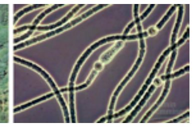
The ***Producers***

- Produce the food (photosynthesis)
- Condition the environment
- Create shelter and habitat

Photosynthetic bacteria

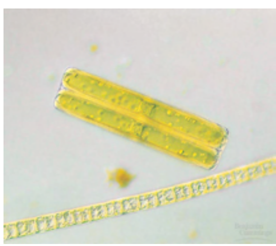
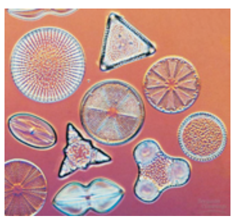



Cyanobacteria —
"blue-green algae"
use chlorophyll

Halophilic archaea
"purple bacteria"
use bacteriorhodopsin

Photosynthetic protists

Phytoplankton — earth's dominant producers!
- diatoms

Algae — Aquatic Plants

- Three Divisions (Phyla)

Chlorophyta
"Green Algae"

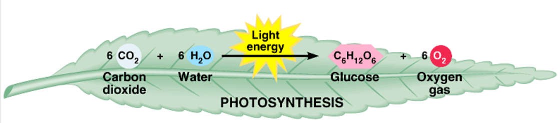


Rhodophyta
"Red Algae"

Phaeophyta
"Brown Algae"
{ including the "kelp" family }

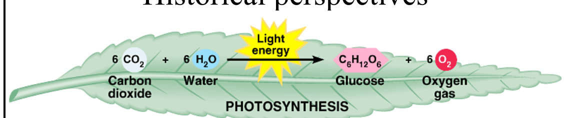
- Not directly related to each other, nor to terrestrial vascular plants.
- Accessory pigments allow greater light sensitivity at depth.

Photosynthesis



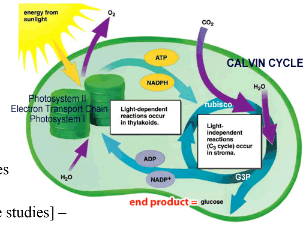
- Glucose for energy fuel, organic chemical monomers, structural polymers.
- Oxygen for aerobic respiration.

Historical perspectives



- 1600s – JB van Helmont: willow sapling grown in closed container with just watering for 5 years.
  Tree gained mass without loss of soil mass → gain mass from air.
- 1770s – J Priestly: Discovered oxygen. Discovered that animals require oxygen.
  Discovered that plants produce oxygen ∴ plants improve the air.
- 1790s – J. Senebier & J Ingenhouz: "***Carbon fixation***"
  Plant mass "fixed" from CO_2 in air. Dependent on light.
- 1890s – TW Engelmann: Oxygen specifically produced by chloroplasts.
  Related to absorption of red & blue light.
- – J von Sachs: Chlorophyll required. Chloroplasts also produce starch.
  (Derived the equation above)

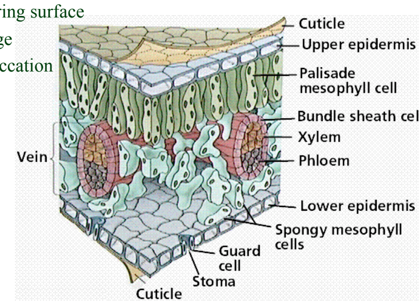
Historical perspectives



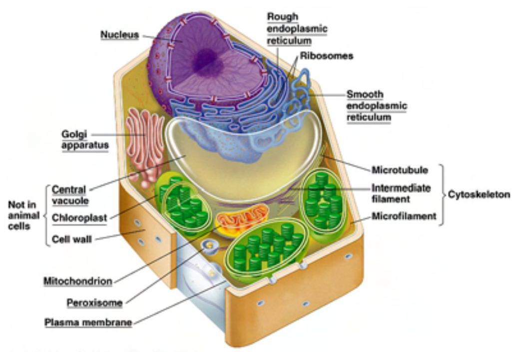
- 1925 – O Warburg: separate "light" and "dark" reactions.
- 1930s – R Hill: Oxygen comes from water; not CO_2.
- 1940s [advent of radioisotope studies] –
  - SM Ruben, *et al*: $H_2{}^{18}O \rightarrow {}^{18}O_2$ in light-dependent reactions.
  - M. Calvin: ${}^{18}CO_2 \rightarrow$ sugar in light-independent ("dark") reactions.
- University of Aberdeen Learning Technology Unit — Photosynthesis
  - http://www.abdn.ac.uk/~clt011/flash/samples/photosyn.swf

Leaf: photosynthetic organ of terrestrial plants

- Many tissues
- Specialized structure for
  - Light-gathering surface
  - Gas exchange
  - Reduce desiccation
  - Vasculature

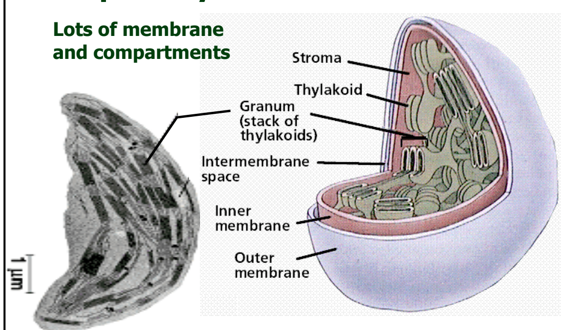


Plants Cells

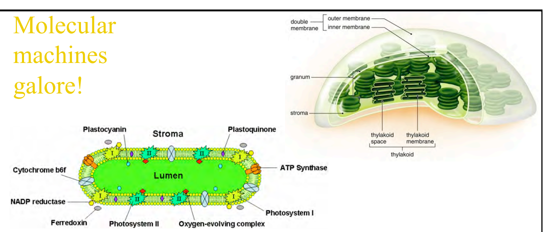


Chloroplast structure allows photosynthesis to work

Lots of membrane and compartments



Molecular machines galore!

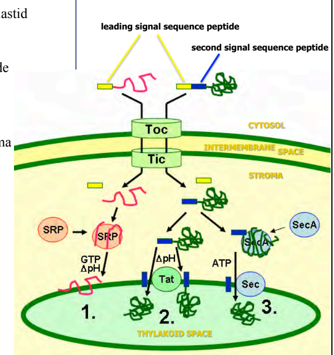


>335 different proteins associated with the thylakoid
- 89 in lumen
- 116 thylakoid membrane integral proteins
- 62 peripheral on stromal side
- 68 peripheral on lumenal side

- most involved in photosynthesis
- but many for targeting, folding, & processing other proteins

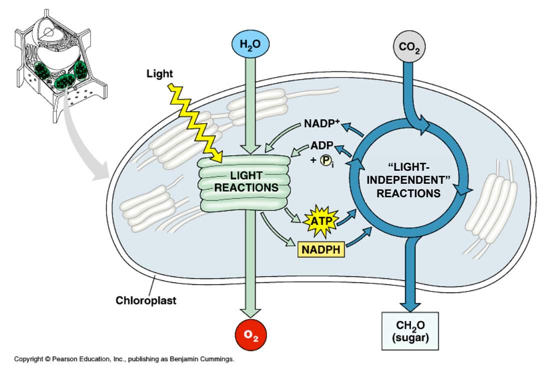
Protein targeting to the thylakoids

- ~95% of plastid proteins coded by nuclear DNA
- Cytosolic proteins targeted across plastid envelope to stroma
  - leading **signal sequence** peptide of a newly synthesized polypeptide as it emerges from the ribosome
  - via protein-conducting channels, **translocon** (T_{oc} & T_{ic})
  - signal peptide cleaved off in stroma
- Target to thylakoid membrane or lumen by <u>second</u> signal peptide
  - via T_{at}
- Stromal DNA-coded proteins may also be targeted to thylakoid
  - via **signal recognition particles** (SRP & SecA)
- Active transport
  - powered by ATP, GTP, or H^+-gradient cotransport



Photosynthesis: 2 main parts

- 1. **Light reactions:**
  - in grana
  - light energy ➔ e^-, ATP
- 2. **Light-independent reactions:**
  - in stroma
  - e^-, ATP ➔ sugar



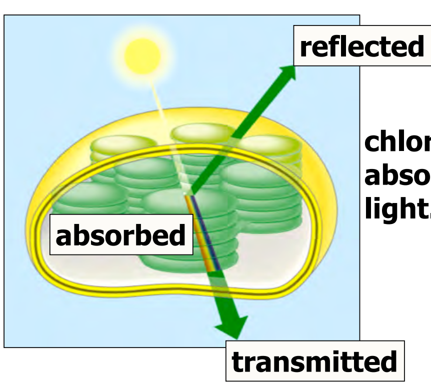
Photosynthesis: 2 main parts

- 1. **Light reactions:**
  light energy ➔ e^-, ATP
  - Photosystem 1
  - Photosystem 2

Photosystem 2

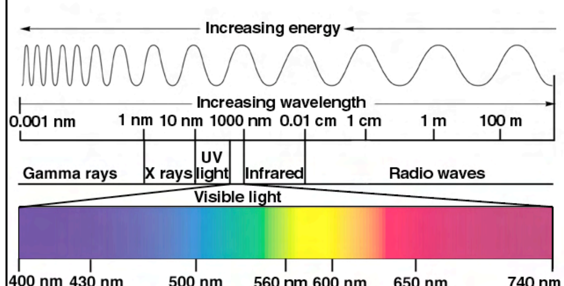
- Light excites e^- in PS2 chlorophyll.

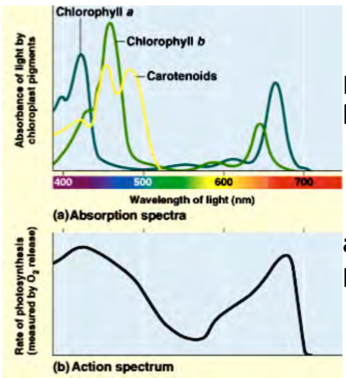
Light reactions



chloroplasts absorb some light.

Electromagnetic Spectrum

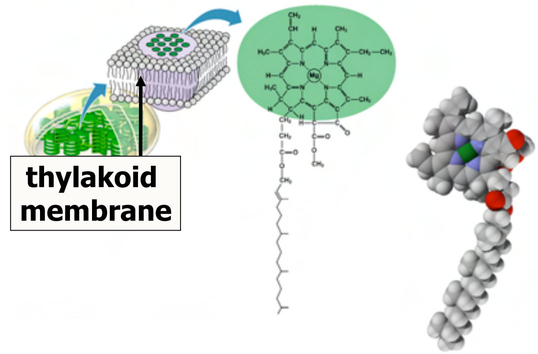




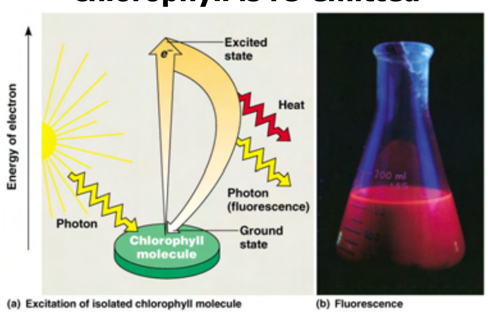
Pigments absorb light --

and power photosynthesis.

Chlorophyll: location & structure



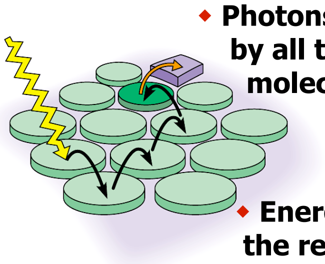
Energy absorbed by chlorophyll is re-emitted



Photosynthesis captures this energy

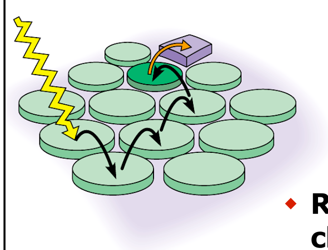
- Light excites e$^-$ in PS2 chlorophyll.
- Energy is passed to reaction center chlorophyll.

Photosystems concentrate energy



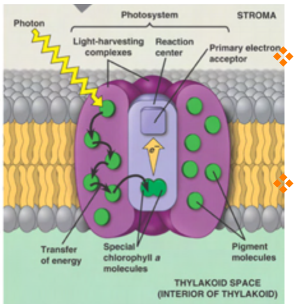
- Photons are absorbed by all the pigment molecules.
- Energy is passed to the reaction center chlorophyll by resonance transfer.

Photosystems concentrate energy



- Reaction center chlorophyll loses electrons.

Photosystems concentrate energy

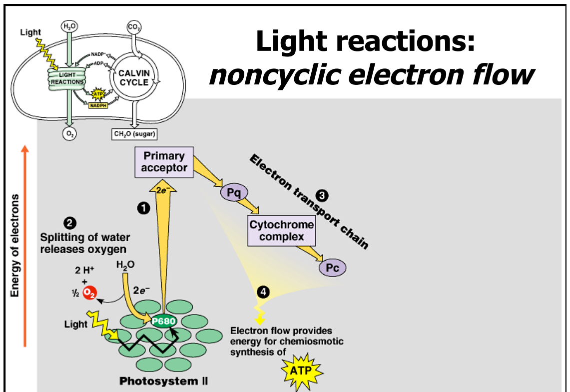


- Photons are absorbed by all the chlorophylls.
- Energy is passed to reaction center chlorophyll.

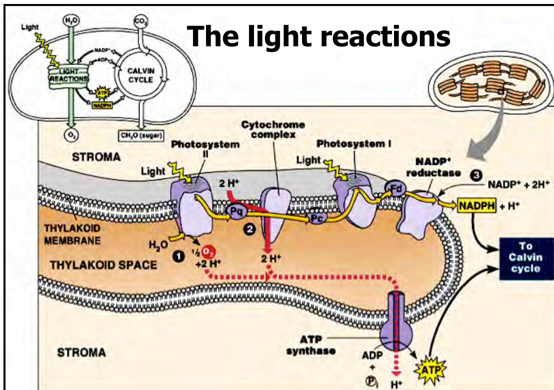
- Light excites e^- in PS2 chlorophyll.
- Energy is passed to reaction center chlorophyll.
- High-energy e^- are passed to an electron transport chain.
- H^+ gradient used for ATP synthesis.

Light reactions

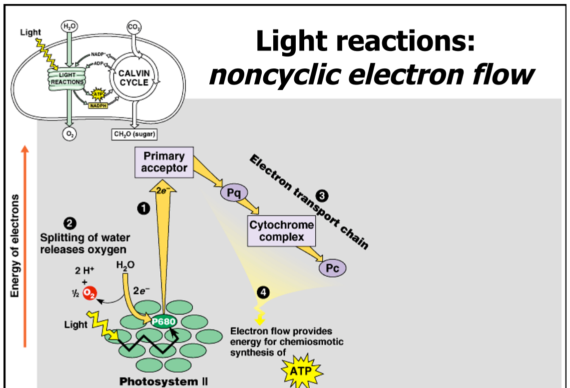
Light reactions: *noncyclic electron flow*



The light reactions



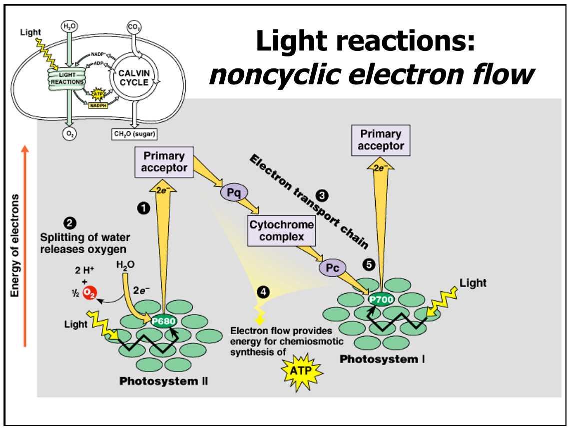
Light reactions: *noncyclic electron flow*



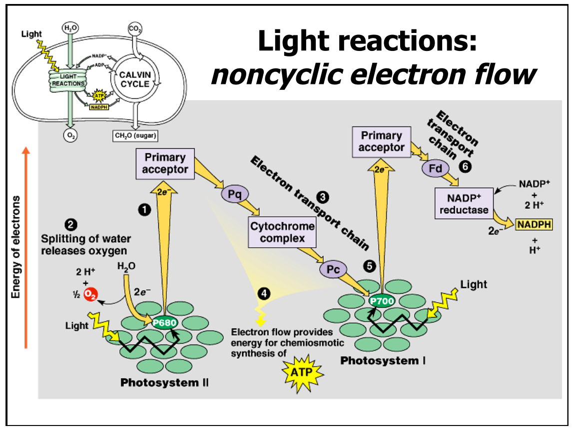
- Light excites e^- in PS2 chlorophyll.
- Energy is passed to reaction center chlorophyll.
- High-energy e^- are passed to an electron transport chain.
- H^+ gradient used for ATP synthesis.
- PS1 excites e^- again; e^- passed to NADP.

Light reactions

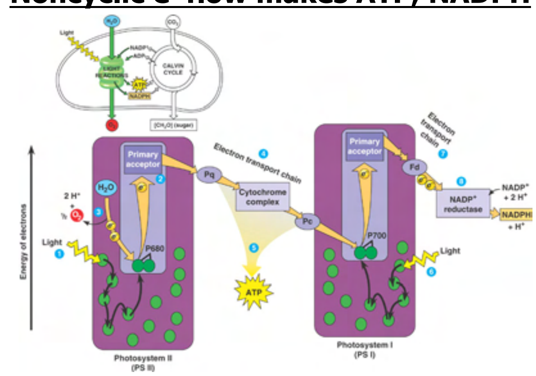
Light reactions: *noncyclic electron flow*



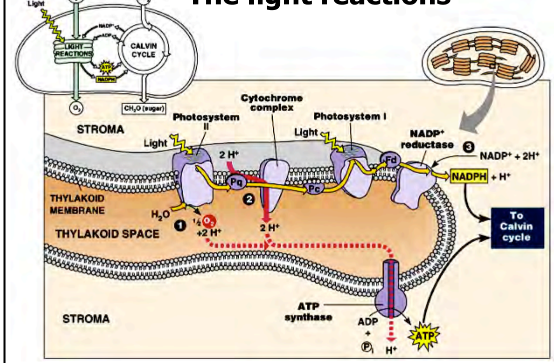
Light reactions: *noncyclic electron flow*



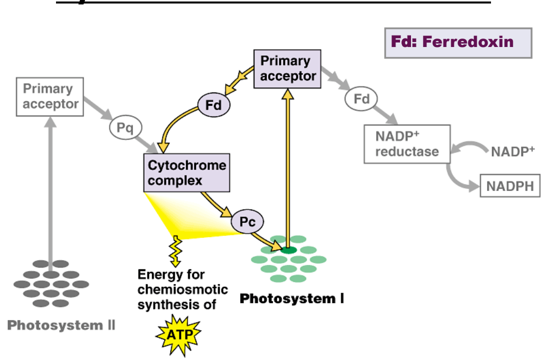
Noncyclic e- flow makes ATP, NADPH



The light reactions



Cyclic e- flow makes extra ATP



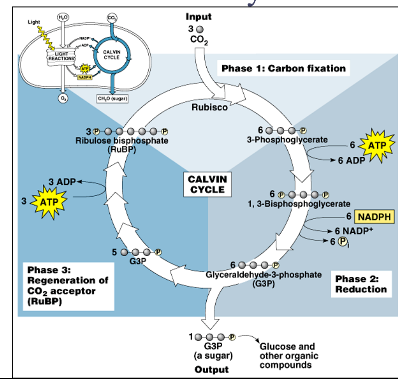
Photosynthesis: 2 main parts

- 1. Light reactions:
  light energy → e^-, ATP
- 2. Light-independent reactions:
  e^-, ATP → sugar
  - Calvin cycle

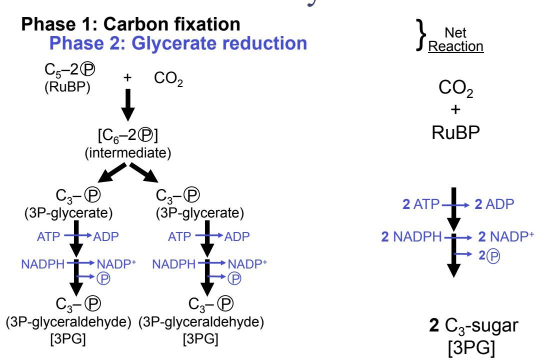
Calvin Cycle

- **Melvin Calvin**, UC Berkeley, 1937–1980
- Nobel prize, Chemistry, 1961
- at Lawrence Berkeley Radiation Lab, used [14]C-labeled compounds to map out complete photosynthetic carbon pathway

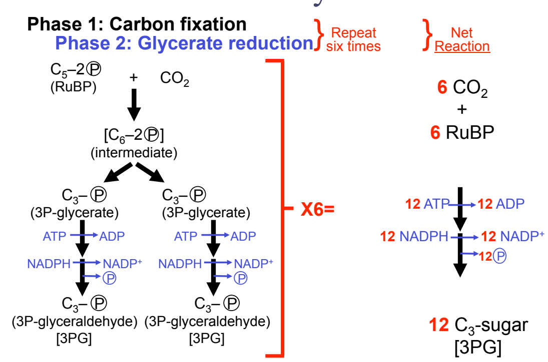
Calvin Cycle



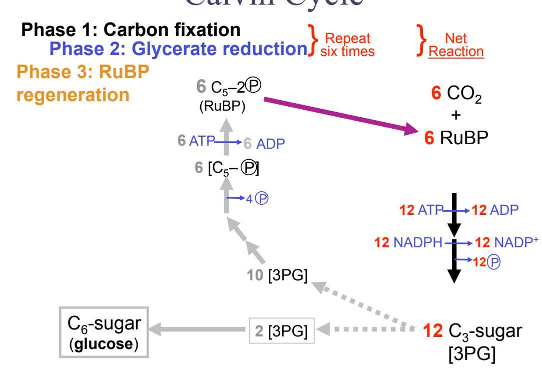
Calvin Cycle



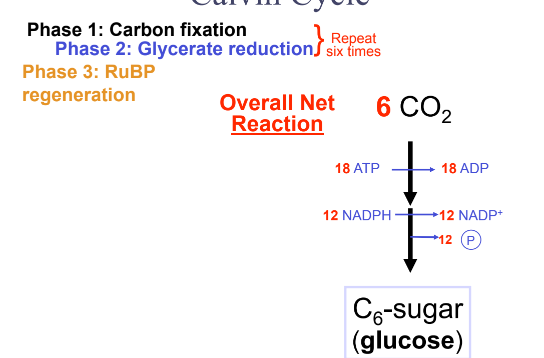
Calvin Cycle



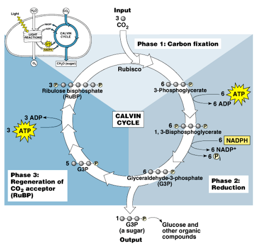
Calvin Cycle



Calvin Cycle

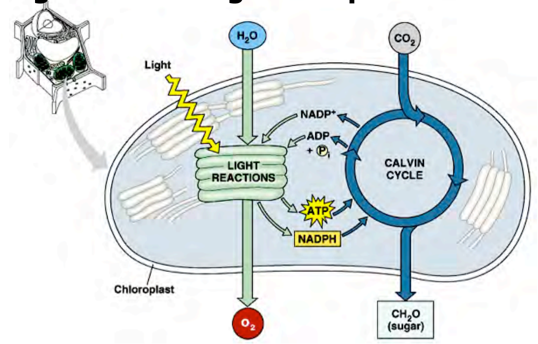


Calvin Cycle Summary



- Uses ATP, NADPH.
- Reduces CO_2 to make G3P.
- **Rubisco** is the carbon-fixing enzyme.
  - (16% of chloroplast protein content)

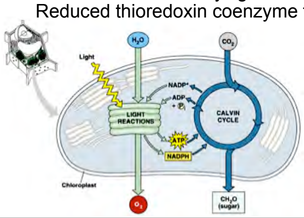
Photosynthesis: Light rxns & "Light-independent" rxns



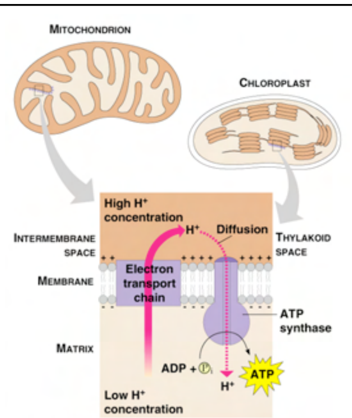
Calvin Cycle: not completely "light-independent"

Calvin cycle does go faster in the light

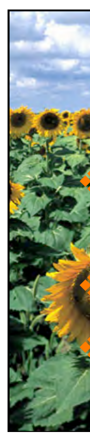
- Dependent upon ATP & NADPH production from light rxns
- Light reactions ⇑ permeability of stromal membranes to cofactors (esp. Mg^{++}) required for Calvin cycle enzymes
- Ferredoxin oxidized by light reactions reduces thioredoxin. Reduced thioredoxin coenzyme for Calvin cycle enzymes



Comparing Photosynthesis & Respiration



Electron transport chain & ATP synthase



Photosynthesis & Respiration

Similarities:

- Both use ETC ➔ proton gradient ➔ ATP
- Both have redox cycles
- Both use electron carriers

Photosynthesis & Respiration

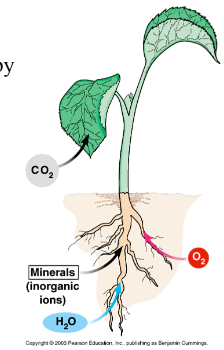
Differences:

- **Source of energy, e⁻**
- **Where e⁻ go**
- **Oxidize vs. reduce carbon**

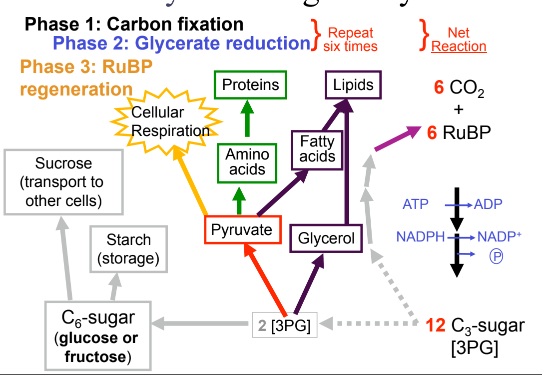
Plants must do both!

Gas exchange in vascular plants

- CO_2 taken *in* and O_2 given *out* by leaves for/from **photosynthesis**.
- Dissolved O_2 taken *in* with H_2O from soil by roots for tissue **respiration**.
- During daylight: O_2 *out* **>** O_2 *in*
- In dark of night: O_2 *out* **<** O_2 *in*



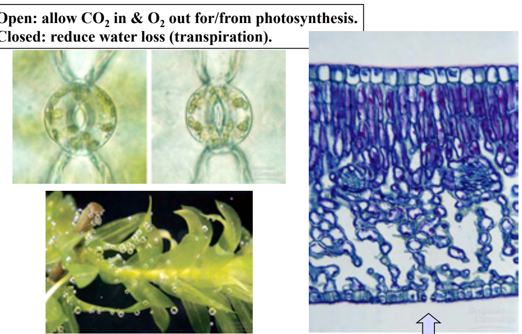
Calvin Cycle — organic synthesis



Stomata — "little mouths"

— adjustable openings for gas exchange on the undersides of leaves

- **Open: allow CO_2 in & O_2 out for/from photosynthesis.**
- **Closed: reduce water loss (transpiration).**

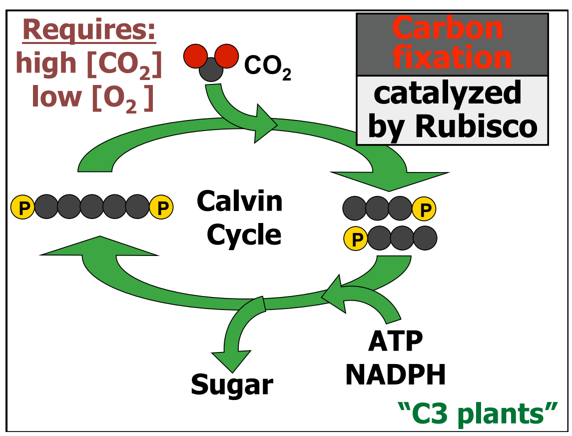


O_2 bubbles forming from stomata

next:

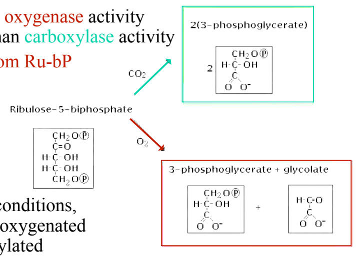
Photorespiration:

When a good enzyme turns bad.



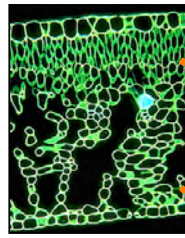
Rubisco:
ribulose-bisphosphate carboxylase/oxygenase

- At typical conditions, carboxylase activity is much greater than oxygenase activity
  - Add C to Ru-bP
- But at ↓CO_2 /↑O_2, oxygenase activity becomes greater than carboxylase activity
  - Remove C's from Ru-bP

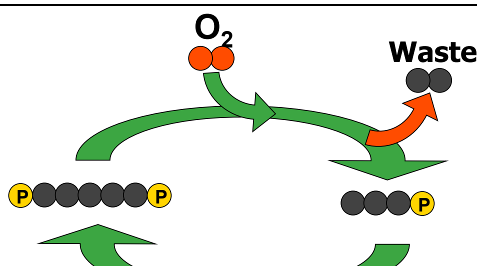


- Even under good conditions, ~20% of Ru-bP is oxygenated rather than carboxylated

Photorespiration:



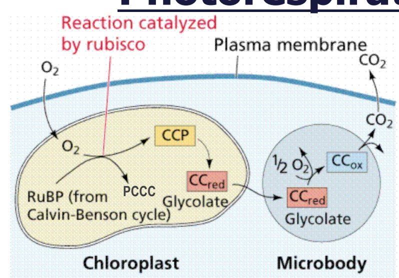
- Stomata close when leaf gets dehydrated to retain water.
- [O_2] increases; [CO_2] decreases.



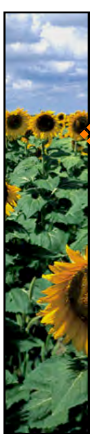
Photorespiration

catalyzed by Rubisco if: low CO_2 / high O_2

Photorespiration



- RuBP is oxidized (destroyed) rather than recycled
- CO_2 is produced rather than consumed (fixed)

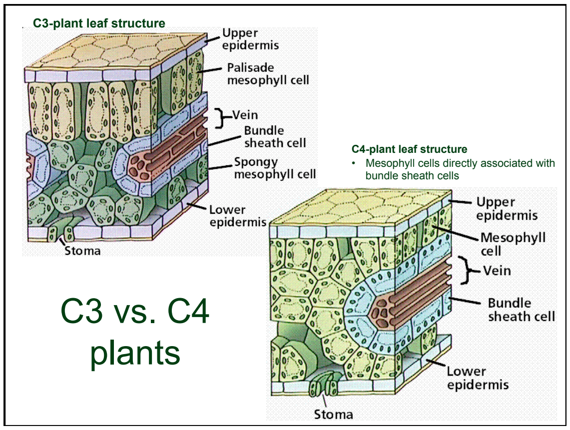


Minimizing photorespiration:

- C4 plants have carbon fixation & Calvin cycle in different cells.

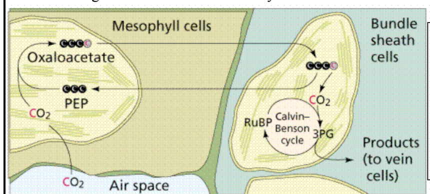
C4 Photosynthesis

- 1960's — Australian sugarcane researchers trying to replicate Calvin's experiments
- Mostly in tropical grasses
  - Hardy weeds: crab grass, summer annuals
  - Important drought-resistant crops: corn, sugar cane, sorghum
- Independent convergence — Developed independently 45 times!
  - >10,000 spp in 19 families (at least 2 monocot & 14 dicot fams)

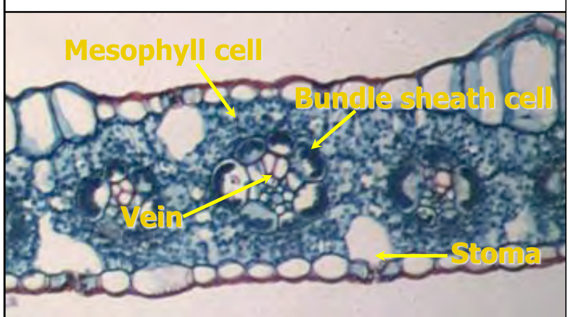


C4 Photosynthesis

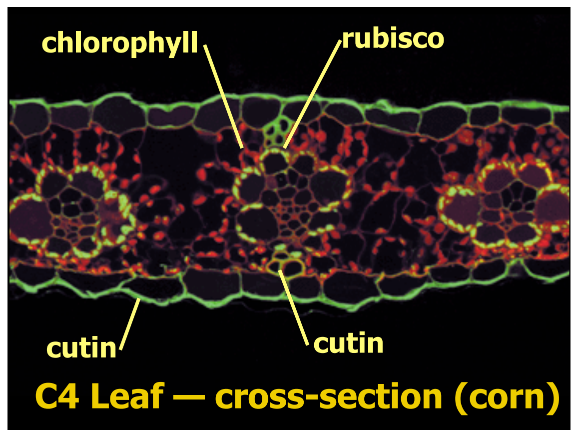
- Photophosphorylation & C_4-carbon fixation in mesophyll cells
  - PEP carboxylase insensitive to O_2
  - O_2 from photophosphorylation diffuses back to air space
- Oxaloacetate shuttles CO_2 to bundle sheath cells
- Calvin cycle uses CO_2 for synthesis of organic macromolecules
  - ↑↑CO_2 favors photosynthesis rather than photorespiration
  - Sugars secreted into vascular system

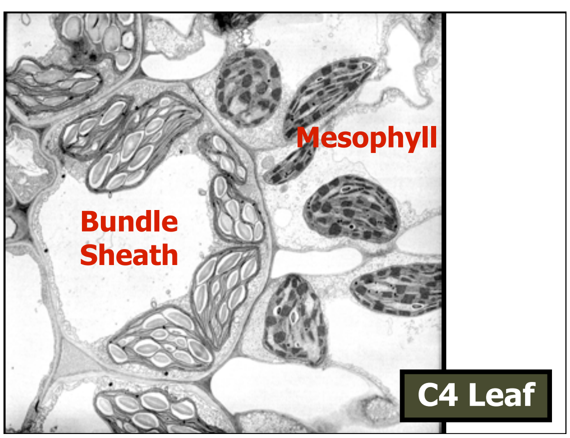


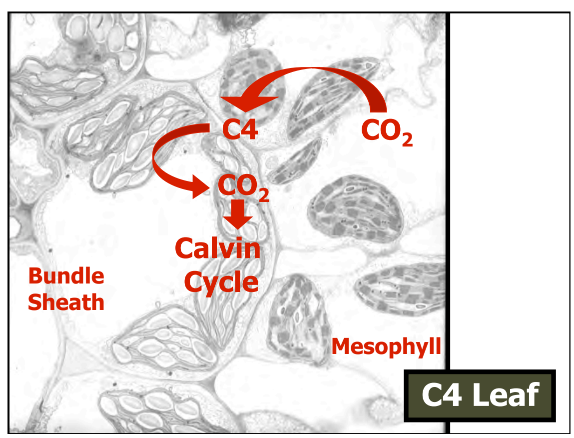
Called "C4" because first step of carbon-fixation produces C_4-oxaloacetate instead of C_3-glycerate

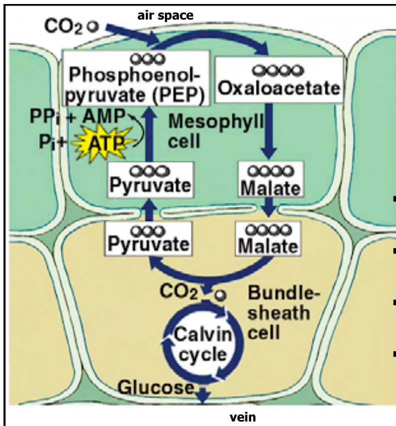


C4 Leaf — cross-section (corn)







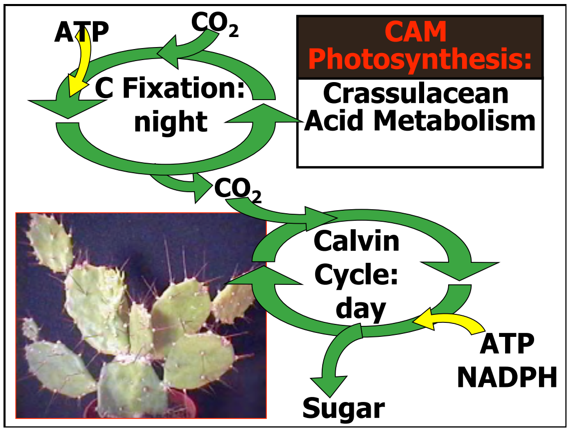


Carbon Fixation in C4 Plants

- PEP + CO_2 → oxaloacetate
- Oxaloacetate reduced to malate
- Malate moves to bundle-sheath cell
- Malate oxidized/ decarboxylated to pyruvate + CO_2

Minimizing photorespiration:

- C4 plants have carbon fixation & Calvin cycle in different cells.
- **CAM plants do carbon fixation & Calvin cycle at different times.**



Crassulacean Acid Metabolism

- Ancient Romans noted certain succulents tasted bland in the afternoon, but sour in the morning.
- 1940s: studying South African succulents (Family: **Crassulacea**)

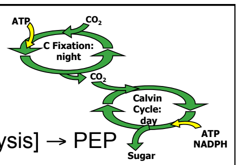
daytime⇒↑starch /↓malic acid
nighttime⇒↓starch / ↑malic acid

"Crassulacean acid metabolism" (CAM)

Crassula ovata (jade plant)

- 1980: CAM model of alternative photosynthesis
- Mostly in desert succulents and tropical epiphytes
  - –Independent convergence again! — >20,000 spp in 33 families!

CAM Photosynthesis



- At night—stomata open
  - Starch → [hydrolysis/glycolysis] → PEP
  - C4 carbon fixation:
    - PEP + CO_2 → oxaloacetic acid → malic acid
  - Malic acid stored in vacuole
- At day—stomata close tightly
  - Malic acid released from vacuole
  - Malic acid → pyruvate + CO_2
    - Pyruvate → back to starch
  - CO_2 increases within cell to 0.2–2.5%
  - ⇒ photosynthesis with minimal photorespiration

CAM variants

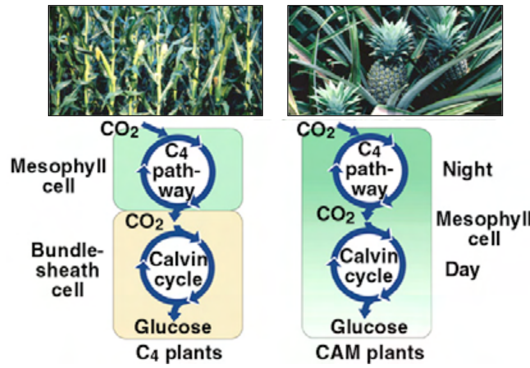
- **Facultative CAM photosynthesis**
  - During heat of day or dry season: stomata close / CAM photosynthesis
  - During cooler, humid late day or wet season: stomata open / switch to C3 photosynthesis
- **"CAM idling"**
  - During dry season or extended drought, stomata remain closed day and night
  - Extreme recycling!

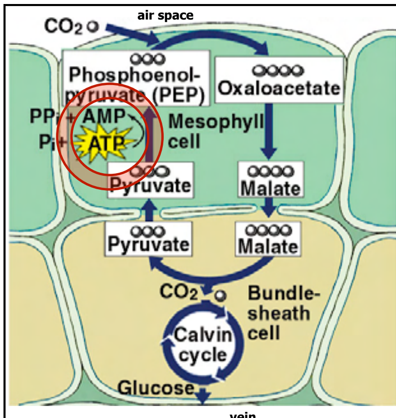
    CO_2 → CAM photosynthesis
    ↑ ← Respiration ← O_2 ↲
  - Not much growth; but can survive for extended periods without any external source of CO_2 or H_2O
    - Sometimes for years!

Minimizing photorespiration:

- C4 & CAM plants avoid photorespiration by providing more CO_2 for rubisco.
- They use a separate carbon fixation step before the Calvin cycle.

C4 & CAM Plants





So why don't most plants use the C4 pathway?

It's expensive!

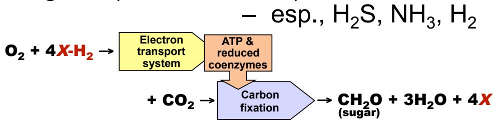
Most environments are moist enough that the energy expense is not worth the increased fixation efficiency.

Minimizing photorespiration:

- Photorespiration can be minimized by providing more CO_2 for rubisco.
- Many aquatic algae & cyanobacteria concentrate with CO_2/HCO_3^- pumps.
  - Pumps activated when CO_2 drops to ~0.03%.
  - Can ↑CO_2 1000-fold inside cell.

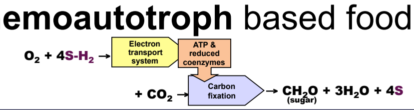
Chemosynthesis: *the* ***other*** *autotrophs*

- Some archea & eubacteria (& fungi?) can fix inorganic carbon into organic molecules *without* sunshine.
- Powered by strong inorganic reducing agents (electron donors).
  - esp., H_2S, NH_3, H_2

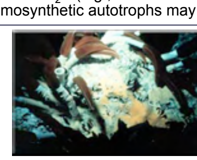


Note: reaction requires O_2 & CO_2.
Still dependent on inputs from photosynthesis & aerobic respiration.

Chemoautotroph based food webs



- In a few regions with no sunlight, little organic carbon input, and a source of H_2S (e.g., oceanic deep hydrothermal vents), chemosynthetic autotrophs may provide the primary production



- Mats of chemosynthetic bacteria cover the rocks.
- Clouds of chemosynthetic bacteria fill the water column.
- Mouthless tubeworms host symbiotic chemosynthetic bacteria.
- Suspension feeders filter the chemosynthetic bacteria from the water.
- Grazers scrape the chemosynthetic bacterial mats.