CHAPTER 10-Photosynthesis

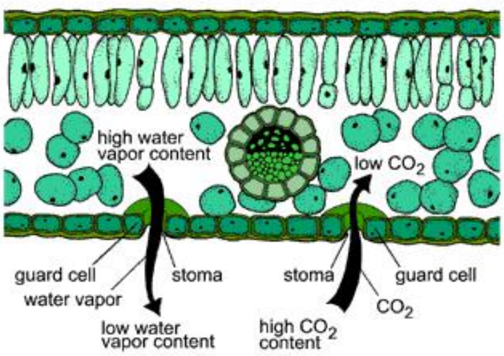
- Life on Earth is solar powered
- Photosynthesis nourishes almost all the living world directly or indirectly
  - All organisms use organic compounds for energy and for carbon skeletons.
  - Organisms obtain organic compounds by one of two major modes: autotrophic or heterotrophic

AUTOTROPHS (=producers)
- produce organic molecules from CO_2 and other inorganic raw materials obtained from the environment
- ultimate source of organic compounds for heterotrophs

*Photo*autotrophs use light as a source of energy to synthesize organic compounds.
- Photosynthesis occurs in plants, algae, some other protists, and some prokaryotes.

*Chemo*autotrophs
- harvest energy from oxidizing inorganic substances, such as sulfur and ammonia
- unique to prokaryotes

HETEROTROPHS (=consumers)
- live on organic compounds produced by other organisms
- dependent on photoautotrophs for food and for oxygen (by-product of photosynthesis)



PHOTOSYNTHESIS:
- converts light energy to the chemical energy of food
  $6CO_2 + 6H_2O$ + light energy $\rightarrow C_6H_{12}O_6 + 6O_2$

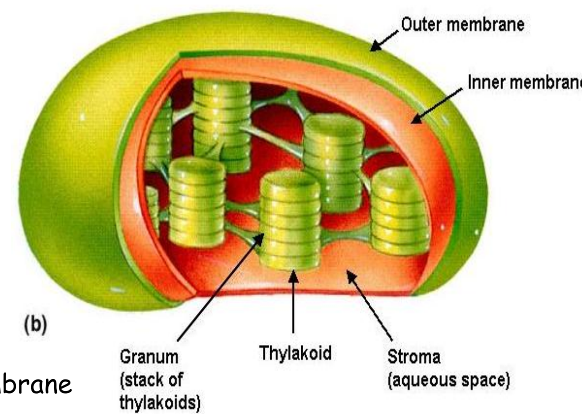
- Happens in all green parts of plants but leaves = major site

~ about half a million chloroplasts/mm^2 of leaf surface
- Color of leaf due to green pigment **chlorophyll**

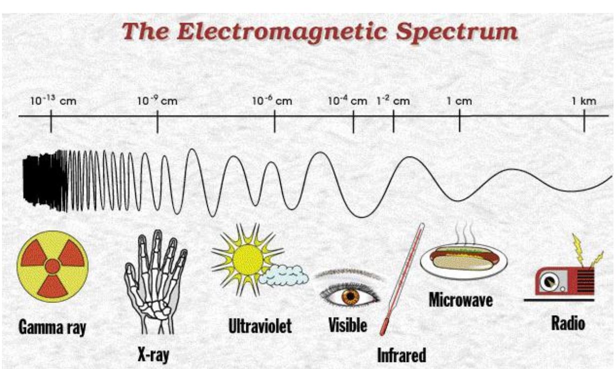
Chloroplasts mainly in **mesophyll** cells in the interior of the leaf
30–40 chloroplasts/typical mesophyll cell
O_2 and water vapor exits and CO_2 enters leaf through microscopic pores on underside of leaf = **stoma (*pl.* stomata)**

GUARD CELLS control openings- **OPEN if TURGID; CLOSED if FLACCID**
VEINS bring water from the roots and carry off sugar from mesophyll cells to nonphotosynthetic areas of plant
XYLEM-carries water/**PHLOEM** carries sugar/nutrients

CHLOROPLAST:
- Surrounded by **DOUBLE** membrane
- Central fluid filled space = **STROMA**
- System of interconnected membranous sacs = **THYLAKOIDS**
- Stack of thylakoids = **GRANUM (pl. GRANA)**
- Fluid filled compartment inside thylakoid =**THYLAKOID SPACE (lumen)**
- Chlorophyll is located in membranes of thylakoid sacs



Photosynthetic prokaryotes lack chloroplasts
- photosynthetic membranes = infolded regions of the plasma membrane



LIGHT
= form of electromagnetic radiation

Energy = inversely related to its wavelength
(ie, shorter wavelengths pack more energy)

Visible light = 380-750 nm

PIGMENTS = *light absorbing molecules*

- Only chlorophyll *a* participates directly in the light reactions;
- Other pigments have different absorption spectra;
  funnel energy to chlorophyll a

Chlorophyll *a* (the dominant pigment)

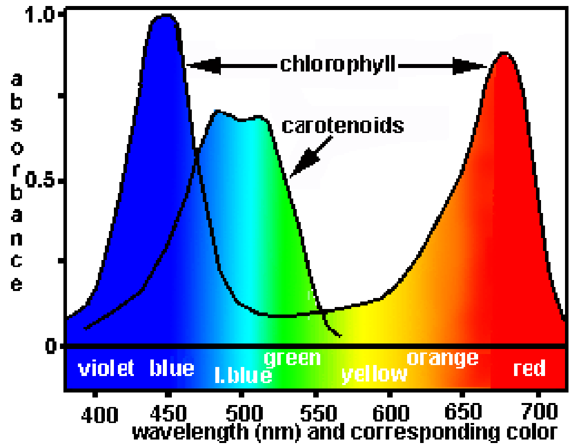
- **ABSORBS** best in the red & violet-blue wavelengths;
- **REFLECTS** green wavelengths = reason plants "look" green

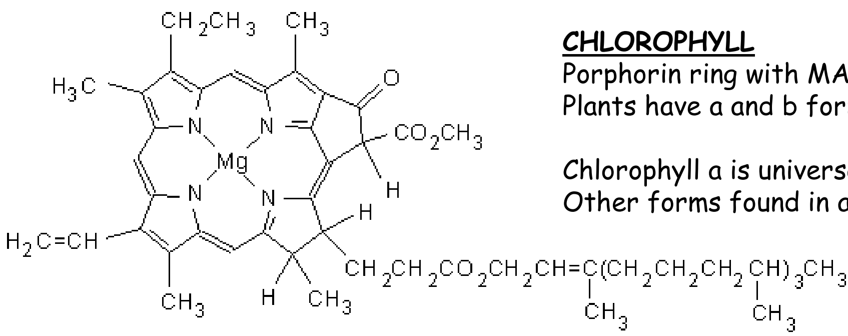
Chlorophyll b- slightly different structure

- funnels energy to chlorophyll a

CAROTENOIDS = accessory pigments (red, yellow, orange);

- Include: **CAROTENES** (orange) and **XANTHOPHYLLS** (yellow)
- funnel the energy to chlorophyll *a*
- *photoprotection*- protect chlorophyll from excessive light





CHLOROPHYLL
Porphorin ring with MAGNESIUM cofactor in center
Plants have a and b forms- slight difference in functional groups

Chlorophyll a is universal
Other forms found in algae and cyanobacteria

SPECTROPHOTOMETER

- measures the ability of pigment to absorb various wavelengths of light
- beams narrow wavelengths of light through a solution containing the pigment
- measures the fraction of light transmitted at each wavelength
- **Absorption spectrum** plots a pigment's light absorption versus wavelength.

EXCITING ELECTRONS:
When a molecule absorbs a photon of light an electron is elevated to an orbital with more potential energy
Electron moves from ground state → excited state
Excited electrons are unstable
They drop to their ground state in a billionth of a second, releasing heat energy
Some pigments, including chlorophyll, can also release a photon of light when excited (= FLUORESCENCE)
Outside of chloroplasts, if chlorophyll is illuminated, it will fluoresce and give off heat

PHOTOSYSTEMS **in thylakoid membranes**

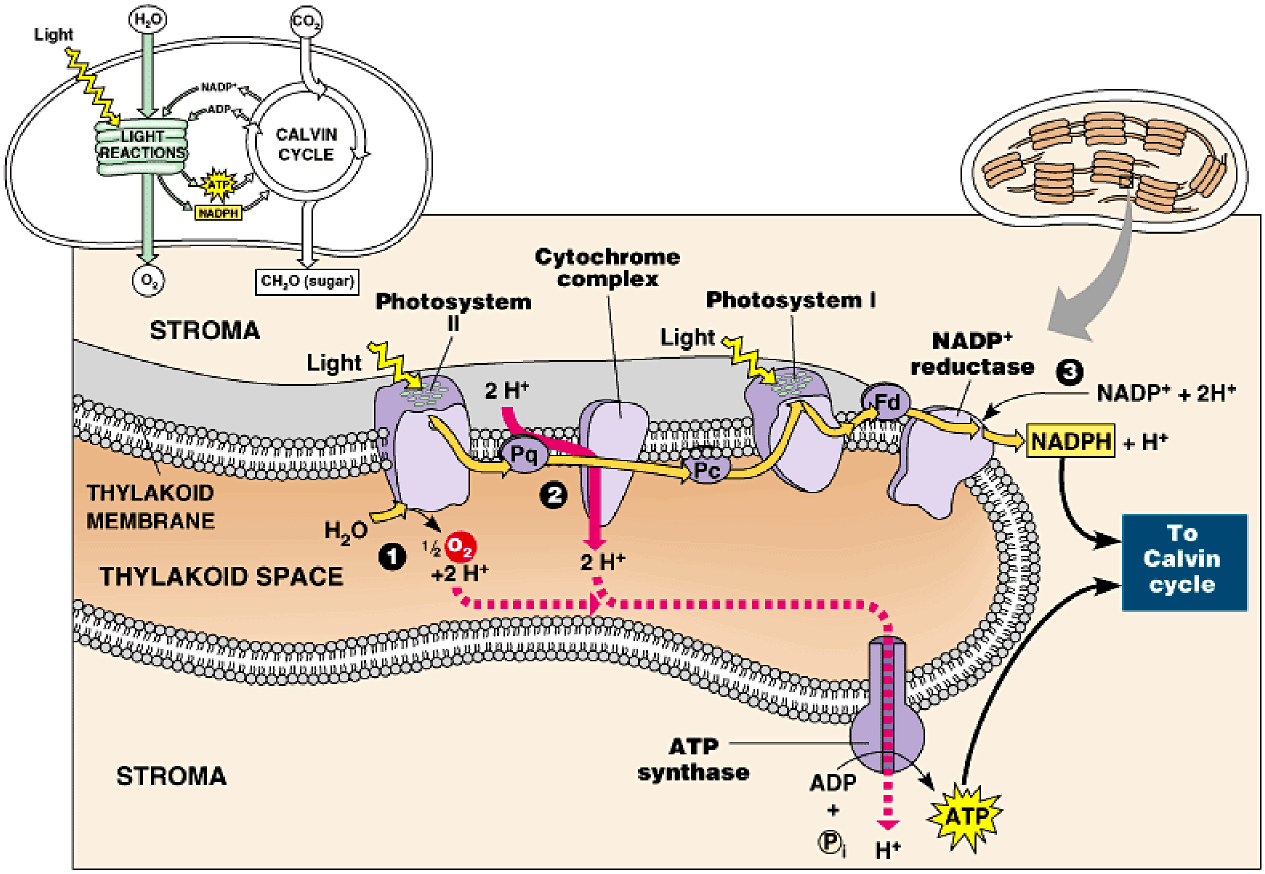
- reaction center containing chlorophyll a and "primary electron acceptor"
- surrounded by a light-harvesting complex of other pigments and proteins (chlorophyll b, carotenoids)
- act as "antenna" to collect light energy → chlorophyll a → "primary electron acceptor"

Photosystem I (PS I) reaction center absorption peak at 700 nm (P_{700})
Photosystem II (PS II) reaction center absorption peak at 680 nm (P_{680})

TWO STAGES OF PHOTOSYNTHESIS:

1) LIGHT REACTIONS (Light dependent reactions)
convert solar energy to the chemical energy of ATP and NADPH

2) CALVIN CYCLE (Light *in*dependent reactions)
uses energy from the light reactions to incorporate CO_2 from the atmosphere into sugar.
Named for Melvin Calvin (Got Nobel in 1961 for figuring out pathway)



<u>LIGHT REACTIONS:</u>

- Use solar power to store chemical energy in ATP and reducing power in electron carrier NADPH
- REQUIRE sunlight
- Two possible routes

1) **NONCYCLIC ELECTRON FLOW** (= predominant route) produces both ATP and NADPH
   - Photosystem II absorbs a photon of light
   - One of the electrons of P_{680} reaction center is excited to a higher energy state
   - Electron is captured by the primary electron acceptor, leaving the reaction center oxidized
   - Electrons are replaced by splitting a water molecule in thylakoid space
   - Oxygen released from water splitting combines with another oxygen atom; released as O2 to atmosphere
   - Hydrogen released from water splitting accumulates in thylakoid space
   - Photoexcited electrons pass along electron transport chain ending up at Photosystem I reaction center
     - energy from electrons "falling down" ETC is used by **CYTOCHROMES** to pump H^+ ions into thylakoid space
       - When chloroplasts are illuminated, thylakoid space pH ~5; stroma pH ~ 8 (1000 fold difference)
   - Photosystem I absorbs a photon of light
   - One of the electrons of P_{700} reaction center is excited to a higher energy state
   - Electron is captured by the primary electron acceptor, leaving the reaction center oxidized
     - Electrons are replaced by electrons passed from PS II down ETC
   - Photoexcited electrons pass down a second electron transport chain through the protein **FERRIDOXIN (Fd)**
   - Enzyme transfers 2 electrons to **$NADP^+$ (nicotinamide adenine dinucleotide phosphate)** to produce **NADPH**
   - H+ ions in thylakoid space provide energy to produce ATP as they diffuse down their gradient (**ELECTROMOTIVE FORCE**) back into the stroma through **ATP SYNTHASE**

2) *CYCLIC* ELECTRON FLOW

- alternative pathway for photoexcited electrons from photosystem I = CYCLIC PHOTOPHOSPHORYLATION
- Photoexcited electrons return to CYTOCHROMES instead of passing to Ferridoxin
- So produces only ATP; NO NADPH; no OXYGEN
- Used because NON CYCLIC FLOW makes equal amounts of ATP and NADPH
  - Calvin cycle requires more ATP than NADPH
  - Way to regulate amounts of ATP and NADPH needed for Calvin cycle

CHEMIOSMOSIS IN CHLOROPLASTS AND MITOCHONDRIA

SIMILARITIES

- Used by chloroplasts and mitochondria to generate ATP
- Energy from ELECTRON TRANSPORT CHAIN used to pump protons across a membrane
- Creates a H^+ gradient across membrane
- ATP SYNTHASE uses energy from diffusion of H^+ ions back across membrane to generate ATP
- Some electron carriers (cytochromes) are similar in both chloroplasts/mitochondria

DIFFERENCES:

OXIDATIVE PHOSPHORYLATION in MITOCHONDRIA

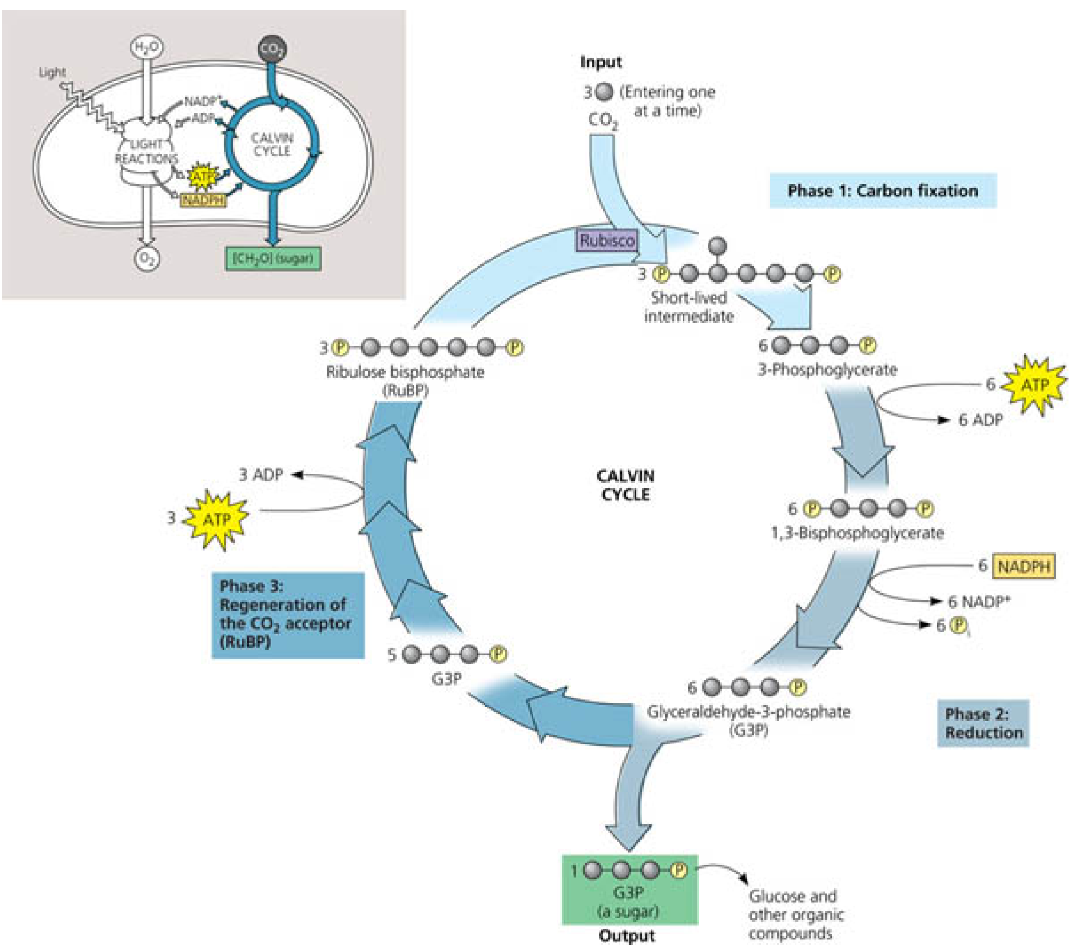
- Mitochondria transfer chemical energy from food molecules to ATP
- Mitochondrial INNER MEMBRANE pumps protons from MATRIX out to the INTERMEMBRANE SPACE
- ATP made as H^+ ions diffuse back to stroma

PHOTOPHOSPHORYLATION in CHLOROPLASTS

- Chloroplasts transform light energy into the chemical energy of ATP
- Chloroplast THYLAKOID membrane pumps protons from the stroma into the thylakoid space

CALVIN CYCLE (= LIGHT INDEPENDENT PHASE)

Originally called "Dark reactions" but don't just happen at night
Happens in stroma
Uses ATP and NADPH (made in Light Reactions) to convert CO_2 to sugar
regenerates its starting material after molecules enter and leave the cycle
= anabolic -uses energy to build sugar from smaller molecules
Carbon enters the cycle as CO_2 and leaves as sugar
Actual sugar product = three-carbon sugar, **glyceraldehyde-3-phosphate (G3P)**
Each turn of the Calvin cycle fixes carbon from 1 CO_2; 3 turns to make 1 G3P; 6 turns to make 1 glucose
Uses 18 ATP's and 12 NADPH's to make 1 glucose



CALVIN CYCLE

Phase 1: Carbon fixation

Each CO_2 molecule is attached to a five-carbon sugar, **RIBULOSE BISPHOSPHATE (RuBP)**

- This is catalyzed by RuBP carboxylase (=**RUBISCO)**
- Rubisco = most abundant protein in chloroplasts; probably the most abundant protein on Earth
- Unstable six-carbon intermediate splits in half to form two three carbon 3-phosphoglycerate for each CO_2

Phase 2: Reduction

ATP provides energy; NADPH provides reducing power to reduce intermediates
Three carbon **GLYCERALDEHYDE-3-PHOSPHATE (G3P)** is produced
G3P exits the cycle; = starting material for metabolic pathways that synthesize other organic compounds, including glucose and other carbohydrates

Phase 3: Regeneration

Rest of molecules rearrange to regenerate the starting RuBP molecules
For the net synthesis of one G3P molecule, the Calvin cycle consumes nine ATP and six NADPH (X 2 for glucose)
Light reactions regenerate ATP and NADPH

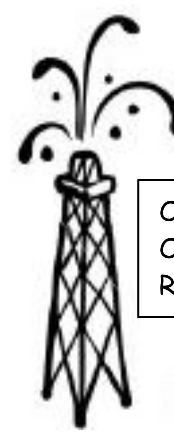
WHERE DOES THE OXYGEN IN SUGAR COME FROM: H_2O or CO_2?

$CO_2 + H_2O + \text{light energy} \rightarrow [CH_2O] + O_2$
$[CH_2O]$ represents the general formula for a sugar
Before 1930's thought splitting H_2O provided oxygen for sugar
Experiments with radio-labeled oxygen isotopes in H_2O and CO_2 showed oxygen in carbo's comes from CO_2

Evidence that chloroplasts split water molecules enabled researchers to track atoms through photosynthesis.
Powered by light, the green parts of plants produce organic compounds and O_2 from CO_2 and H_2O

Photosynthesis is a **REDOX REACTION**

- It reverses the direction of electron flow in cellular respiration
- H_2O is OXIDIZED (loses electrons)
- CO_2 is REDUCED (gains electrons) to make sugar
- Process requires energy (provided by light)



OIL RIG
Oxidation Is Losing
Reduction Is Gaining

C_3 PLANTS = Most plants (EX: rice, wheat, and soybeans)
Rubisco fixes CO_2 into three carbon compound (3PGA)
Calvin cycle happens during day when ATP and NADPH are available from light reactions

PROBLEM: Closing stomata on hot dry days to conserve water, reduces CO_2 needed for photosynthesis
When CO_2 is low Rubisco adds O_2 to RuBP instead of CO_2
= PHOTORESPIRATION

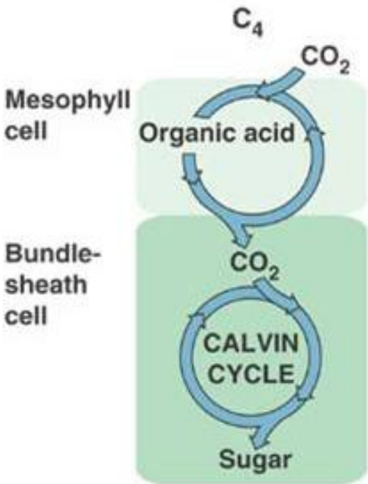
Rubisco adds O_2 to RuBP, RuBP splits into a three-carbon piece and a two-carbon piece
Two-carbon fragment is exported from chloroplast and degraded to CO_2 by mitochondria and peroxisomes.

- Unlike normal respiration, *consumes* ATP instead of making it
- Unlike photosynthesis, siphons organic material from the Calvin cycle instead of making sugar
- Photorespiration can drain away as much as 50% of the carbon fixed by the Calvin cycle on a hot, dry day.

PHOTORESPIRATION may be evolutionary baggage
When rubisco first evolved, the atmosphere had far less O_2 and more CO_2 than it does today
Inability of the active site of rubisco to exclude O_2 would have made little difference then, BUT makes a difference today when O_2 in atmosphere is higher

Alternative mechanisms of carbon fixation

Certain plant species have evolved alternate modes of carbon fixation to minimize photorespiration



C_4 PLANTS- EX: sugarcane and corn

Minimizes photorespiration and allows plant to efficiently fix CO_2 at low concentrations

Allows plants to thrive in hot regions with intense sunlight

Unique leaf anatomy; spatial separation of CO2 fixation from air/into sugar

BUNDLE SHEATH cells arranged into tightly packed sheaths around leaf veins

MESOPHYLL cells more loosely arranged cells located between bundle sheath cells and leaf surface

PEP CARBOXYLASE in mesophyll cells has very high affinity for CO_2;

Can fix CO_2 efficiently at low levels when rubisco can't

CO_2 fixed into a **FOUR CARBON** compound/ pumped into BUNDLE SHEATH cells

CO_2 is released in Bundle sheath cells, keeping CO_2 levels high enough for rubisco to work in Calvin cycle

PEP Carboxylase also found in some bacteria, but not animals or fungi.

CRASSULACEAN ACID METABOLISM (CAM) PLANTS- EX: *Succulents, cacti, pineapples*

Evolved in hot, dry environments

TEMPORAL separation of CO_2 fixation from air/into sugar

Open stomata during night when temps are lower and humidity higher

Close them during the day to save water

AT NIGHT: Fix CO_2 in mesophyll cells

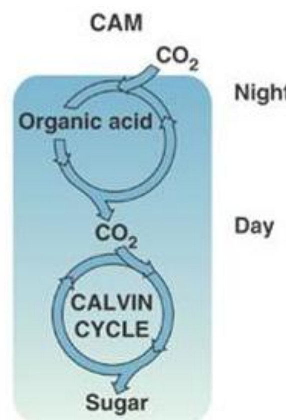
Use **PEP carboxylase**, like C_4 plants, to fix CO_2 forming four carbon compounds

Stored in vacuoles

DURING DAY:

Light reactions supply ATP & NADPH;

CO_2 is released from organic acids to complete Calvin cycle



IMPORTANCE OF PHOTOSYNTHESIS:

Energy from sunlight = stored as chemical energy in organic compounds

Sugar made in the chloroplasts supplies the entire plant with chemical energy AND with carbon skeletons to synthesize all the major organic molecules of cells

- Carbohydrate (as disaccharide sucrose) travels via the veins to nonphotosynthetic cells
- About 50% = consumed as fuel for cellular respiration in plant mitochondria

Also provides raw materials for anabolic pathways, including synthesis of proteins and lipids and formation of the extracellular polysaccharide cellulose

Cellulose = main ingredient of cell walls; = most abundant organic molecule in the plant, maybe on Earth

Plants also store excess sugar by synthesis of starch in chloroplasts and in storage cells in roots, tubers, seeds, and fruits.

On a global scale, photosynthesis is the most important process on Earth

- Provides food energy for heterotrophs, including humans
- It is responsible for the presence of oxygen in our atmosphere.
- Each year, photosynthesis synthesizes 160 billion metric tons of carbohydrate