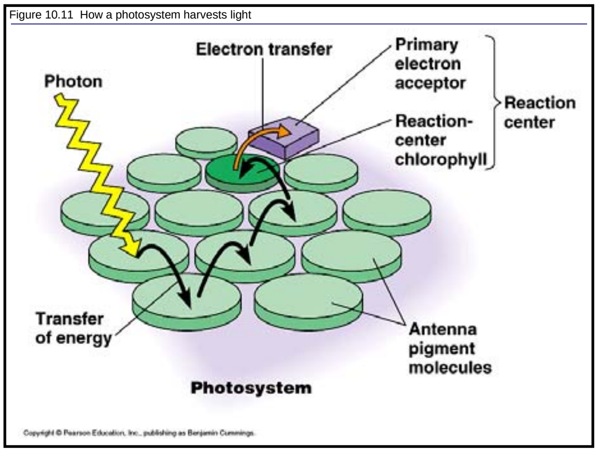
Chlorophyll a and accessory pigments are organized in photosystems = PS

- PS = several hundred molecules of pigments + proteins clustered together
- PS are embedded in thylakoids
- There are two distinct PS: I and II = PSI and PSII

Structure/function of PS

- Each PS has a light harvesting complex = LHC = antenna
- Each PS has a reaction center containing Chla
- Light energy is first absorbed by accessory pigments and Chlb in the LHC
- Energy absorbed by LHC is transferred to Chla in the reaction center

Figure 10.11 How a photosystem harvests light



Structure/function of PS (cont.)

- Light oxidizes Chla in the reactions centers of PSI and PSII simultaneously
- PSII is connected to PSI by an electron transport chain (ETC) = enzymes that are sequentially reduced and then re-oxidized
- There is a second ETC beyond PSI
- The final electron acceptor beyond PSI is $NADP^+$

Figure 10.10 Excitation of isolated chlorophyll by light

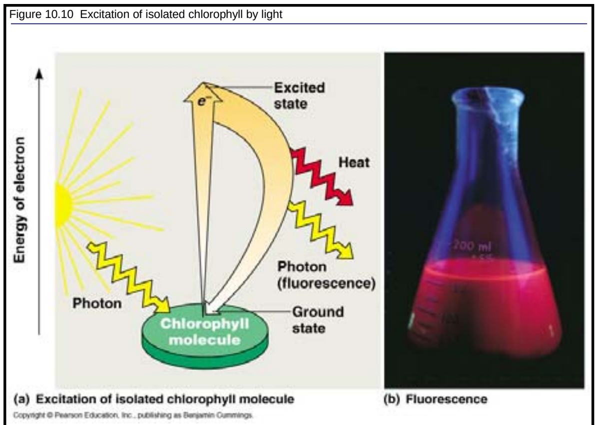
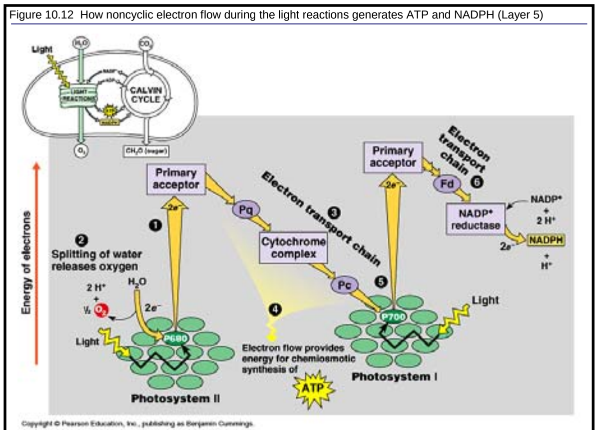


Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 5)



Events overview – light reactions

- PSII Chla e^- reduce quinone A (Q_A)
- Lost PSII Chla e^- are replaced with e^- from light-driven water splitting = photolysis
- PSI Chla e^- reduce ferrodoxin
- e^- from Q_A flow through ETC to replace e^- lost from PSI Chla
- e^- from ferrodoxin flow through ETC beyond PSI to reduce $NADP^+$ to NADPH

Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 1)

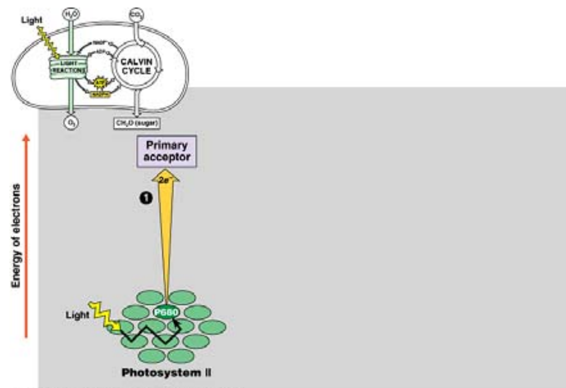


Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 2)

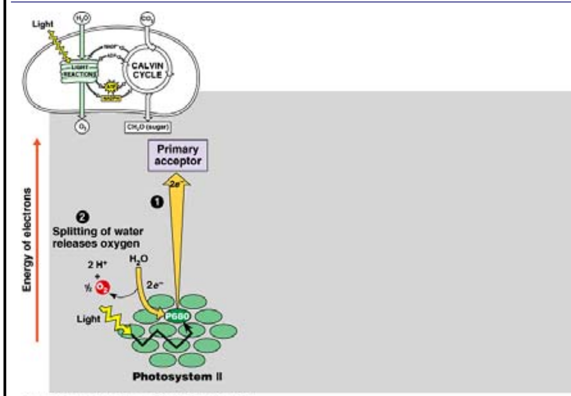


Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 3)

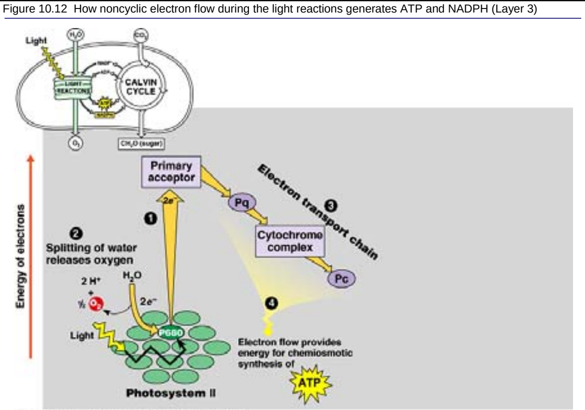


Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 4)

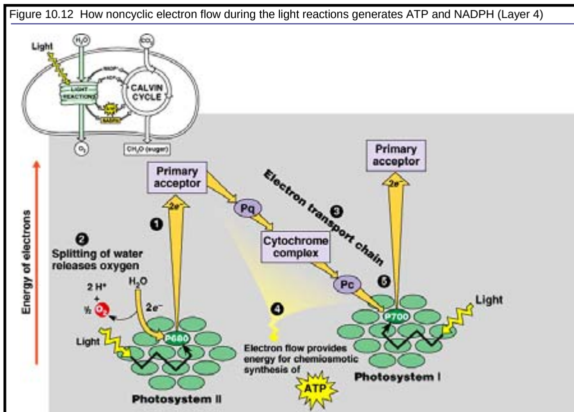


Figure 10.12 How noncyclic electron flow during the light reactions generates ATP and NADPH (Layer 5)

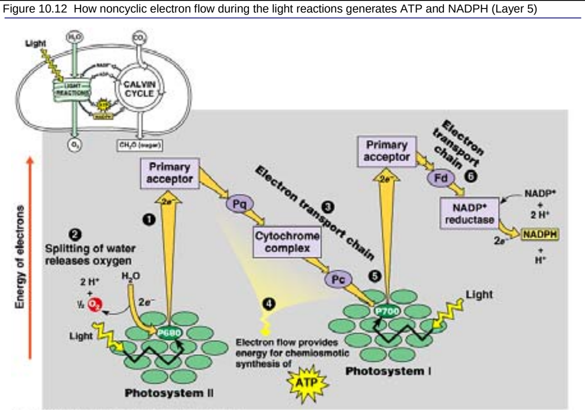
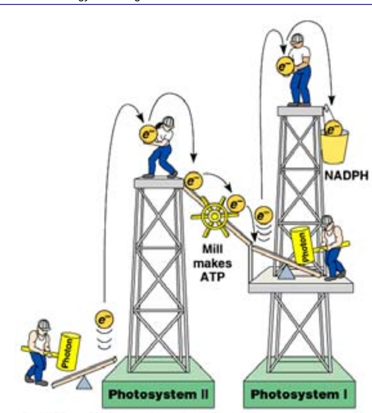


Figure 10.13 A mechanical analogy for the light reactions



The light reactions generate ATP by chemiosmosis

- Protons accumulate inside the thylakoid as a result of electron transport
- Low pH inside the thylakoid activates a proton-dependent ATP synthase
- Bacteria and mitochondria also produce ATP by chemiosmosis

Figure 10.16 The light reactions and chemiosmosis: the organization of the thylakoid membrane

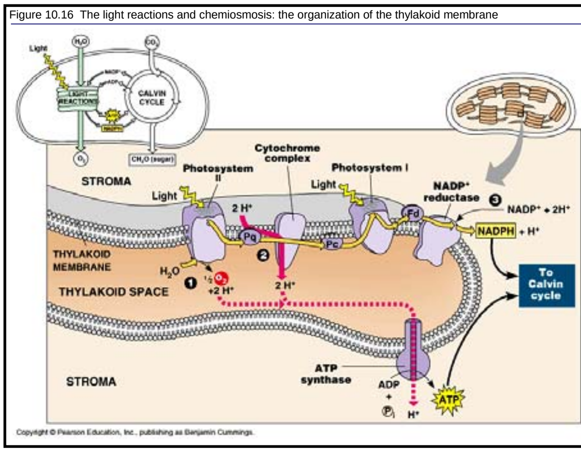
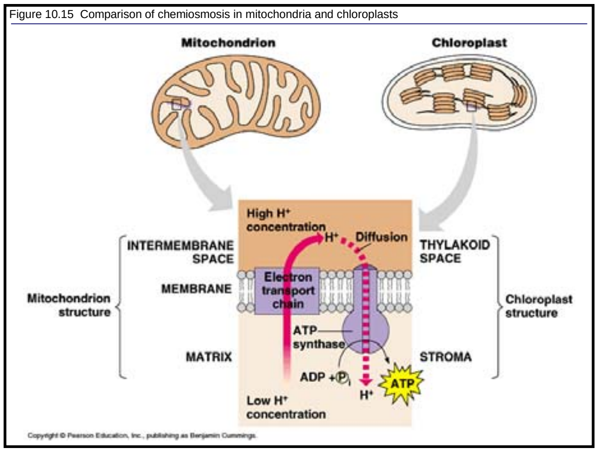


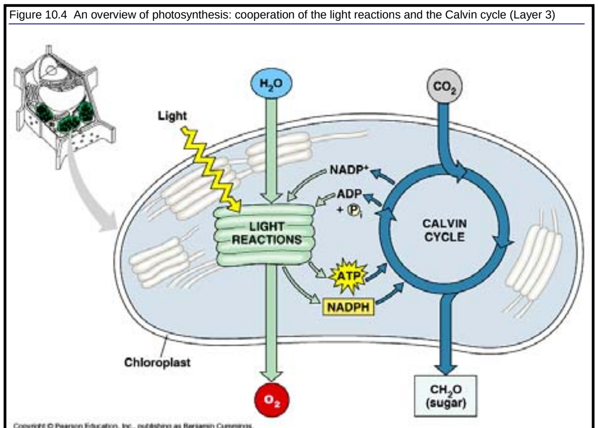
Figure 10.15 Comparison of chemiosmosis in mitochondria and chloroplasts



Overview of the Calvin Cycle

- Occurs in the stroma of the chloroplast
- CO_2 + H_2O + energy = sugar
- Energy comes from ATP produced in light reactions
- Electrons come from NADPH made in light reactions
- Occurs in 3 stages – the first is "carbon fixation"

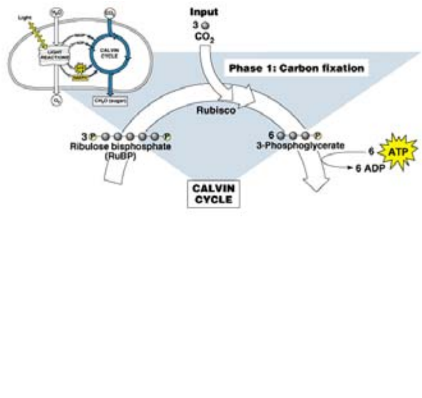
Figure 10.4 An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle (Layer 3)



Stage 1: Carbon fixation

- Stomata open in response to light and lowered CO_2 concentration inside the leaf; CO_2 enters mesophyll *tissue* by simple diffusion
- CO_2 enters mesophyll *cells* and becomes covalently bonded to the 5-carbon ribulose 1,5 bis-phosphate (diphosphate) = RuDP = RuBP
- The enzyme that catalyzes the reaction is ribulose 1,5 bis-phosphate (= diphosphate) carboxylase-oxygenase = Rubisco
- CO_2 is converted from a gas to a solid = "fixed"
- The 6-carbon compound formed is VERY unstable; it immediately breaks down to form two, 3-carbon molecules of 3-phosphoglyceric acid (3-phosphoglycerate) = PGA
- Plants that produce a 3-carbon compound as the first measurable product of carbon fixation are called C3 plants

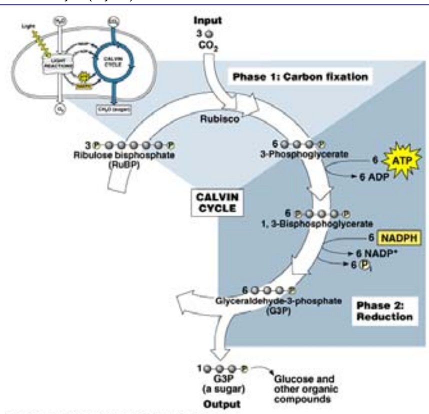
Figure 10.17 The Calvin cycle (Layer 1)



Stage 2: Reduction

- Requires energy from ATP produced in light reactions
- Requires electrons stored in NADPH produced by light reactions
- The product is an aldehyde – glyceraldehyde-3-phosphate (G3P = GAP = PGAL)
- Half of the G3P molecules are used to make 6-carbon sugars (glucose or fructose = $C_6H_{12}O_6$ = “monosaccharides”; NOTE: glucose + fructose = sucrose, a “disaccharide” that is the main transport form of sugars in plants)
- Half of the GAP molecules are used to make more RuBP

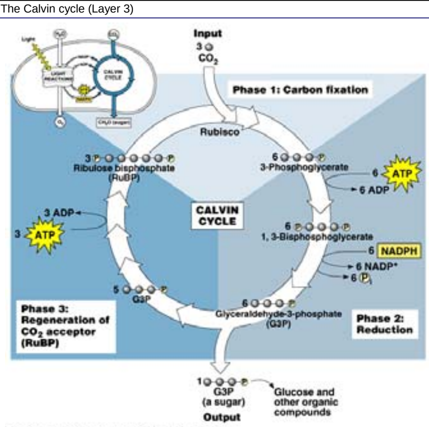
Figure 10.17 The Calvin cycle (Layer 2)



Stage 3: Regeneration of the CO_2 acceptor (RuBP)

- Keeps the cycle running
- Requires additional ATP from the light reactions
- Involves a large set of chemical reactions called the pentose phosphate pathway in which even- and odd-numbered carbon skeletons are rearranged to yield the 5-carbon RuBP

Figure 10.17 The Calvin cycle (Layer 3)



Balancing the Calvin cycle equation

6 RuBP + 6 CO_2 + 18 ATP + 12 NADPH

=

6 RuBP + 18 ADP + 18 Pi + 12 $NADP^+$ + one, 6-carbon sugar (glucose or fructose)

Figure 10.17 The Calvin cycle (Layer 3)

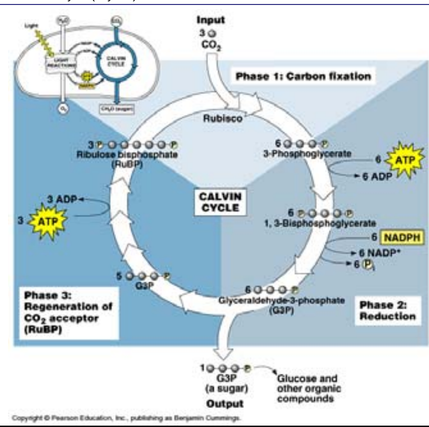
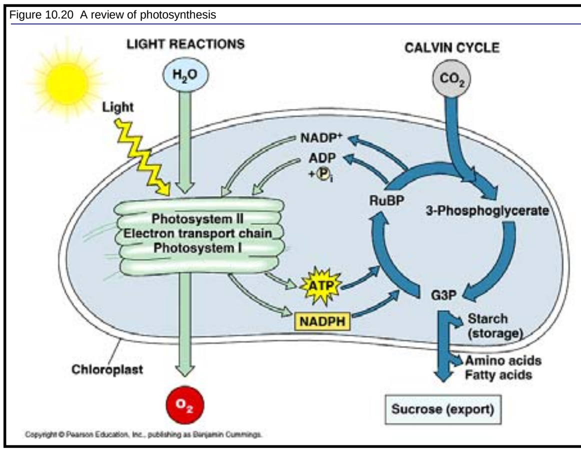


Figure 10.20 A review of photosynthesis



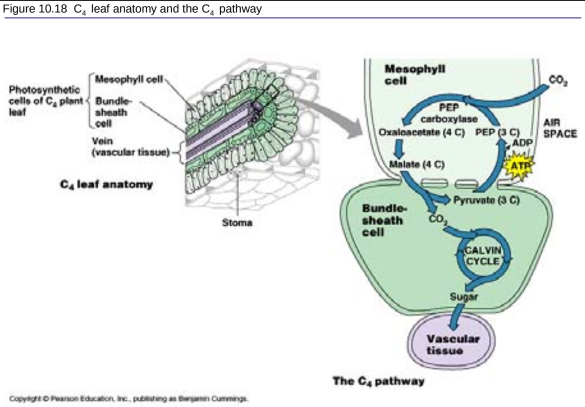
Alternate mechanisms of photosynthesis:
C4 vs. Crassulacean acid metabolism (CAM)

- Help plants in drier climates conserve water
- Help plants minimize carbon loss to photo-respiration = competition between O_2 and CO_2 for the "active site" = catalytic site of Rubisco
- Improve the water use efficiency (WUE) of plants
- Both fix CO_2 to a 4-carbon organic acid first
- Both use the enzyme phosphoenolpyruvate carboxylase (PEPC) to catalyze CO_2 fixation

C4 plants:

- Open their stomata during the day
- Fix CO_2 to phophoenolpyruvate (PEP) in mesophyll cells; the PEP is then converted to malic acid (malate)
- Transport malate from mesophyll to bundle sheath cells
- Decarboxylate the malate in the bundle sheath cells and fix it again by Calvin cycle using Rubisco
- The C4 mechanism increases the concentration of CO_2 in the bundle sheath cells so that CO_2 competes better against O_2 for the active site of Rubisco
- Corn and grasses are C4 plants
- C4 plants open their stomata less to achieve the same carbon capture as C3 plants = greater WUE

Figure 10.18 C_4 leaf anatomy and the C_4 pathway



CAM plants:

- Open their stomata at night
- Fix CO_2 to phophoenolpyruvate (PEP) and convert it to malic acid (malate) overnight in their mesophyll cells
- Close their stomata during the day
- Decarboxylate the malate in the same mesophyll cells and fix it again by Calvin cycle using Rubisco throughout the day
- Many desert plants and succulents (e.g., cacti, pineapple) use CAM

Figure 10.19 C_4 and CAM photosynthesis compared

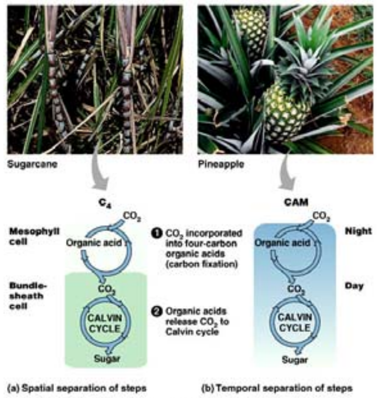


Figure 10.14 Cyclic electron flow