

## 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

*Photoautotrophs* use light as a source of energy to synthesize organic compounds.

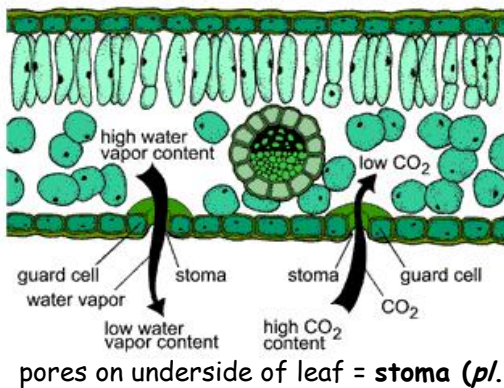
- Photosynthesis occurs in plants, algae, some other protists, and some prokaryotes.

### *Chemoautotrophs*

- 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  
 $6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$
- 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**)

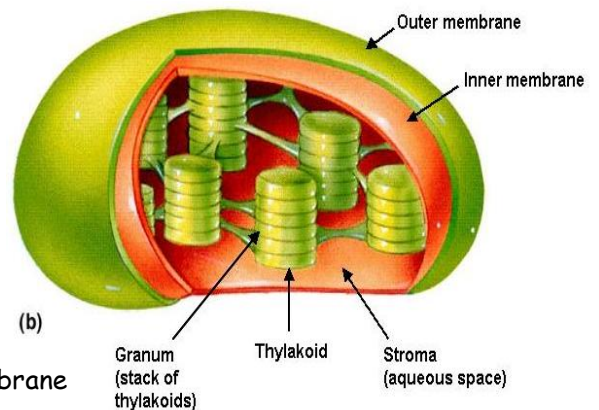
**GUARD CELLS** control openings- **OPEN** if **TURGID**; **CLOSED** if **FLACCID**

**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

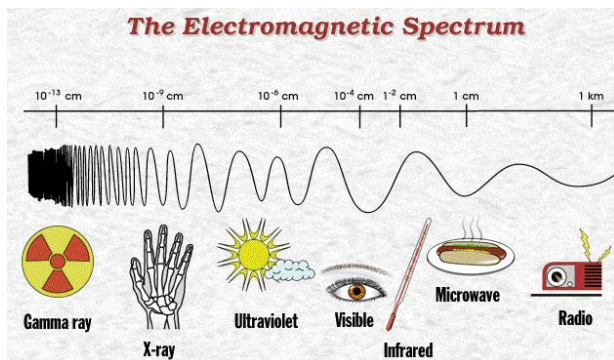
### CHLOROPLAST:

- 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)

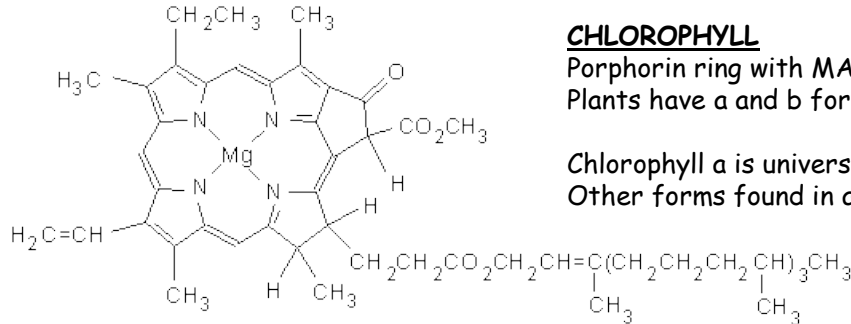
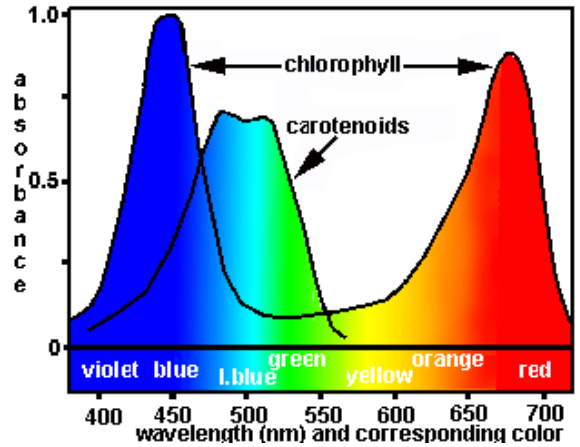
- **ABSORBS** best in the red & violet-blue wavelengths;
- **REFLECTS** green wavelengths = reason plants "look" green

**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**

Porphyrin 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<sub>700</sub>)

**Photosystem II (PS II)** reaction center absorption peak at 680 nm (P<sub>680</sub>)

**TWO STAGES OF PHOTOSYNTHESIS:**

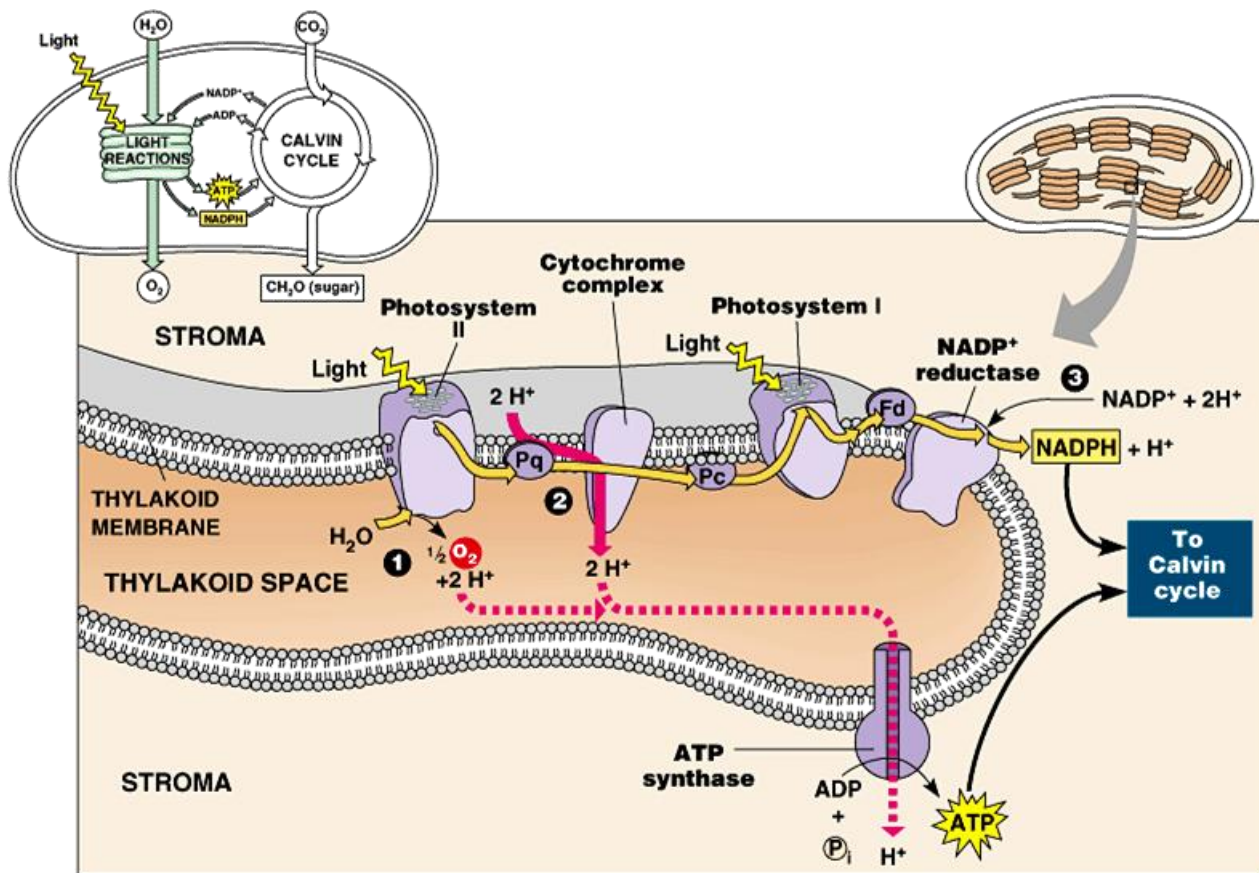
1) **LIGHT REACTIONS** (Light dependent reactions)

convert solar energy to the chemical energy of ATP and NADPH

2) **CALVIN CYCLE** (Light independent reactions)

uses energy from the light reactions to incorporate CO<sub>2</sub> from the atmosphere into sugar.

Named for Melvin Calvin (Got Nobel in 1961 for figuring out pathway)



### LIGHT REACTIONS:

- 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<sub>680</sub> 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 O<sub>2</sub> 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<sup>+</sup> 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<sub>700</sub> 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<sup>+</sup> (nicotinamide adenine dinucleotide phosphate)** to produce **NADPH**
- H<sup>+</sup> 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

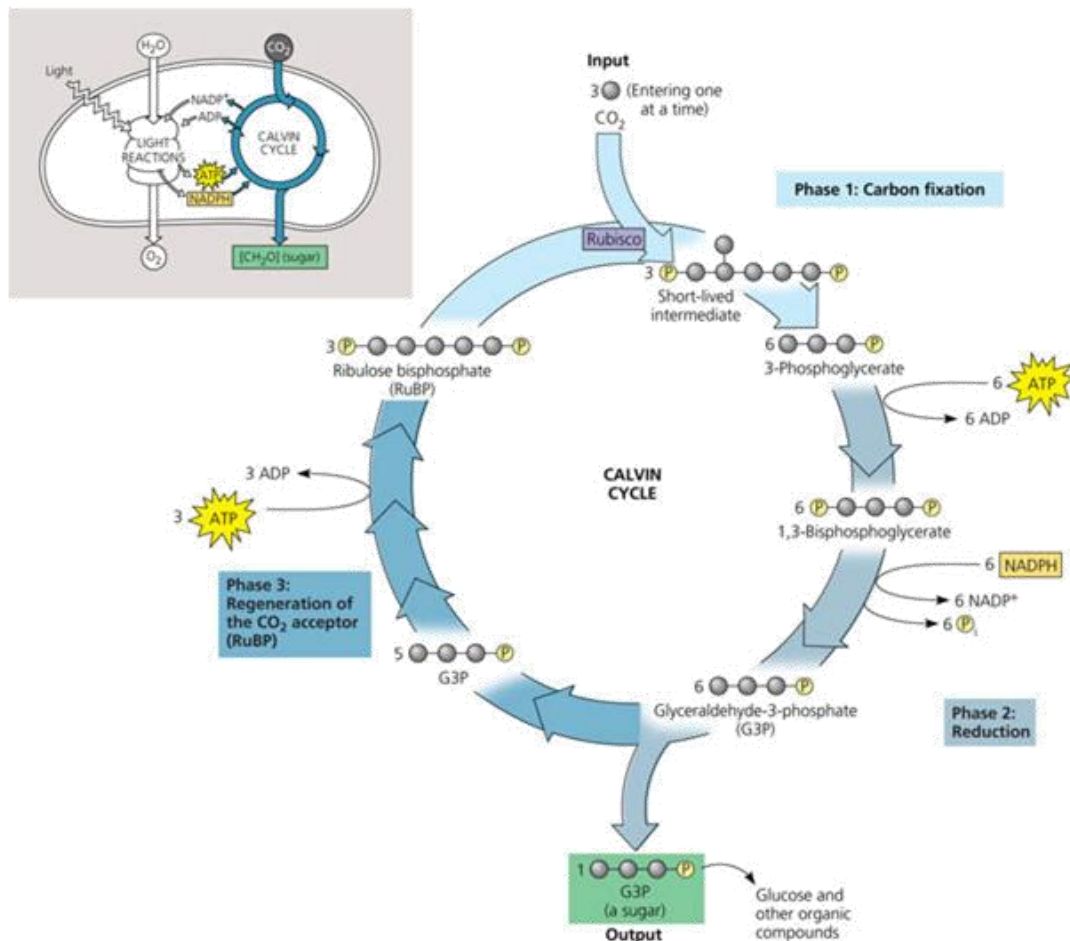
= anabolic -uses energy to build sugar from smaller molecules

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  $\text{CO}_2$  molecule is attached to a five-carbon sugar, **RIBULOSE BISPHTOSPHATE (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  $\text{CO}_2$

### Phase 2: Reduction

ATP provides energy; NADPH provides reducing power to reduce intermediates

Three carbon **GLYCERALDEHYDE-3-PHTOSPHATE (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: $\text{H}_2\text{O}$ or $\text{CO}_2$ ?**

$\text{CO}_2 + \text{H}_2\text{O} + \text{light energy} \rightarrow [\text{CH}_2\text{O}] + \text{O}_2$

$[\text{CH}_2\text{O}]$  represents the general formula for a sugar

Before 1930's thought splitting  $\text{H}_2\text{O}$  provided oxygen for sugar

Experiments with radio-labeled oxygen isotopes in  $\text{H}_2\text{O}$  and  $\text{CO}_2$  showed oxygen in carbo's comes from  $\text{CO}_2$

## **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  $\text{O}_2$  from  $\text{CO}_2$  and  $\text{H}_2\text{O}$

## Photosynthesis is a **REDOX REACTION**

- It reverses the direction of electron flow in cellular respiration
- $\text{H}_2\text{O}$  is **OXIDIZED** (loses electrons)
- $\text{CO}_2$  is **REDUCED** (gains electrons) to make sugar
- Process requires energy (provided by light)

## **C<sub>3</sub> PLANTS** = Most plants (EX: rice, wheat, and soybeans)

Rubisco fixes  $\text{CO}_2$  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  $\text{CO}_2$  needed for photosynthesis

When  $\text{CO}_2$  is low Rubisco adds  $\text{O}_2$  to RuBP instead of  $\text{CO}_2$

## = PHOTORESPIRATION

Rubisco adds  $\text{O}_2$  to RuBP, RuBP splits into a three-carbon piece and a two-carbon piece

Two-carbon fragment is exported from chloroplast and degraded to  $\text{CO}_2$  by mitochondria and peroxisomes.

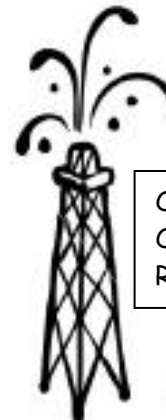
- Unlike normal respiration, *consumes* ATP instead of making it
- Unlike photosynthesis, siphons organic material from the Calvin cycle instead of making sugar
- Photorespiration can drain away as much as 50% of the carbon fixed by the Calvin cycle on a hot, dry day.

PHOTORESPIRATION may be evolutionary baggage

When rubisco first evolved, the atmosphere had far less  $\text{O}_2$  and more  $\text{CO}_2$  than it does today

Inability of the active site of rubisco to exclude  $\text{O}_2$  would have made little difference then,

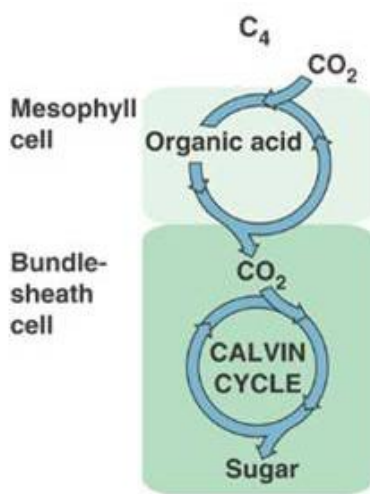
**BUT** makes a difference today when  $\text{O}_2$  in atmosphere is higher



OIL RIG  
Oxidation Is Losing  
Reduction Is Gaining

## Alternative mechanisms of carbon fixation

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



**C<sub>4</sub> PLANTS**- EX: sugarcane and corn

*Minimizes photorespiration and allows plant to efficiently fix CO<sub>2</sub> at low concentrations*

Allows plants to thrive in hot regions with intense sunlight

**Unique leaf anatomy; spatial separation of CO<sub>2</sub> 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<sub>2</sub>;

Can fix CO<sub>2</sub> efficiently at low levels when rubisco can't

CO<sub>2</sub> fixed into a **FOUR CARBON** compound/ pumped into **BUNDLE SHEATH** cells

CO<sub>2</sub> is released in Bundle sheath cells, keeping CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> in mesophyll cells

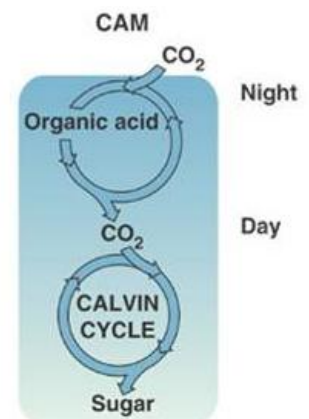
Use **PEP carboxylase**, like C<sub>4</sub> plants, to fix CO<sub>2</sub> forming four carbon compounds

Stored in vacuoles

**DURING DAY:**

Light reactions supply ATP & NADPH;

CO<sub>2</sub> 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