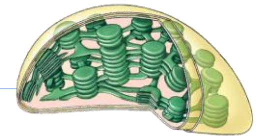
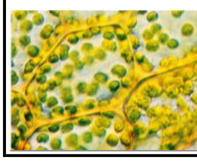


## Photosynthesis:
## Life from Light and Air



## Energy needs of life

- All life needs a constant input of energy
  - Heterotrophs (Animals)
    - get their energy from "eating others"
      - eat food = other organisms = organic molecules
    - make energy through respiration
  - Autotrophs (Plants)
    - produce their own energy (from "self")
    - convert energy of sunlight
    - build organic molecules (CHO) from $CO_2$
    - make energy & synthesize sugars through photosynthesis

consumers

producers



## How are they connected?

**Heterotrophs**

making energy & organic molecules from ingesting organic molecules

glucose + oxygen → carbon dioxide + water + energy

$C_6H_{12}O_6$ + $6O_2$ → $6CO_2$ + $6H_2O$ + ATP

oxidation = exergonic

**Autotrophs**

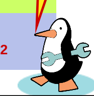
making energy & organic molecules from light energy

carbon dioxide + water + energy → glucose + oxygen

$6CO_2$ + $6H_2O$ + light energy → $C_6H_{12}O_6$ + $6O_2$

reduction = endergonic

Where's the ATP?





## What does it mean to be a plant

- Need to…
  - collect light energy
    - transform it into chemical energy
  - store light energy
    - in a stable form to be moved around the plant or stored
  - need to get building block atoms from the environment
    - C,H,O,N,P,K,S,Mg
  - produce all organic molecules needed for growth
    - carbohydrates, proteins, lipids, nucleic acids

ATP

glucose

$CO_2$

$H_2O$

N K P …



## Plant structure

- Obtaining raw materials
  - sunlight
    - leaves = solar collectors
  - $CO_2$
    - stomates = gas exchange
  - $H_2O$
    - uptake from roots
  - nutrients
    - N, P, K, S, Mg, Fe…
    - uptake from roots

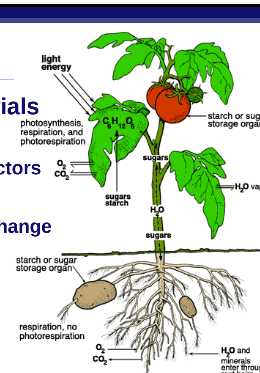
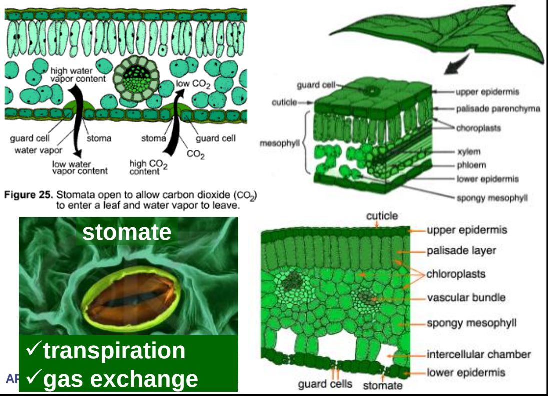
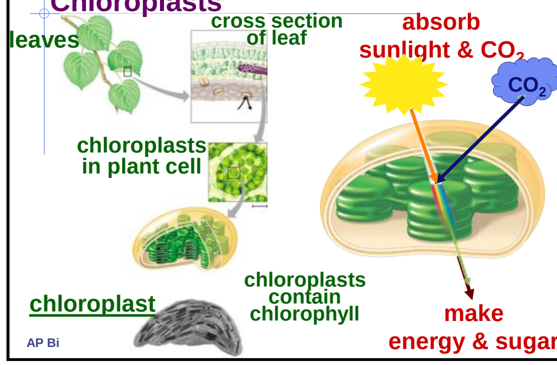



**Figure 24.** Photosynthesis, respiration, leaf water exchange, and translocation of sugar (photosynthate) in a plant.

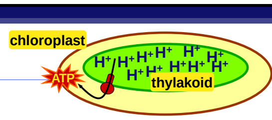



## Chloroplasts

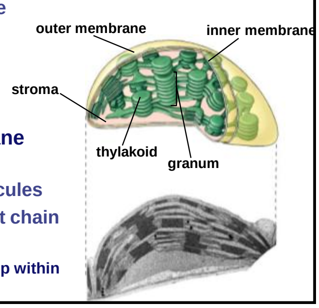



AP Bi

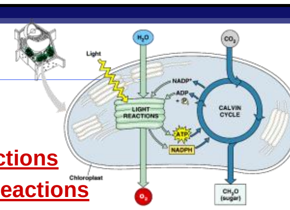
## Plant structure



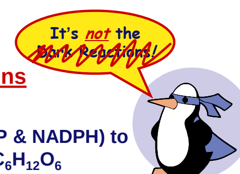

- Chloroplasts
  - double membrane
  - stroma
    - fluid-filled interior
  - thylakoid sacs
  - grana stacks
- Thylakoid membrane contains
  - chlorophyll molecules
  - electron transport chain
  - ATP synthase
    - $H^+$ gradient built up within thylakoid sac



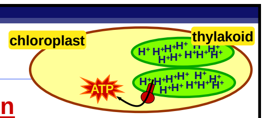

## Photosynthesis



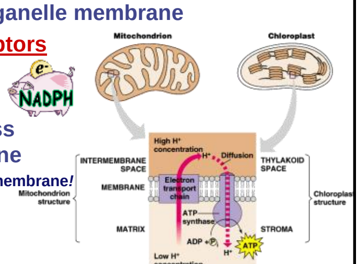

- Light reactions
  - light-dependent reactions
  - energy conversion reactions
    - convert solar energy to chemical energy
    - ATP & NADPH
- Calvin cycle
  - light-independent reactions
  - sugar building reactions
    - uses chemical energy (ATP & NADPH) to reduce $CO_2$ & synthesize $C_6H_{12}O_6$


## Light reactions

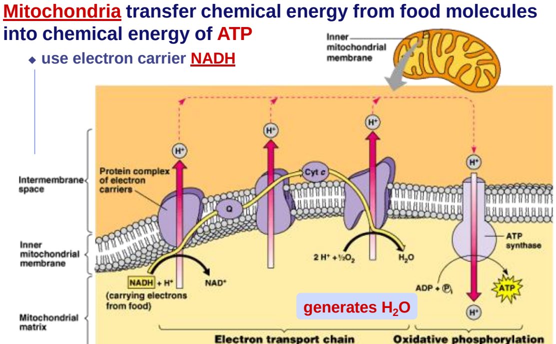



- Electron Transport Chain
  - like in cellular respiration
  - proteins in organelle membrane
  - electron acceptors
    - NADPH
  - proton ($H^+$) gradient across inner membrane
    - find the double membrane!
  - ATP synthase enzyme




## ETC of Respiration

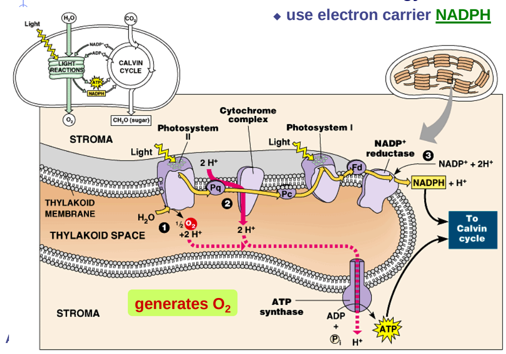
Mitochondria transfer chemical energy from food molecules into chemical energy of ATP
- use electron carrier NADH



# AP Biology

## ETC of Photosynthesis

- Chloroplasts transform light energy into chemical energy of ATP
  - use electron carrier NADPH

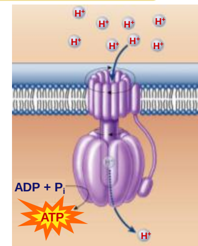



## The ATP that "Jack" built

photosynthesis — **sunlight**

respiration — **breakdown of $C_6H_{12}O_6$**

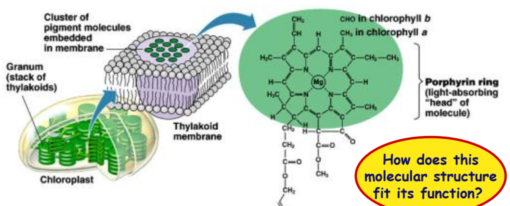
- moves the electrons
- runs the pump
- pumps the protons
- builds the gradient
- drives the flow of protons through ATP synthase
- bonds $P_i$ to ADP
- generates the ATP



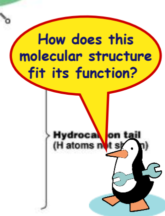

AP

… that evolution built

## Pigments of photosynthesis

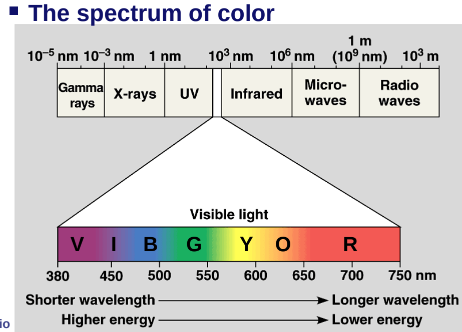



- Chlorophylls & other pigments
  - embedded in thylakoid membrane
  - arranged in a "photosystem"
    - collection of molecules
  - structure-function relationship




## A Look at Light

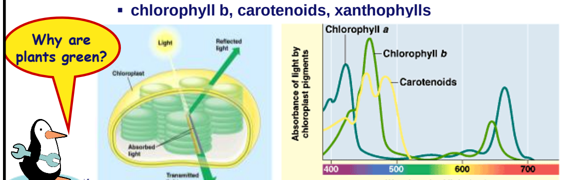
- The spectrum of color




AP Bio

## Light: absorption spectra

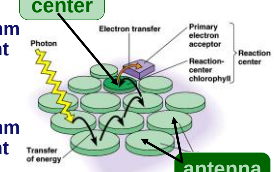
- Photosynthesis gets energy by absorbing wavelengths of light
  - chlorophyll a
    - absorbs best in red & blue wavelengths & least in green
  - accessory pigments with different structures absorb light of different wavelengths
    - chlorophyll b, carotenoids, xanthophylls




## Photosystems of photosynthesis

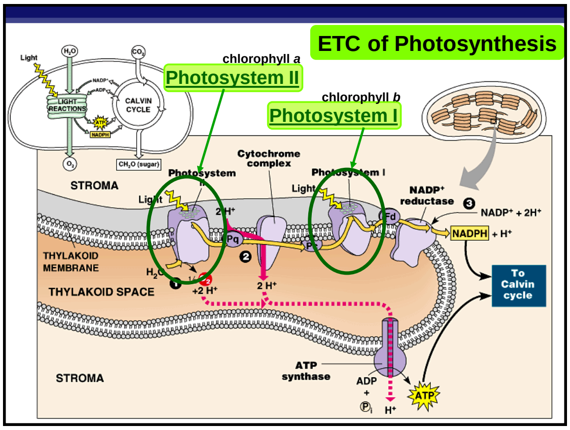
- 2 photosystems in thylakoid membrane
  - collections of chlorophyll molecules
  - act as light-gathering molecules
  - Photosystem II
    - chlorophyll a
    - $P_{680}$ = absorbs 680nm wavelength red light
  - Photosystem I
    - chlorophyll b
    - $P_{700}$ = absorbs 700nm wavelength red light

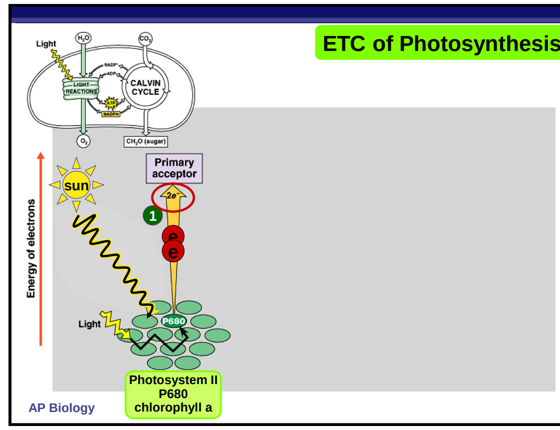
reaction center

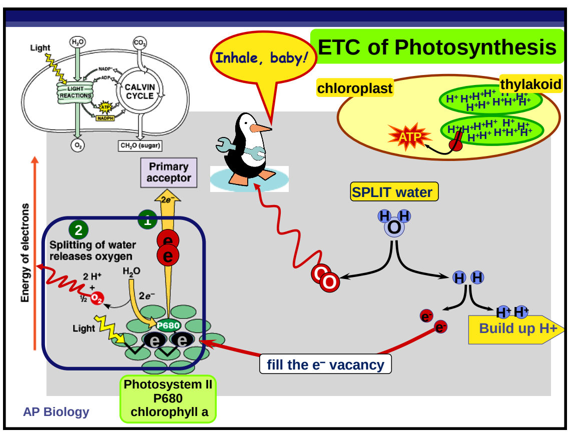


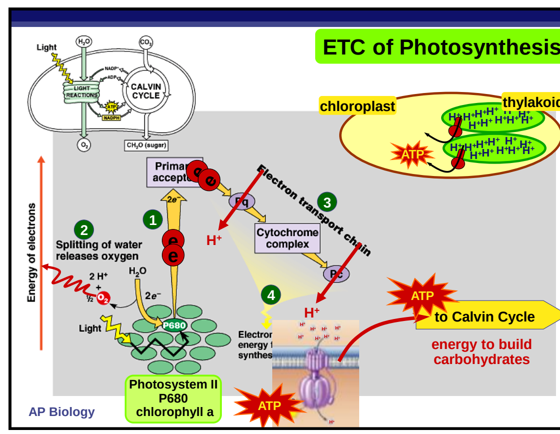

antenna pigments

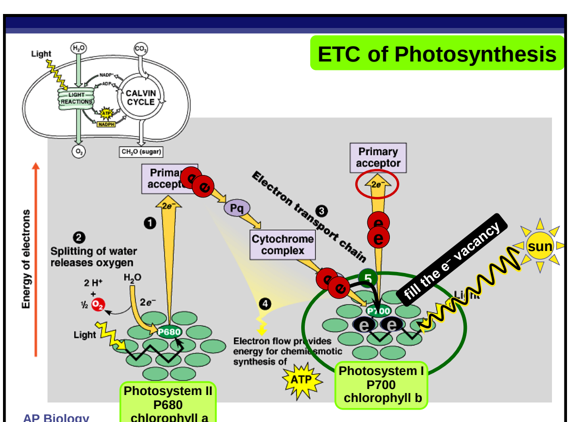
AP Biology

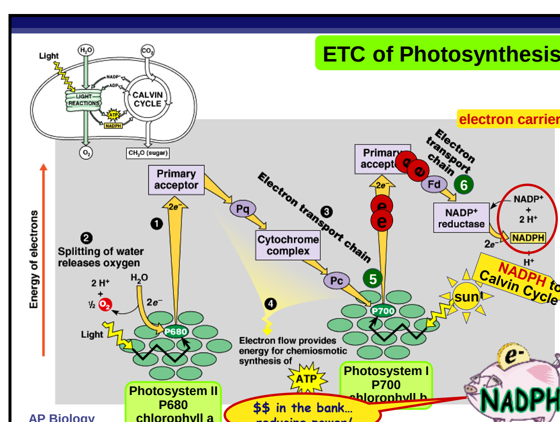

ETC of Photosynthesis
chlorophyll a
Photosystem II
chlorophyll b
Photosystem I
Cytochrome complex
NADP+ reductase
NADP+ + 2H+
NADPH + H+
STROMA
THYLAKOID MEMBRANE
THYLAKOID SPACE
To Calvin cycle
ATP synthase
ADP
ATP
STROMA
CALVIN CYCLE
LIGHT REACTIONS


ETC of Photosynthesis
Primary acceptor
sun
Energy of electrons
Light
P680
Photosystem II
P680
chlorophyll a
AP Biology

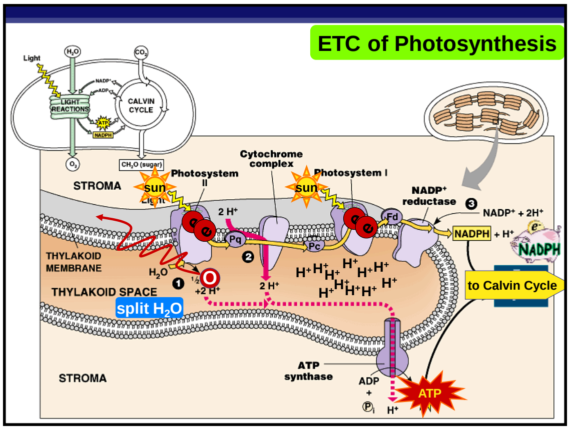

ETC of Photosynthesis
Inhale, baby!
chloroplast
thylakoid
ATP
Primary acceptor
SPLIT water
Splitting of water releases oxygen
Energy of electrons
Build up H+
fill the e⁻ vacancy
Photosystem II
P680
chlorophyll a
AP Biology


ETC of Photosynthesis
chloroplast
thylakoid
ATP
Electron transport chain
Cytochrome complex
Splitting of water releases oxygen
Energy of electrons
ATP
to Calvin Cycle
energy to build carbohydrates
ATP
Photosystem II
P680
chlorophyll a
AP Biology


ETC of Photosynthesis
Primary acceptor
Electron transport chain
Cytochrome complex
fill the e⁻ vacancy
sun
Splitting of water releases oxygen
Energy of electrons
Electron flow provides energy for chemiosmotic synthesis of
ATP
Photosystem II
P680
chlorophyll a
Photosystem I
P700
chlorophyll b
AP Biology


ETC of Photosynthesis
electron carrier
Electron transport chain
Primary acceptor
Cytochrome complex
NADP+ reductase
NADPH
NADPH to Calvin Cycle
sun
Splitting of water releases oxygen
Energy of electrons
Electron flow provides energy for chemiosmotic synthesis of
ATP
Photosystem II
P680
chlorophyll a
Photosystem I
P700
$$ in the bank... reducing power!
NADPH
AP Biology

## ETC of Photosynthesis




## ETC of Photosynthesis

- ETC uses light energy to produce
  - ATP & NADPH
    - go to Calvin cycle
- PS II absorbs light
  - excited electron passes from chlorophyll to "primary electron acceptor"
  - need to replace electron in chlorophyll
  - enzyme extracts electrons from $H_2O$ & supplies them to chlorophyll
    - splits $H_2O$
    - O combines with another O to form $O_2$
    - $O_2$ released to atmosphere
    - and we breathe easier!

AP Biology

## Experimental evidence

- Where did the $O_2$ come from?
  - radioactive tracer = $O_{18}$

Experiment 1

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

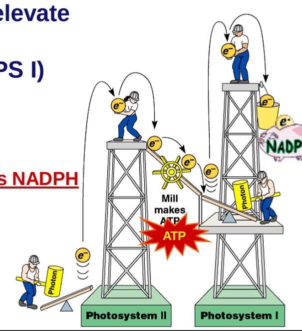
Experiment 2

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

Proved $O_2$ came from $H_2O$ not $CO_2$ = plants split $H_2O$!

## Noncyclic Photophosphorylation

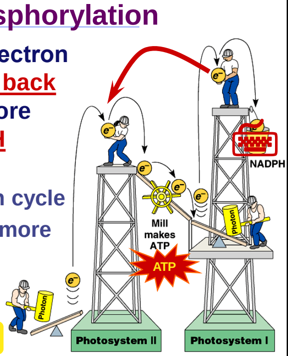
- Light reactions elevate electrons in 2 steps (PS II & PS I)
  - PS II generates energy as ATP
  - PS I generates reducing power as NADPH




AP Biology

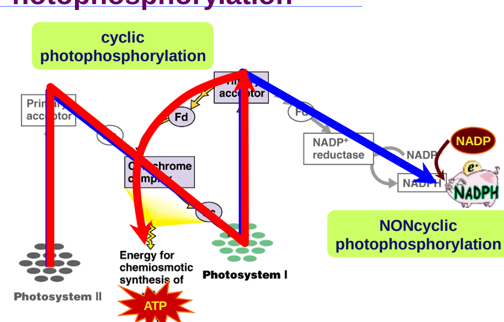
## Cyclic photophosphorylation

- If PS I can't pass electron to NADP…it cycles back to PS II & makes more ATP, but no NADPH
  - coordinates light reactions to Calvin cycle
  - Calvin cycle uses more ATP than NADPH




18 ATP + 12 NADPH $\rightarrow$ 1 $C_6H_{12}O_6$

## Photophosphorylation



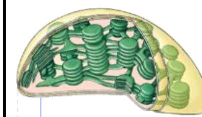

AP Biology

## Photosynthesis summary

- Where did the energy come from?
- Where did the electrons come from?
- Where did the $H_2O$ come from?
- Where did the $O_2$ come from?
- Where did the $O_2$ go?
- Where did the $H^+$ come from?
- Where did the ATP come from?
- What will the ATP be used for?
- Where did the NADPH come from?
- What will the NADPH be used for?



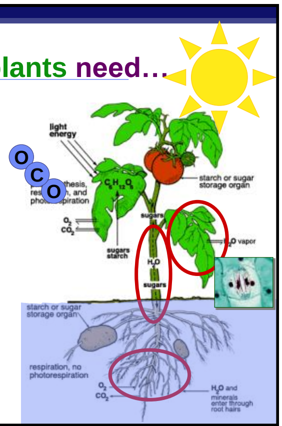
*...stay tuned for the Calvin cycle*




## Photosynthesis: Variations on the Theme


## Remember what plants need…

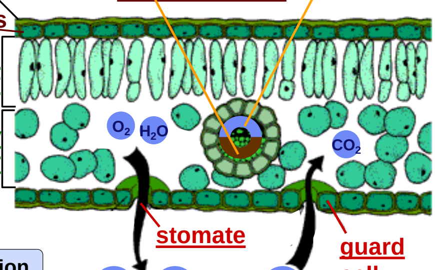
- Photosynthesis
  - light reactions
    - light ← sun
    - $H_2O$ ← ground
  - Calvin cycle
    - $CO_2$ ← air




What structures have plants evolved to supply these needs?

## Leaf Structure

vascular bundle
xylem (water)
phloem (sugar)
cuticle
epidermis
palisades layer
spongy layer




stomate
guard cell

Transpiration

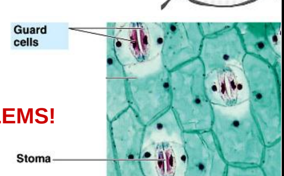
Gas exchange

$O_2$ $H_2O$ $CO_2$

## Controlling water loss from leaves

- Hot or dry days
  - stomates close to conserve water
  - guard cells
    - gain $H_2O$ = stomates open
    - lose $H_2O$ = stomates close
  - adaptation to living on land, but…

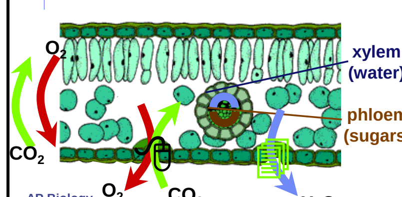
creates PROBLEMS!



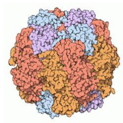



## When stomates close…

- Closed stomates lead to…
  - $O_2$ build up → from light reactions
  - $CO_2$ is depleted → in Calvin cycle
    - causes problems in Calvin Cycle



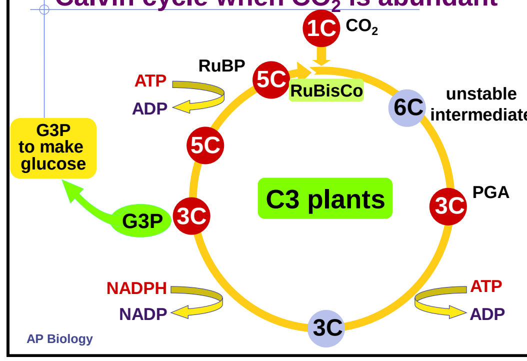

## Inefficiency of RuBisCo: $CO_2$ vs $O_2$



- RuBisCo in Calvin cycle
  - carbon fixation enzyme
    - normally bonds C to RuBP
    - $CO_2$ is the optimal substrate
    - reduction of RuBP
    - building sugars
  - photosynthesis
  - when $O_2$ concentration is high
    - RuBisCo bonds O to RuBP
    - $O_2$ is a competitive substrate
    - oxidation of RuBP
    - breakdown sugars
  - photorespiration

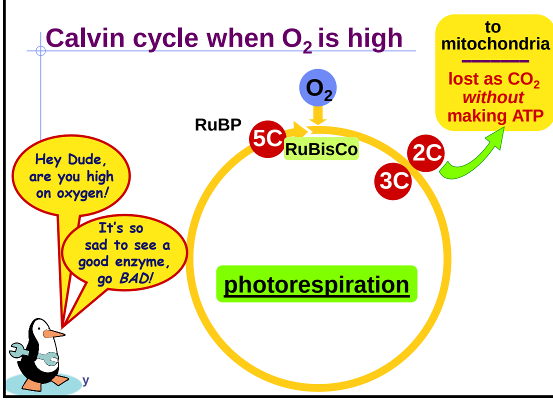


## Calvin cycle when $CO_2$ is abundant






## Calvin cycle when $O_2$ is high




## Impact of Photorespiration

- Oxidation of RuBP
  - short circuit of Calvin cycle
  - loss of carbons to $CO_2$
    - can lose 50% of carbons fixed by Calvin cycle
  - reduces production of photosynthesis
    - no ATP (energy) produced
    - no $C_6H_{12}O_6$ (food) produced
  - if photorespiration could be reduced, plant would become 50% more efficient
    - strong selection pressure to evolve alternative carbon fixation systems



## Reducing photorespiration

- Separate carbon fixation from Calvin cycle
  - C4 plants
    - PHYSICALLY separate carbon fixation from Calvin cycle
      - different cells to fix carbon vs. where Calvin cycle occurs
      - store carbon in 4C compounds
    - different enzyme to capture $CO_2$ (fix carbon)
      - PEP carboxylase
    - different leaf structure
  - CAM plants
    - separate carbon fixation from Calvin cycle by TIME OF DAY
    - fix carbon during night
      - store carbon in 4C compounds
    - perform Calvin cycle during day

## C4 plants

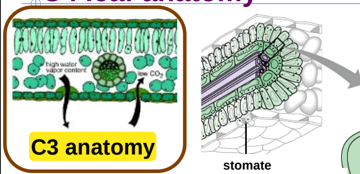
corn

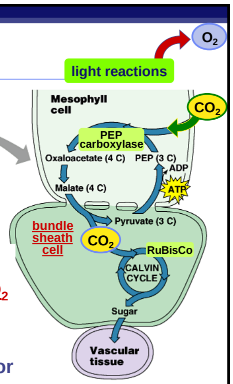
- A better way to capture $CO_2$
  - 1st step before Calvin cycle, fix carbon with enzyme PEP carboxylase
    - store as 4C compound
  - adaptation to hot, dry climates
    - have to close stomates a lot
    - different leaf anatomy
  - sugar cane, corn, other grasses…

sugar cane

PEP (3C) + $CO_2$ → oxaloacetate (4C)

## C4 leaf anatomy



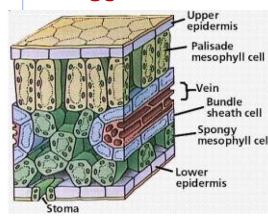




- PEP carboxylase enzyme
  - higher attraction for $CO_2$ than $O_2$
    - better than RuBisCo
  - fixes $CO_2$ in 4C compounds
  - regenerates $CO_2$ in inner cells for RuBisCo
    - keeping $O_2$ away from RuBisCo

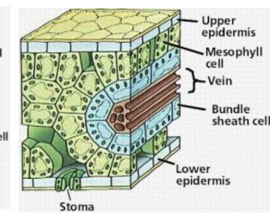
C4 anatomy

## Comparative anatomy


C3




C4




PHYSICALLY separate C fixation from Calvin cycle

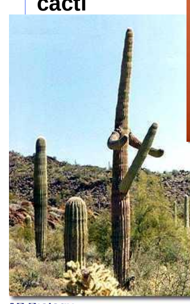
## CAM (Crassulacean Acid Metabolism) plants

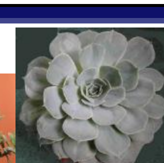
- Adaptation to hot, dry climates
  - separate carbon fixation from Calvin cycle by TIME
    - close stomates during day
    - open stomates during night
  - at night: open stomates & fix carbon in 4C "storage" compounds
  - in day: release $CO_2$ from 4C acids to Calvin cycle
    - increases concentration of $CO_2$ in cells
  - succulents, some cacti, pineapple



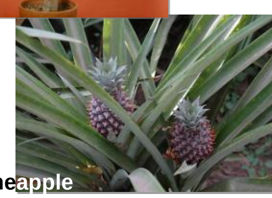

## CAM plants

cacti





succulents



pineapple

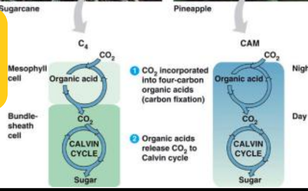


## C4 vs CAM Summary

solves $CO_2$ / $O_2$ gas exchange vs. $H_2O$ loss challenge



**C4 plants**
separate 2 steps of C fixation anatomically in 2 different cells

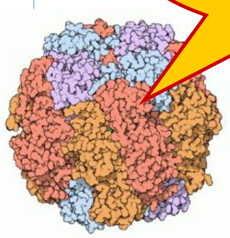



**CAM plants**
separate 2 steps of C fixation temporally = 2 different times
night vs. day



## Why the C3 problem?

- Possibly evolutionary baggage
  - Rubisco evolved in high $CO_2$ atmosphere
    - there wasn't strong selection against active site of Rubisco accepting both $CO_2$ & $O_2$
- Today it makes a difference
  - 21% $O_2$ vs. 0.03% $CO_2$
  - photorespiration can drain away 50% of carbon fixed by Calvin cycle on a hot, dry day
  - strong selection pressure to evolve better way to fix carbon & minimize photorespiration



It's not so easy as it looks…

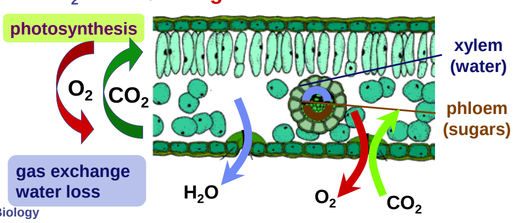
Any Questions??

## Ghosts of Lectures Past (storage)



## A second look inside a leaf…

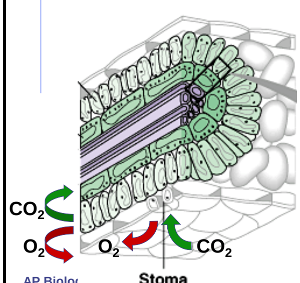
- Gas exchange & water flow
  - $CO_2$ in → for Calvin cycle
  - $O_2$ out → waste from light reactions
  - $H_2O$ out → for light reactions






## C4 photosynthesis

PHYSICALLY separated C fixation from Calvin cycle




- Outer cells
  - light reaction & carbon fixation
  - pumps $CO_2$ to inner cells
  - keeps $O_2$ away from inner cells
    - away from RuBisCo
- Inner cells
  - Calvin cycle
  - glucose to veins