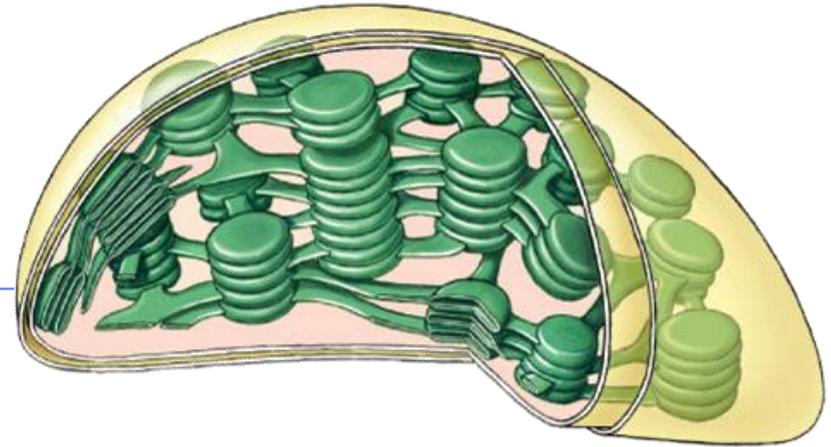




Benjamin
Cummings



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”

consumers

- ◆ eat food = other organisms = organic molecules

- make energy through respiration

- ◆ Autotrophs (Plants)

- produce their own energy (from “self”)

- convert energy of sunlight

producers

- build organic molecules (CHO) from CO₂

- make energy & synthesize sugars through photosynthesis

How are they connected?

Heterotrophs

making energy & organic molecules from ingesting organic molecules

glucose + oxygen → carbon + water + energy
dioxide



oxidation = exergonic

Autotrophs

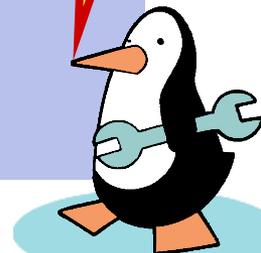
making energy & organic molecules from light energy

carbon + water + energy → glucose + oxygen
dioxide



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

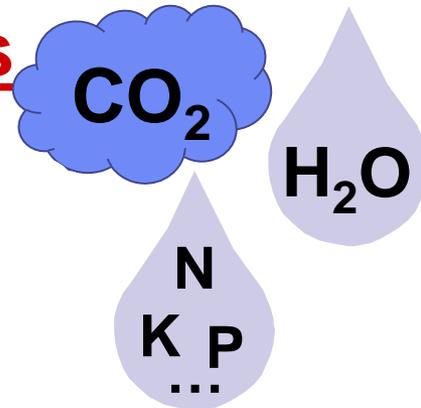
■ C,H,O,N,P,K,S,Mg

◆ produce all organic molecules needed for growth

■ carbohydrates, proteins, lipids, nucleic acids



glucose



Plant structure

■ Obtaining raw materials

◆ sunlight

- leaves = solar collectors

◆ CO₂

- stomates = gas exchange

◆ H₂O

- uptake from roots

◆ nutrients

- N, P, K, S, Mg, Fe...
- uptake from roots

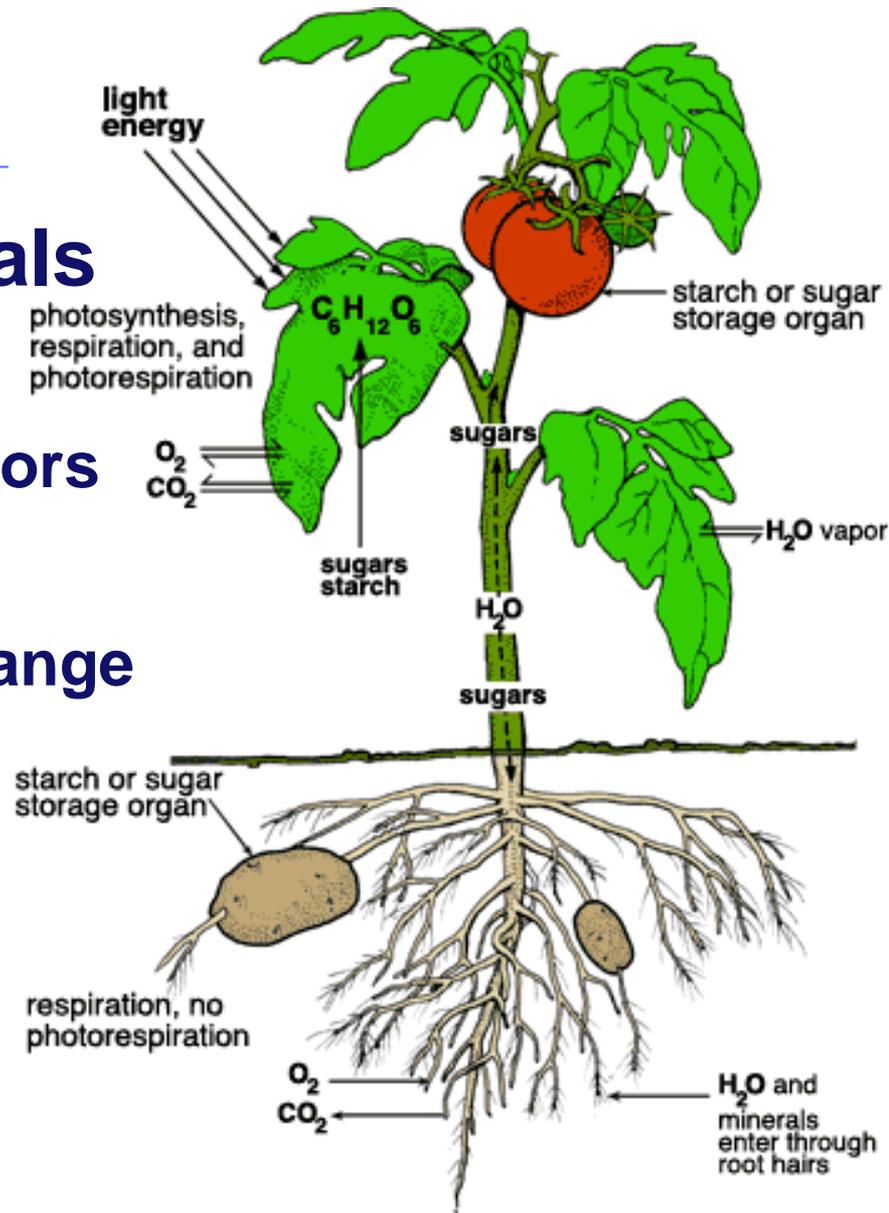


Figure 24. Photosynthesis, respiration, leaf water exchange, and translocation of sugar (photosynthate) in a plant.

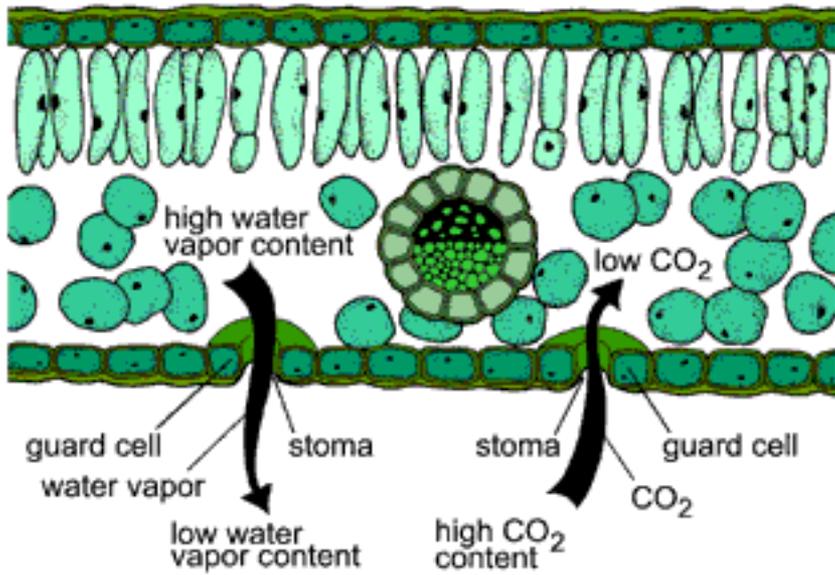
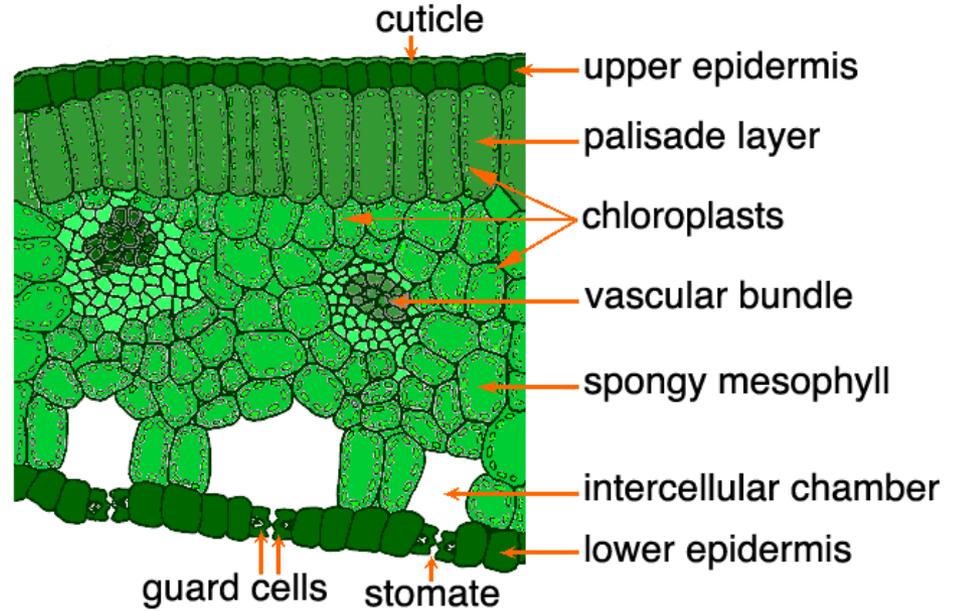
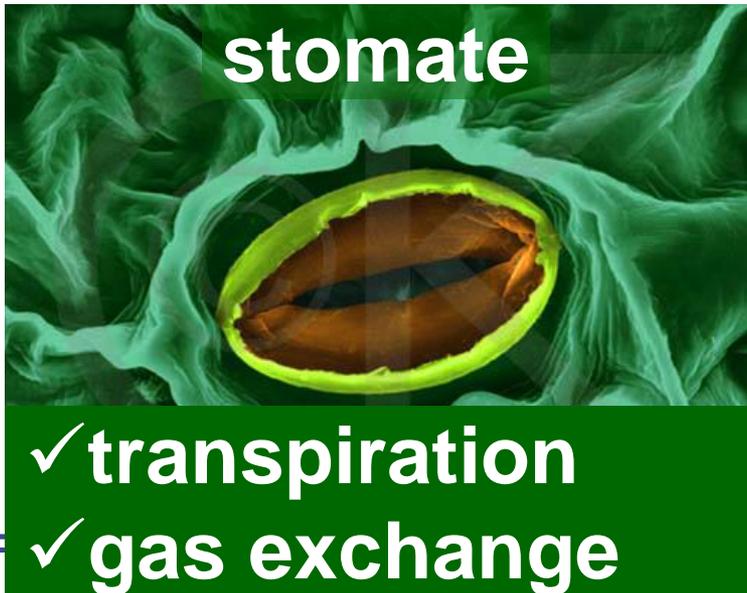
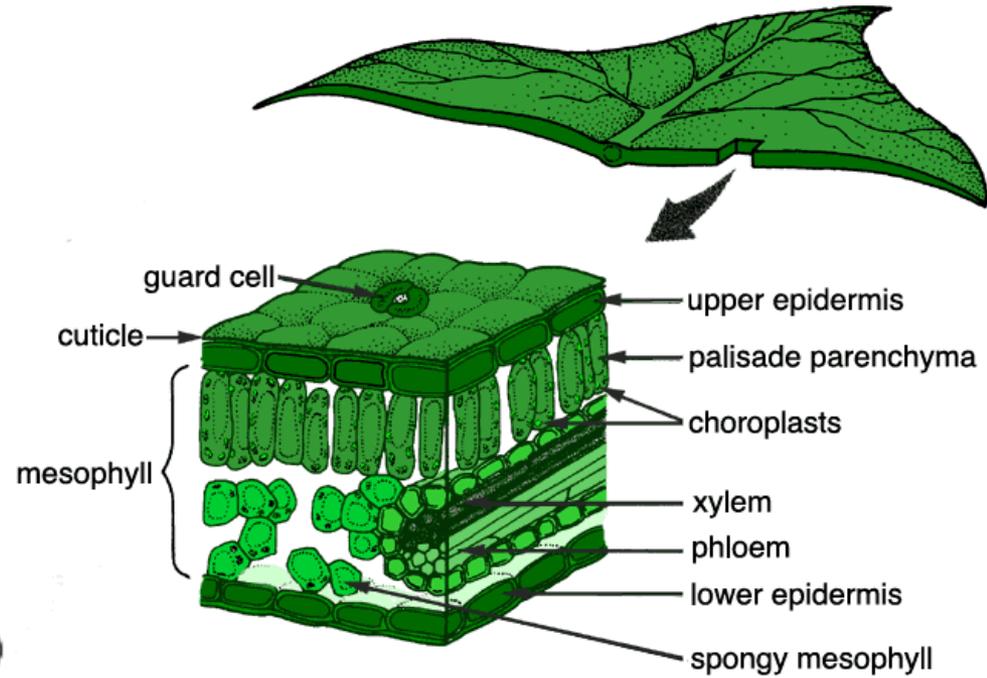
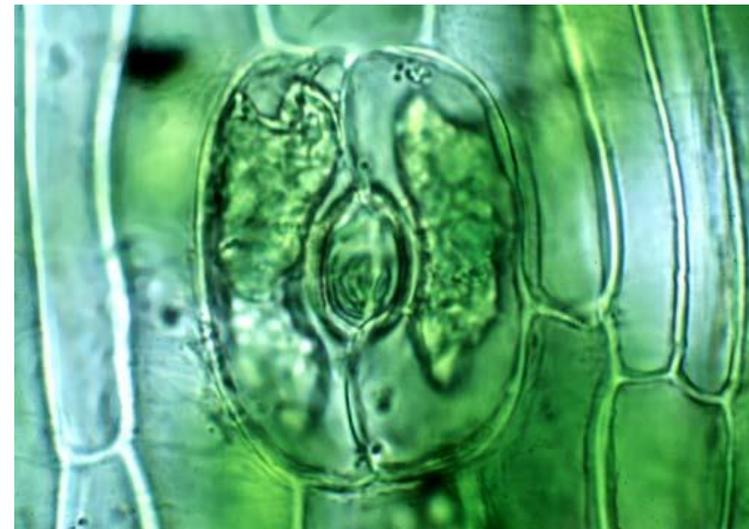
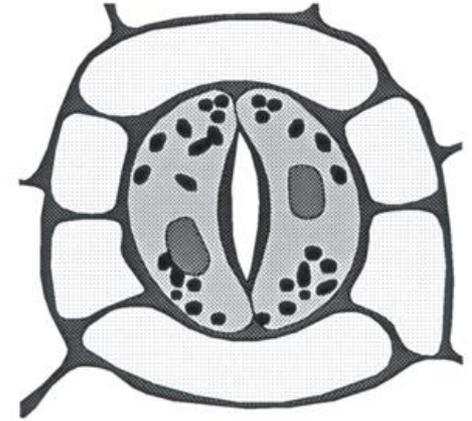


Figure 25. Stomata open to allow carbon dioxide (CO_2) to enter a leaf and water vapor to leave.

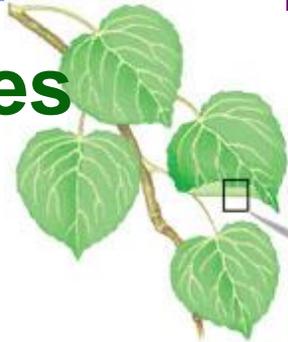


Stomates

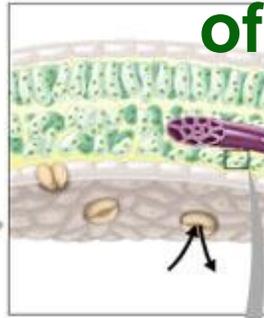


Chloroplasts

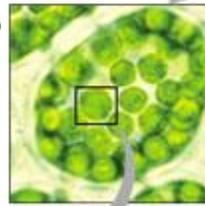
leaves



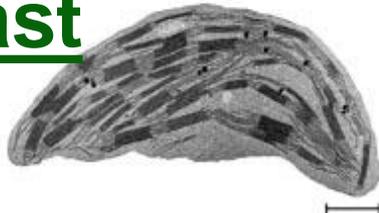
cross section of leaf



chloroplasts in plant cell

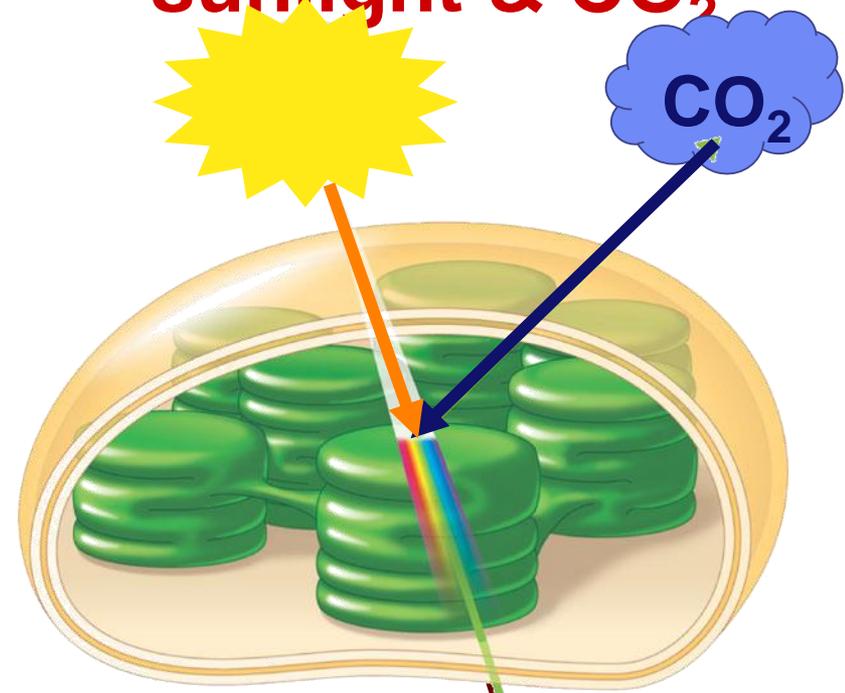


chloroplast



chloroplasts contain chlorophyll

absorb sunlight & CO₂



make energy & sugar

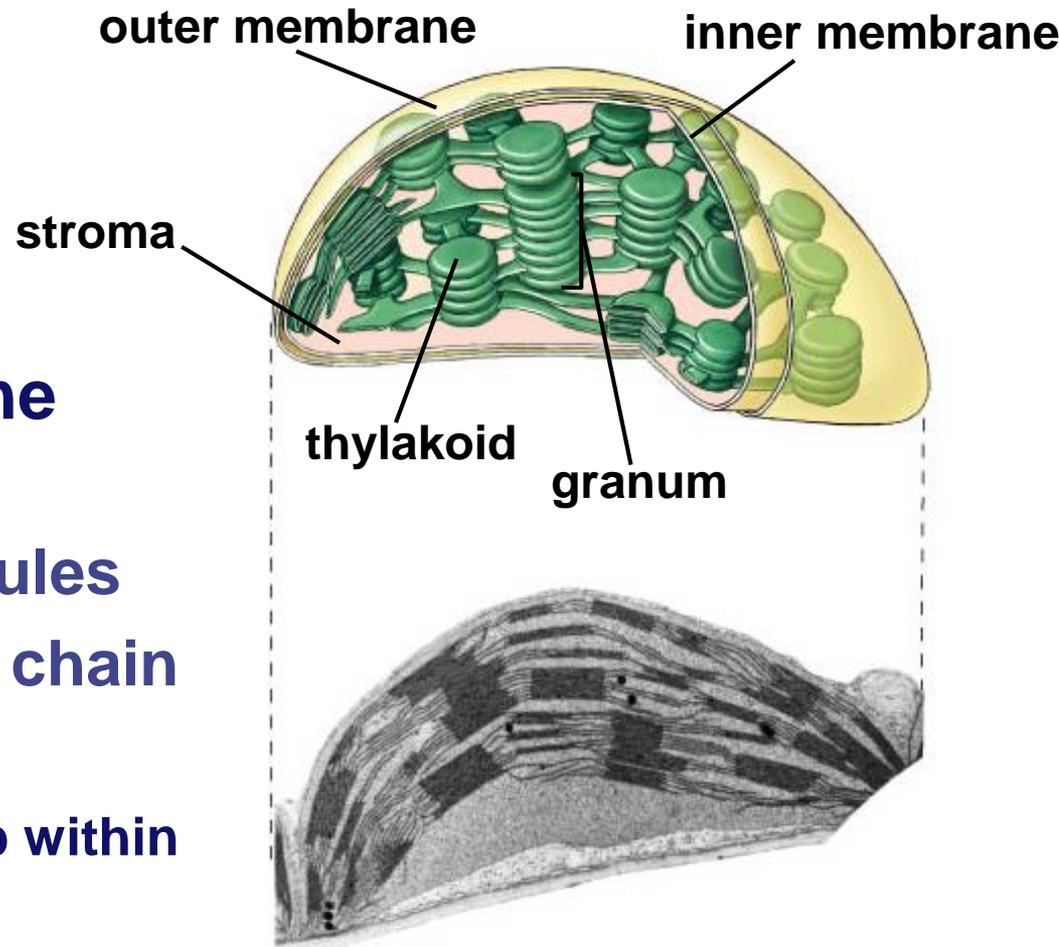
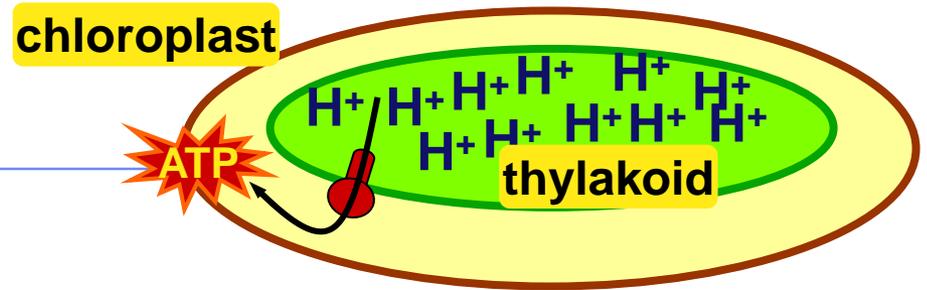
Plant structure

■ Chloroplasts

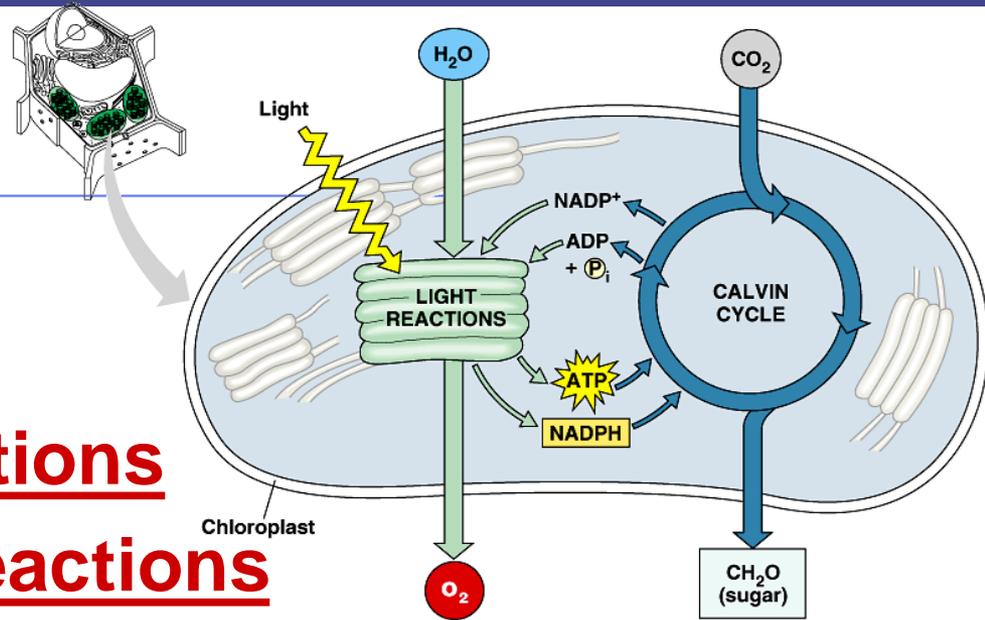
- ◆ double membrane
- ◆ **stroma**
 - fluid-filled interior
- ◆ **thylakoid sacs**
- ◆ **grana stacks**

■ 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

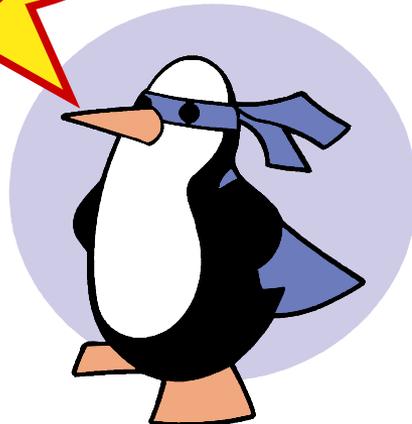


Calvin cycle

- ◆ light-independent reactions
- ◆ sugar building reactions

- uses chemical energy (ATP & NADPH) to reduce CO₂ & synthesize C₆H₁₂O₆

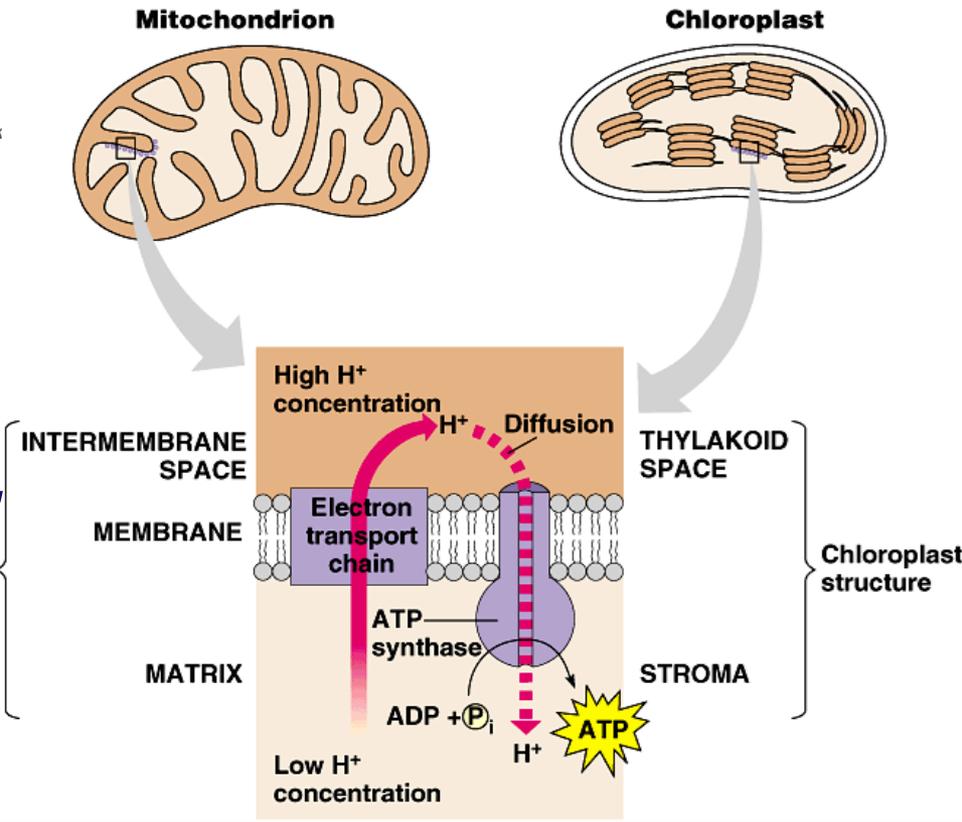
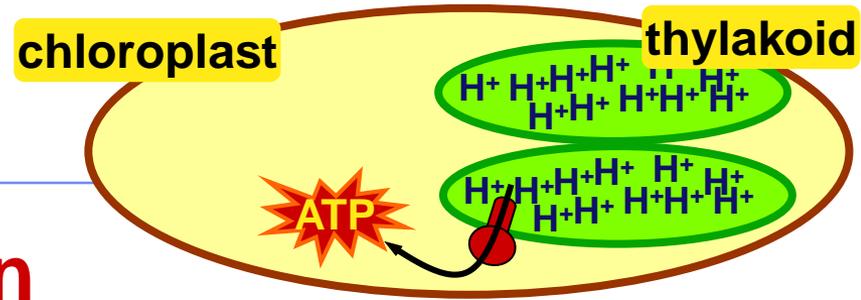
It's not the ~~dark~~ Reactions!



Light reactions

■ Electron Transport Chain

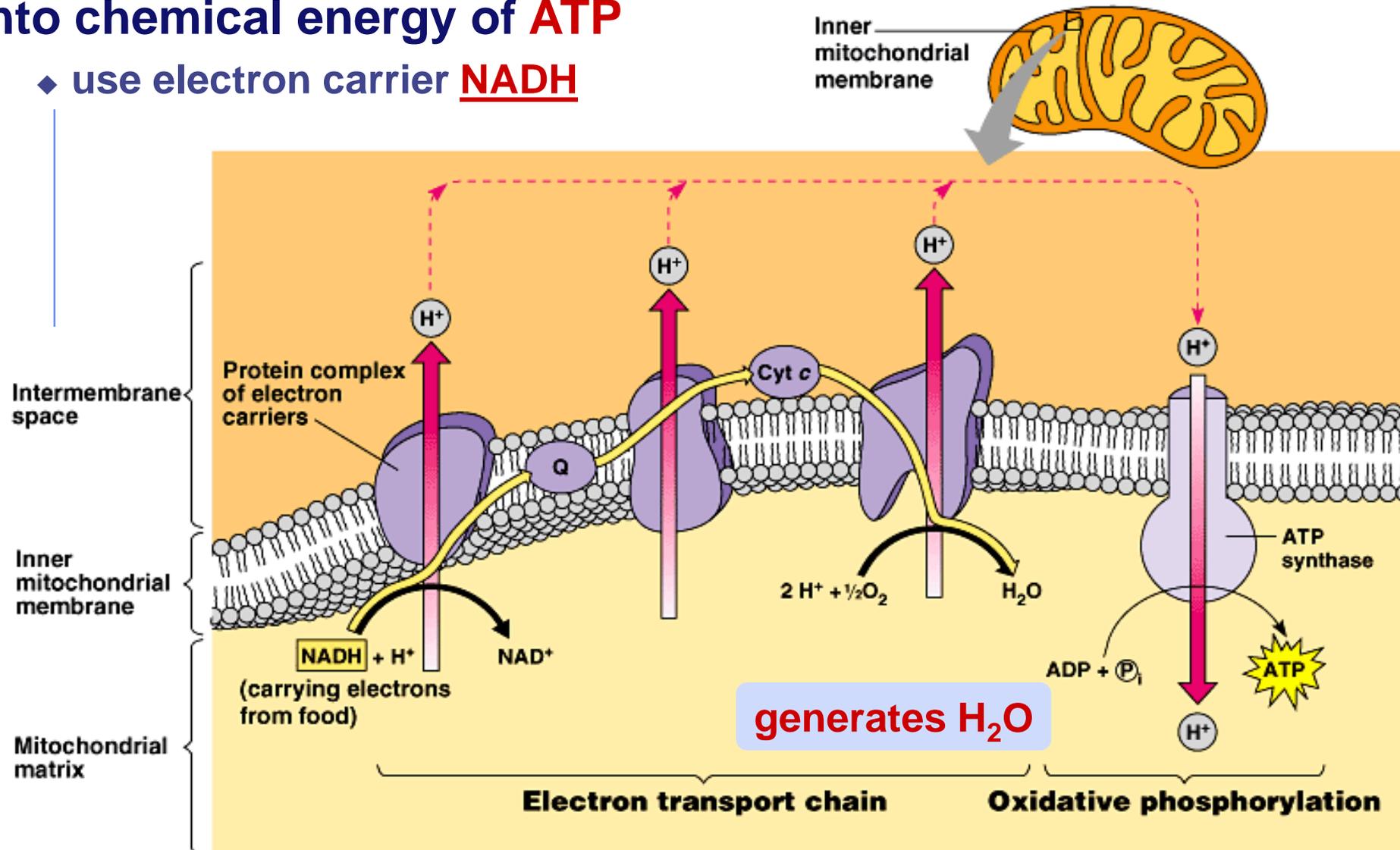
- like in cellular respiration
- ◆ proteins in organelle membrane
- ◆ electron acceptors
 - NADPH
- ◆ proton (H^+) gradient across inner membrane
 - find the double membrane!
- ◆ ATP synthase enzyme



ETC of Respiration

Mitochondria transfer chemical energy from food molecules into chemical energy of **ATP**

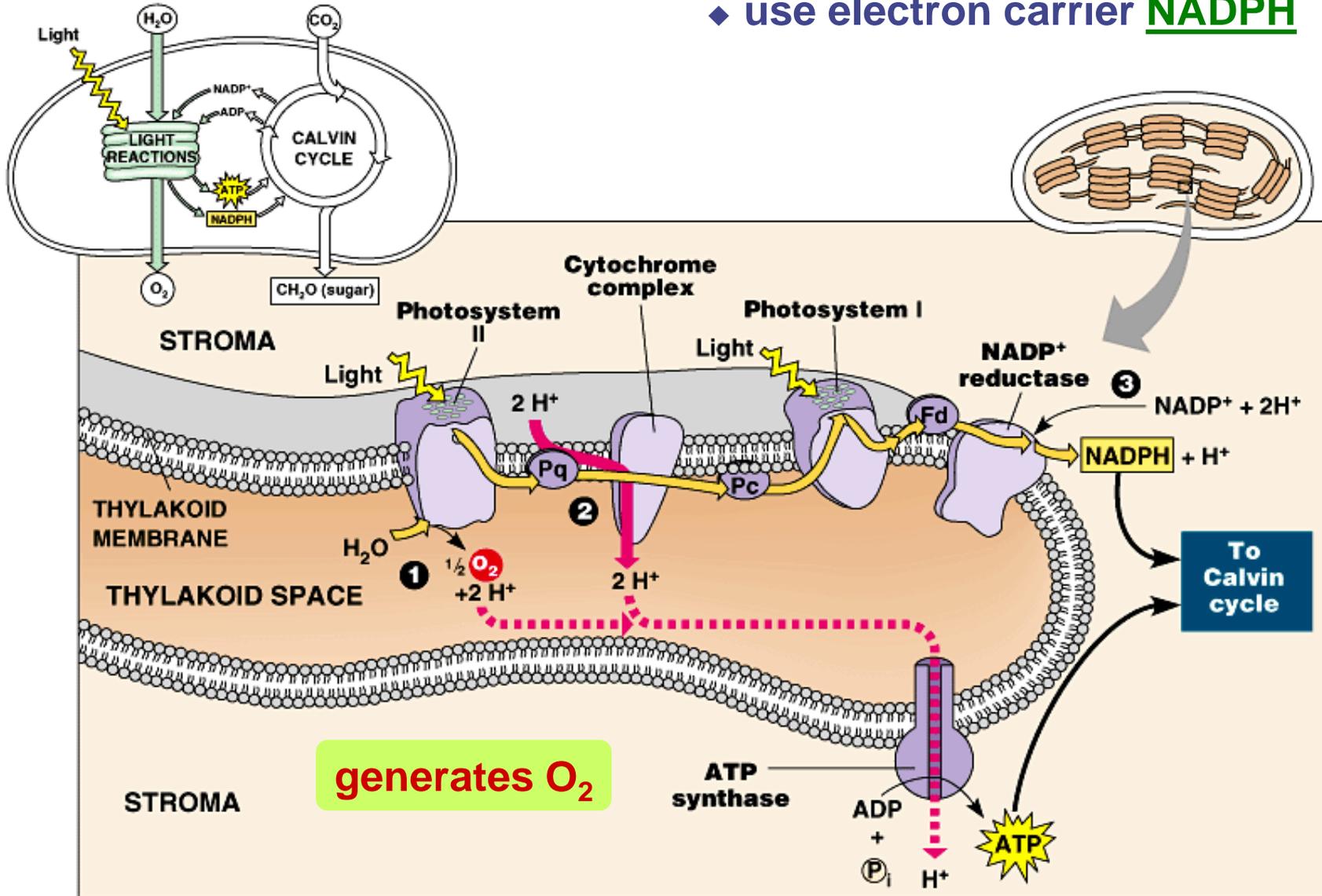
- ◆ use electron carrier NADH



ETC of Photosynthesis

Chloroplasts transform light energy into chemical energy of **ATP**

◆ use electron carrier NADPH



The ATP that “Jack” built

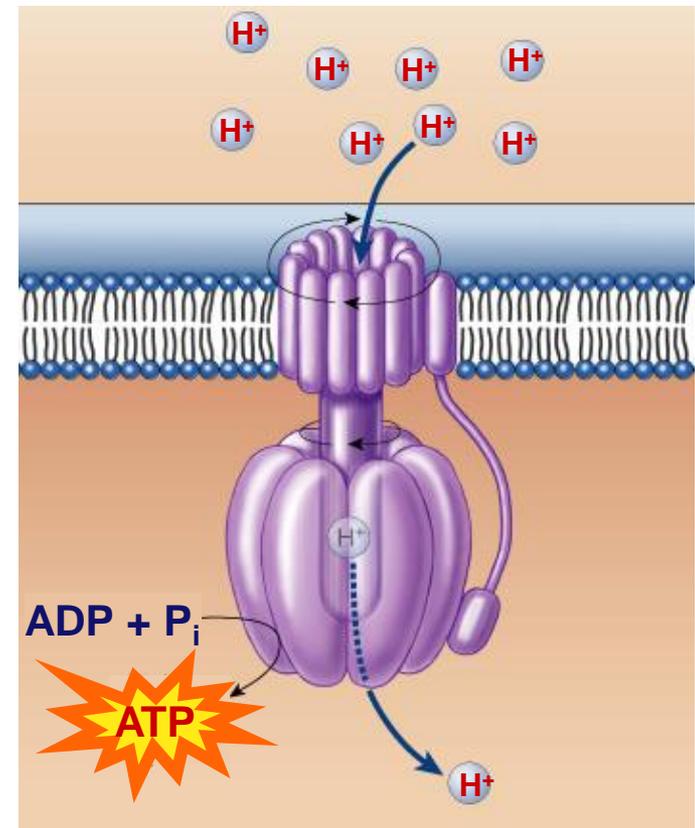
photosynthesis

sunlight

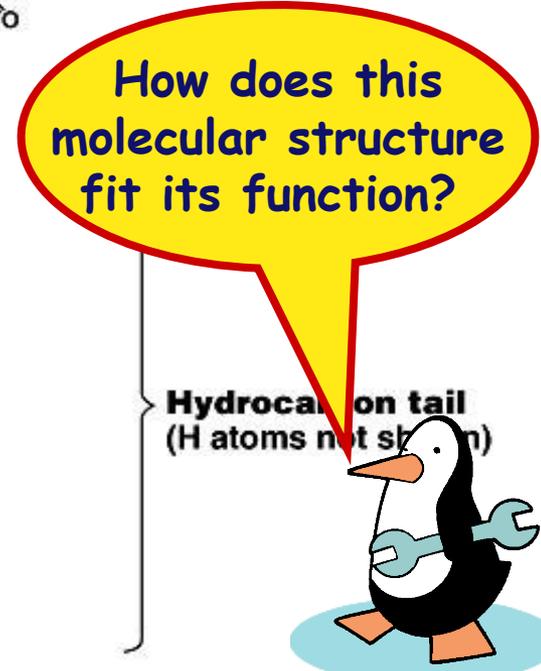
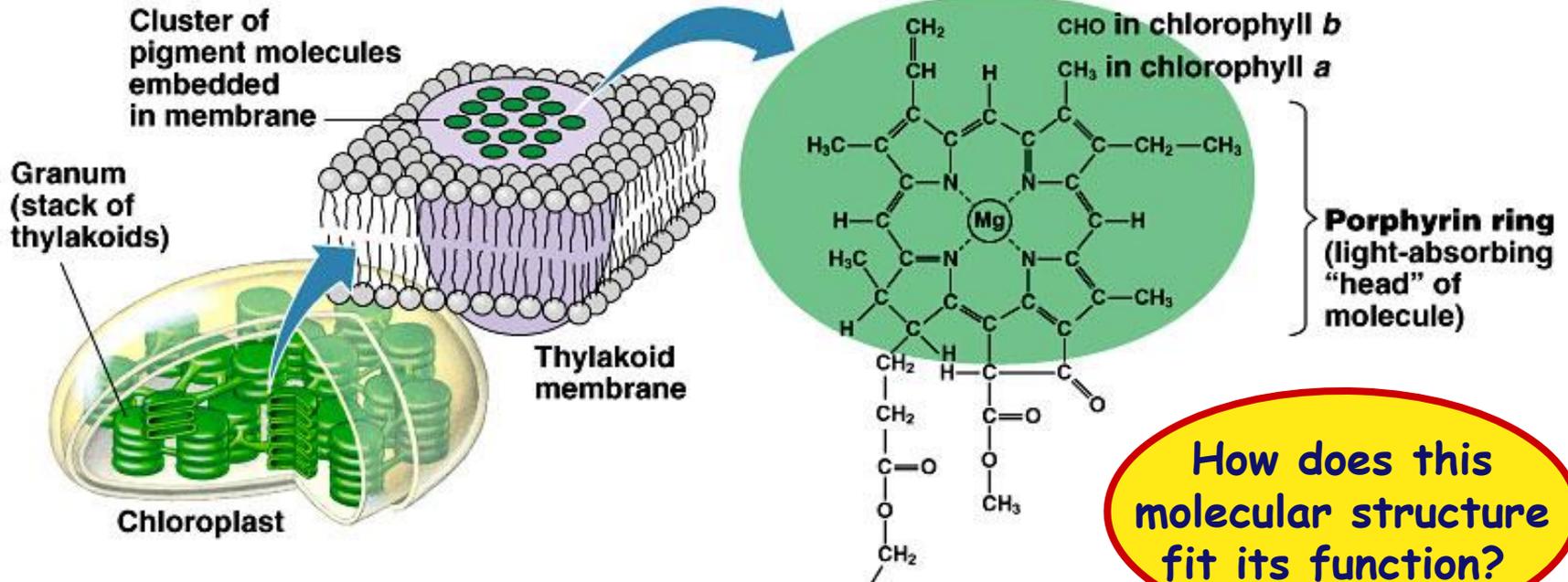
respiration

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



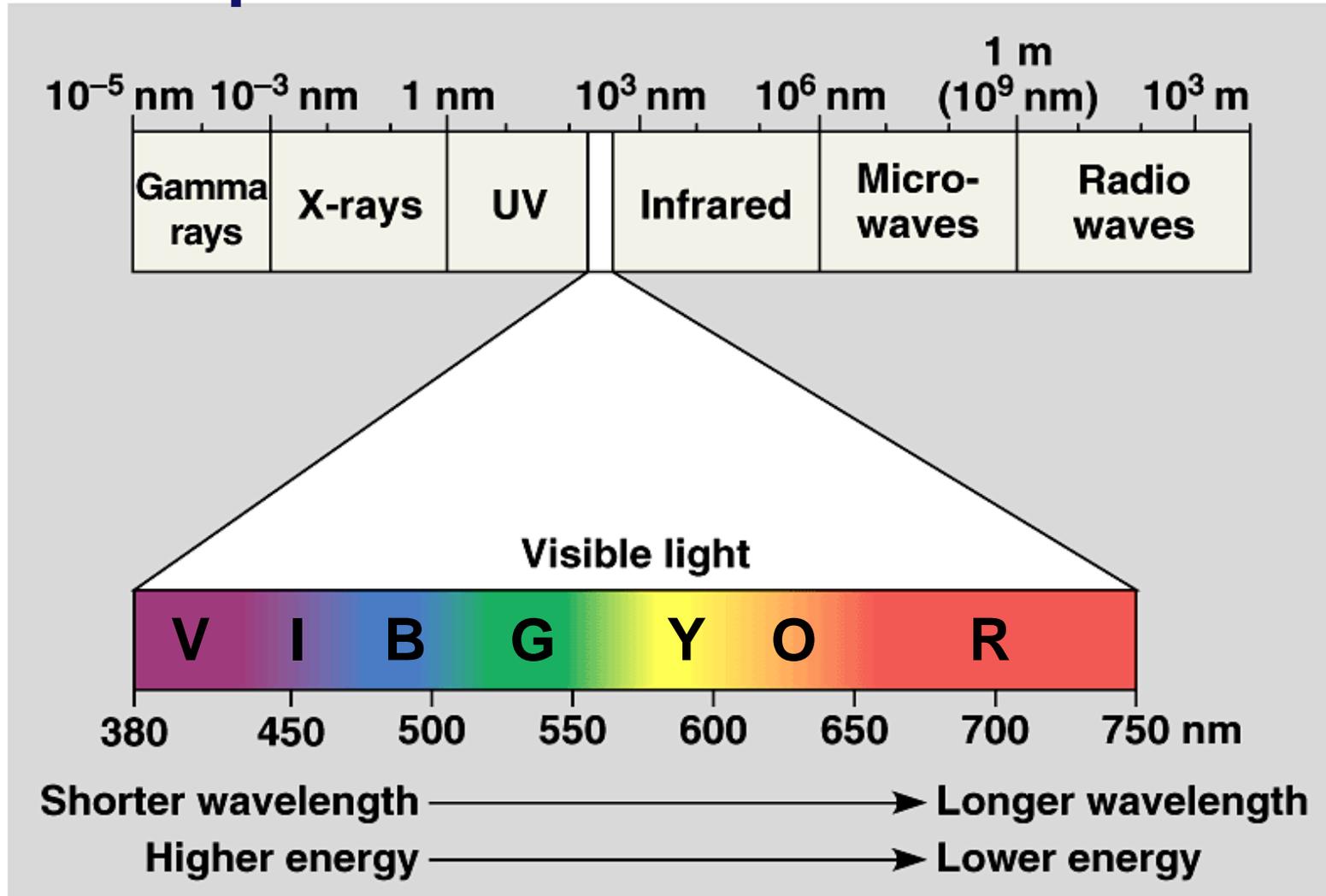
Pigments of photosynthesis



- Chlorophylls & other pigments
 - ◆ embedded in thylakoid membrane
 - ◆ arranged in a “**photosystem**”
 - collection of molecules
 - ◆ structure-function relationship

A Look at Light

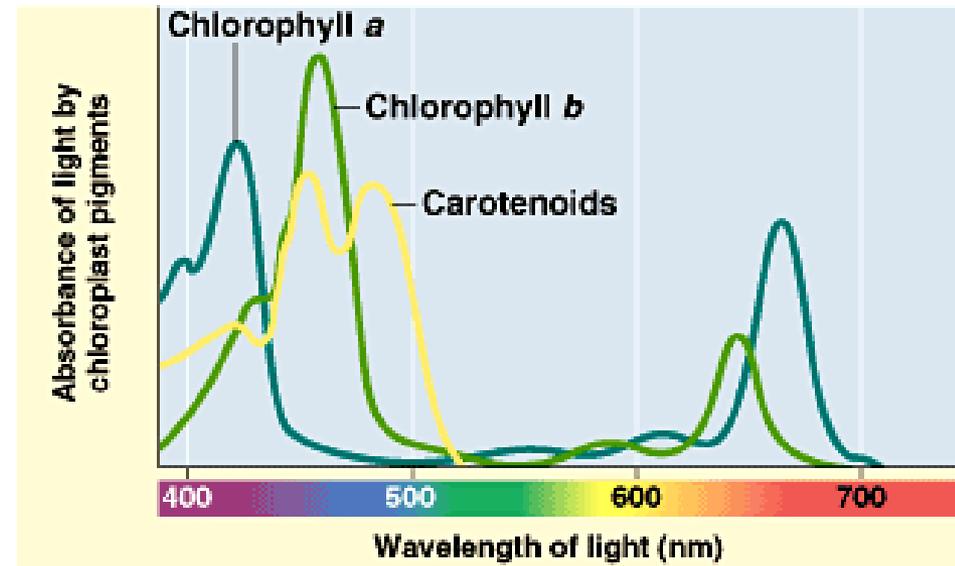
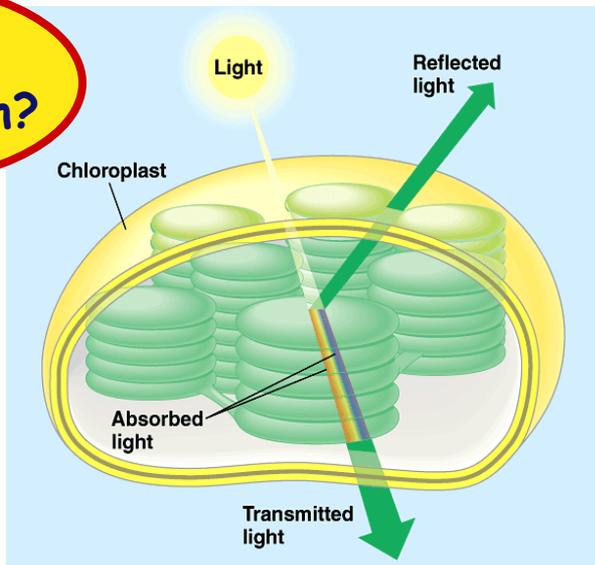
- The spectrum of color



Light: absorption spectra

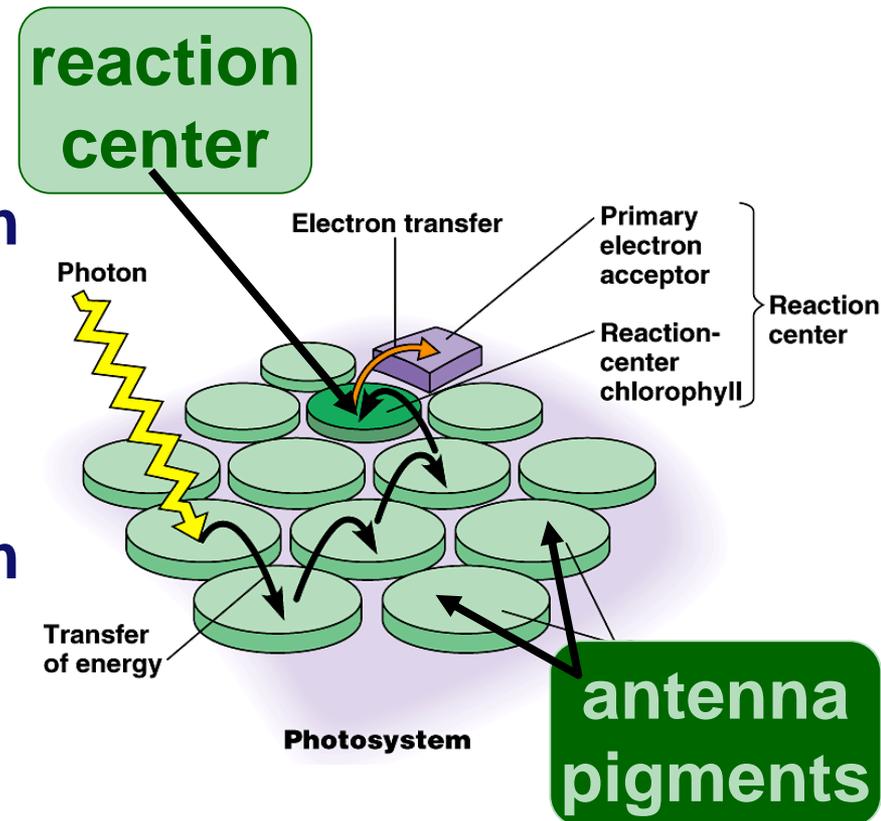
- Photosynthesis gets energy by absorbing wavelengths of light
 - chlorophyll a
 - absorbs best in red & blue wavelengths & least in green
 - accessory pigments with different structures absorb light of different wavelengths
 - chlorophyll b, carotenoids, xanthophylls

Why are plants green?

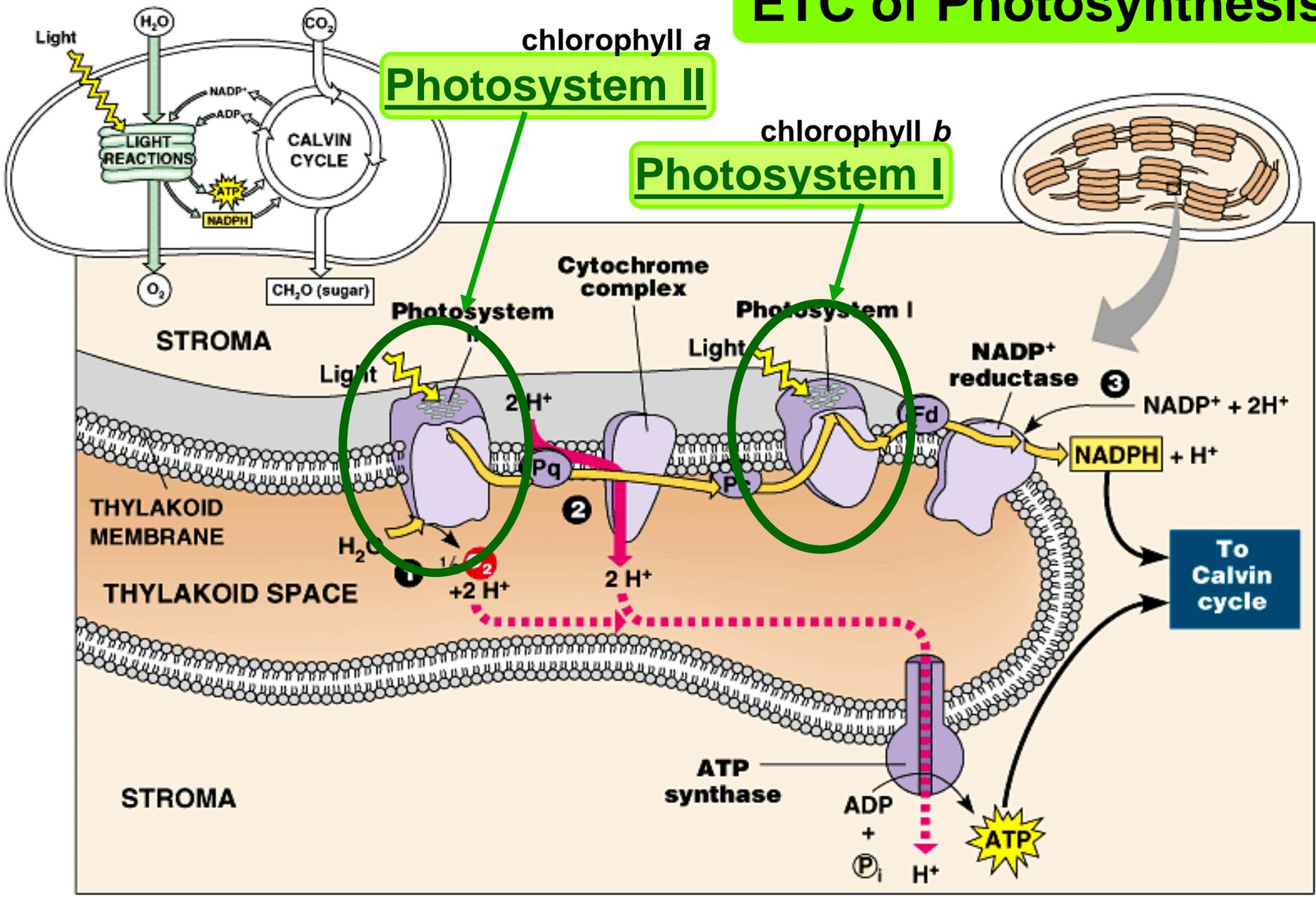


Photosystems of photosynthesis

- 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



ETC of Photosynthesis

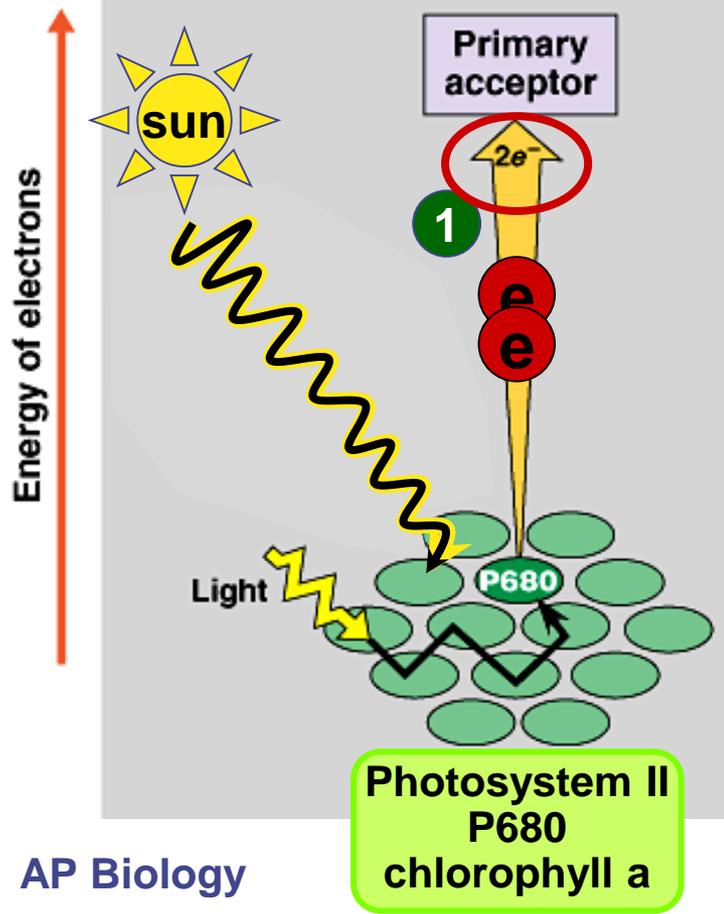
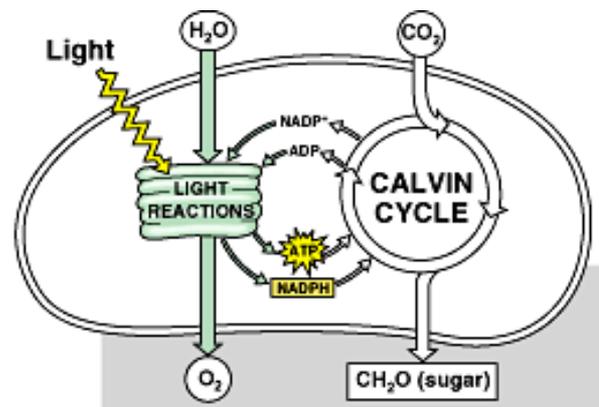


chlorophyll a
Photosystem II

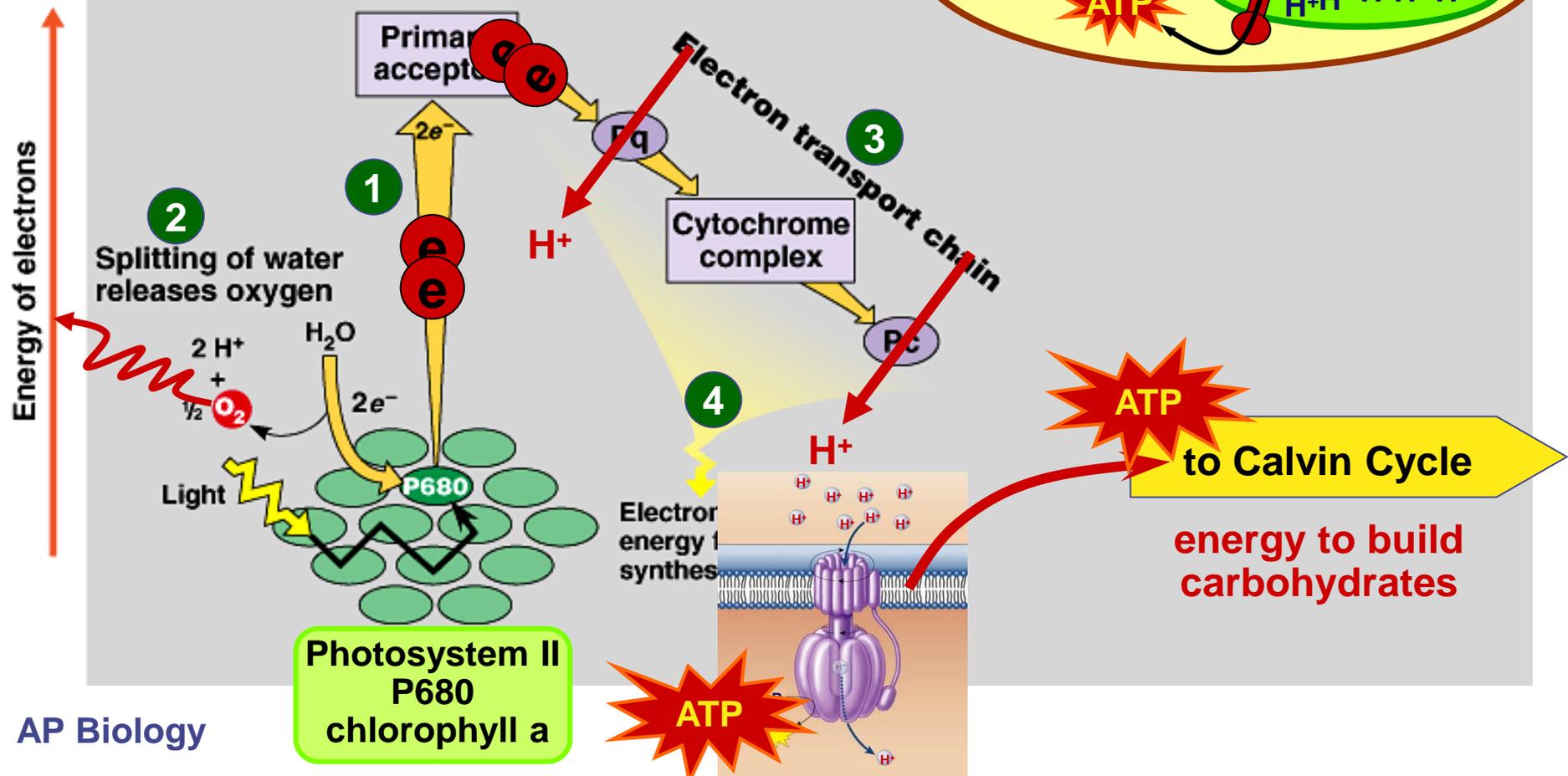
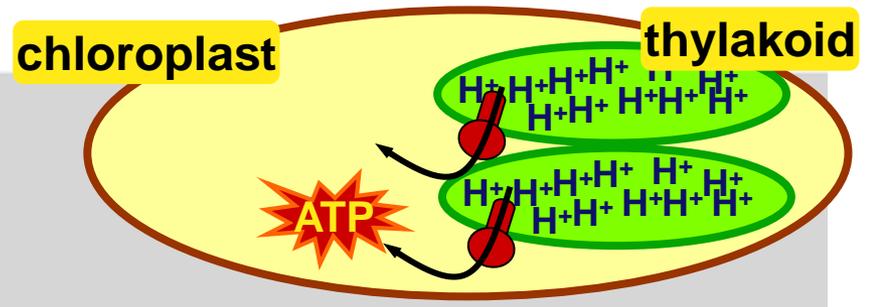
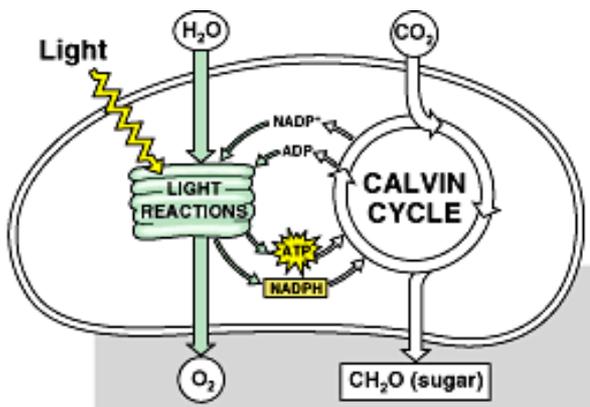
chlorophyll b
Photosystem I

To Calvin cycle

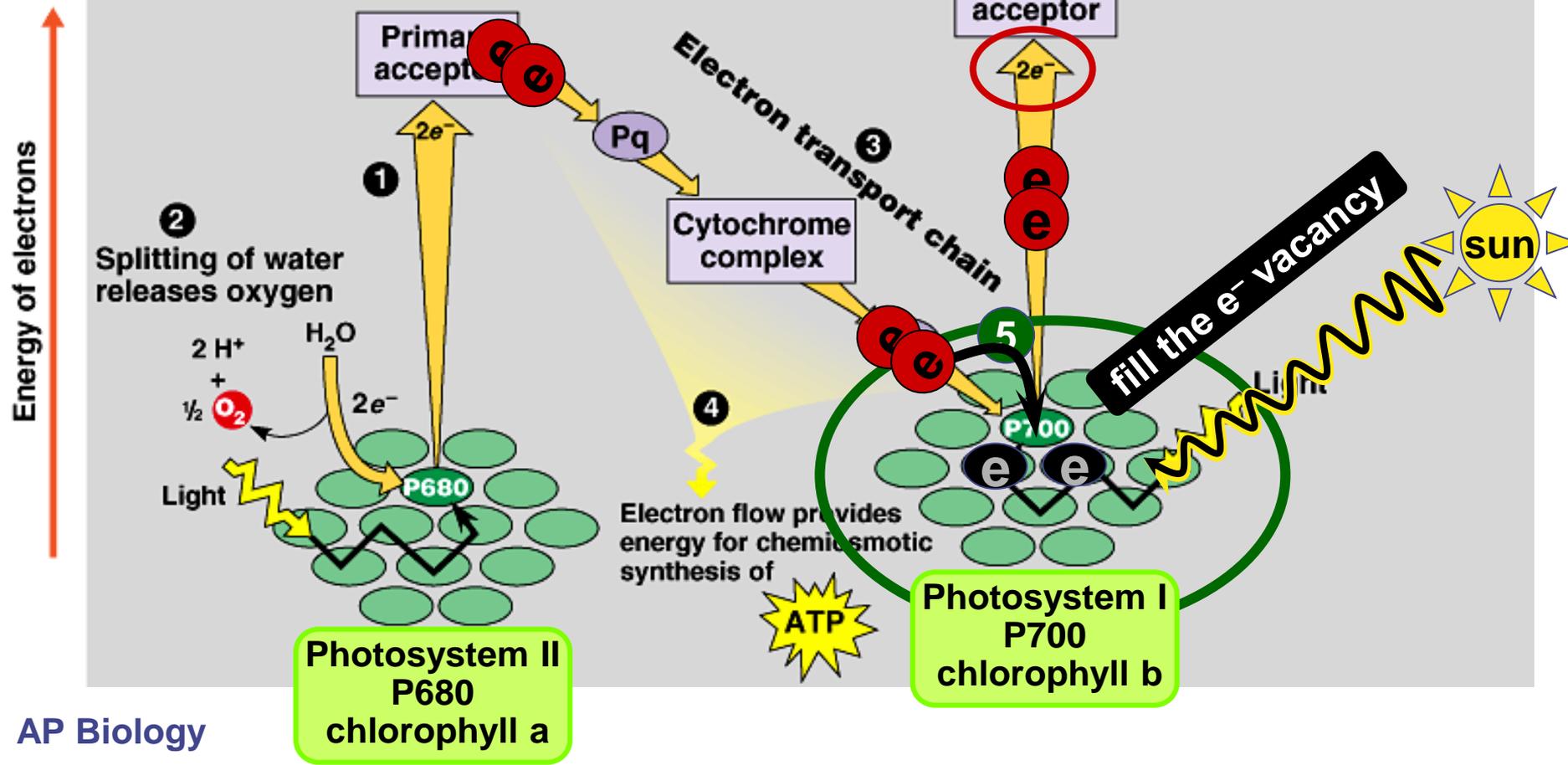
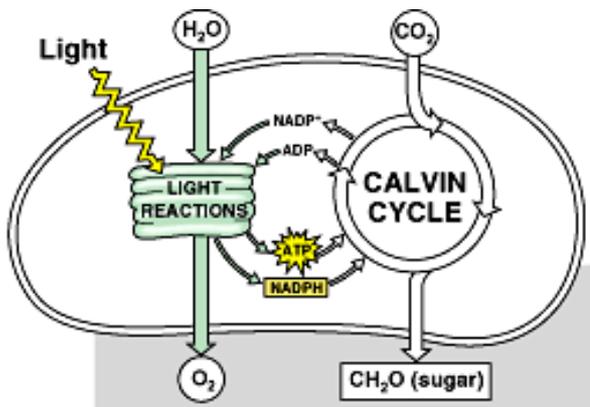
ETC of Photosynthesis



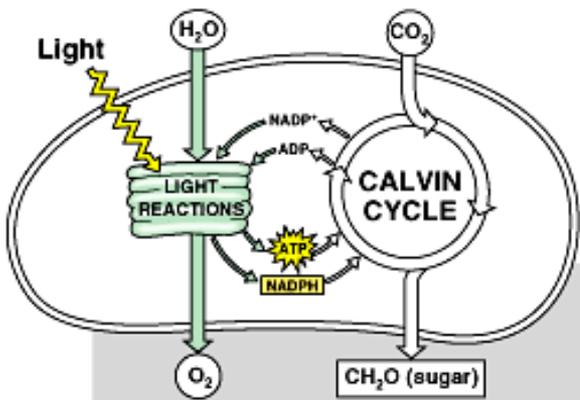
ETC of Photosynthesis



ETC of Photosynthesis

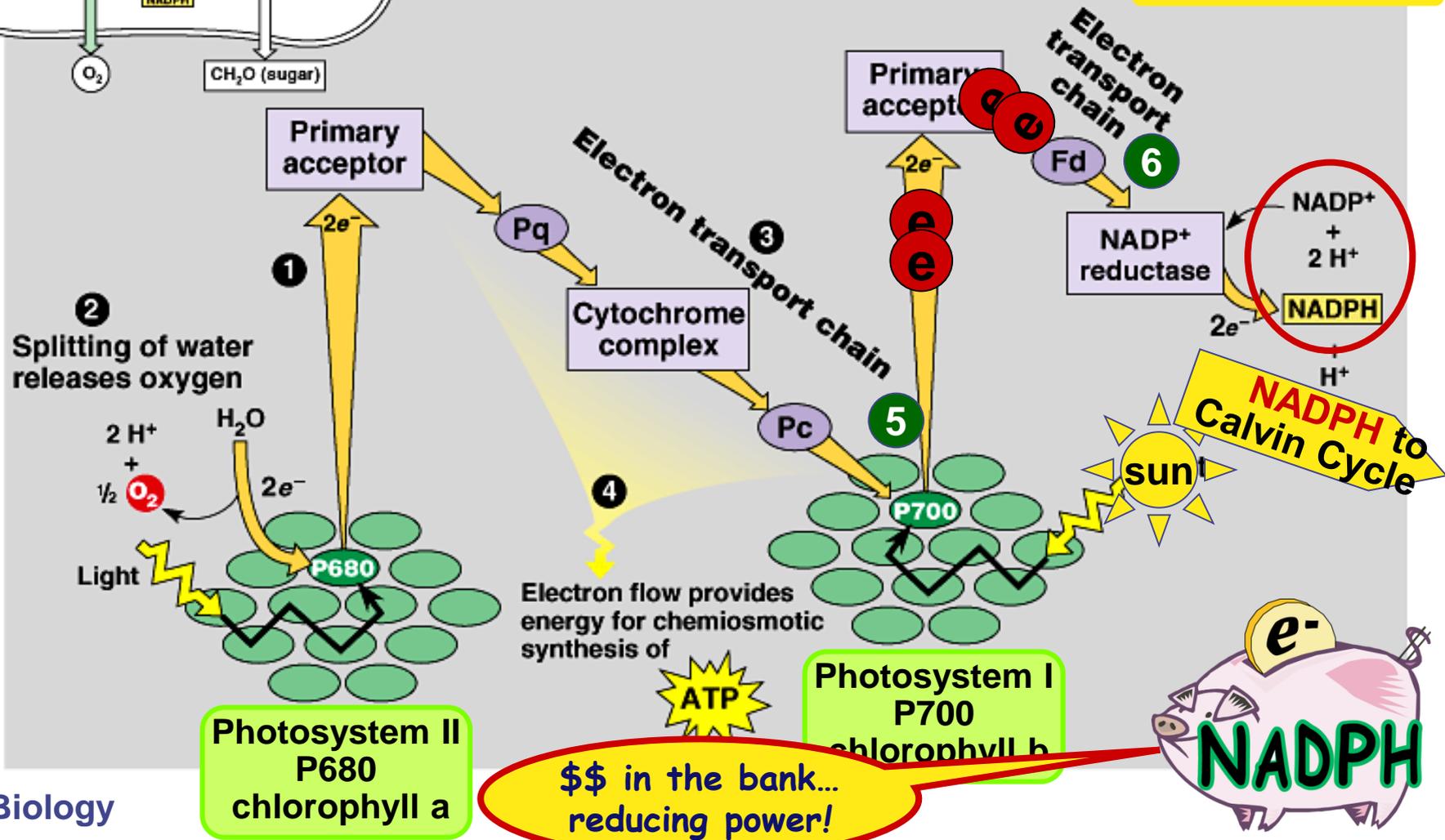


ETC of Photosynthesis



electron carrier

Energy of electrons ↑



Photosystem II
P680
chlorophyll a

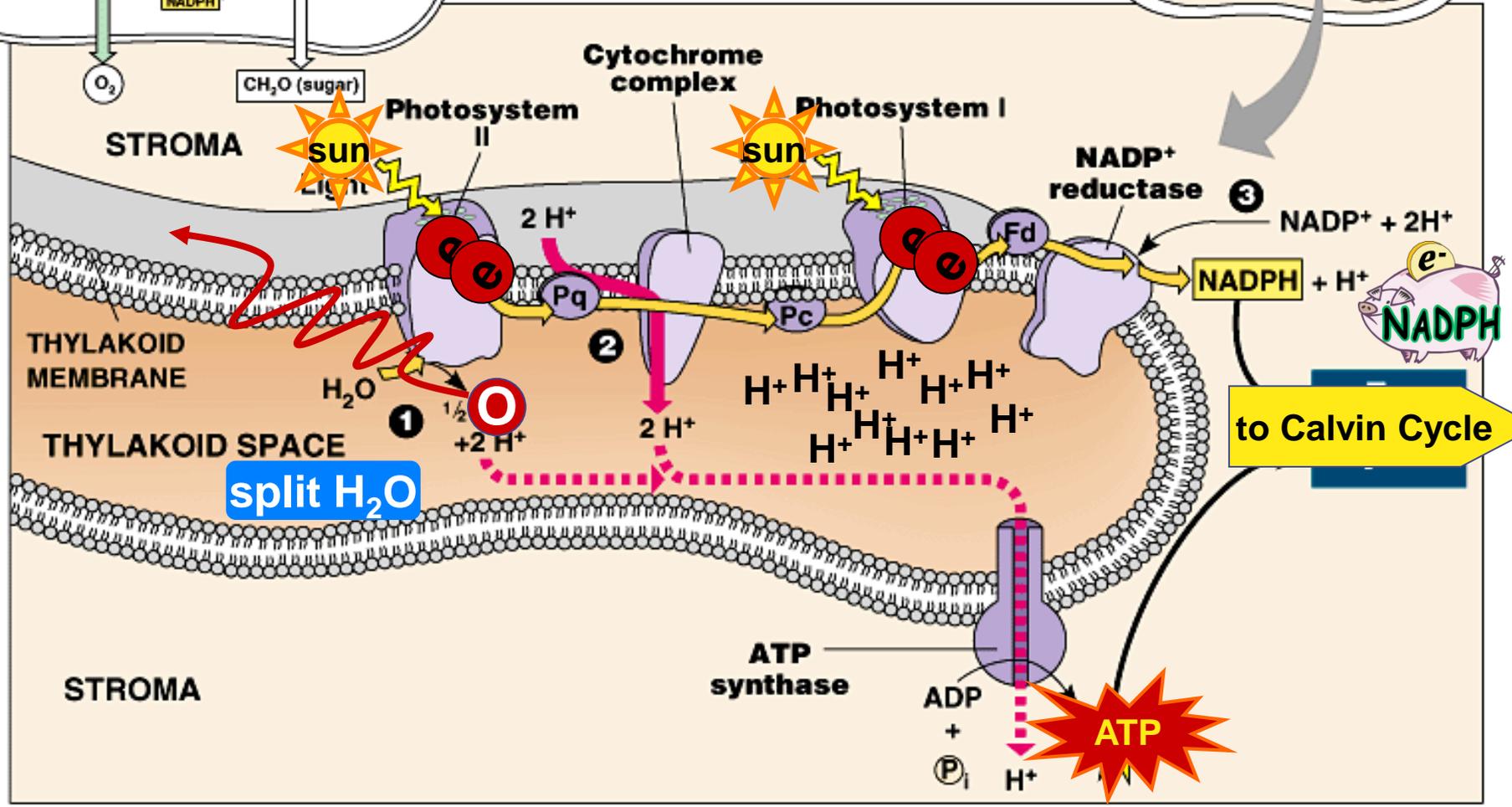
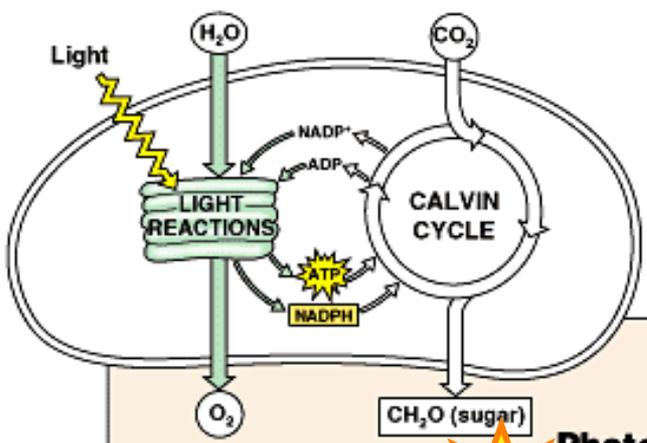
Photosystem I
P700
chlorophyll b

\$\$ in the bank...
reducing power!



NADPH to
Calvin Cycle

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 H₂O & supplies them to chlorophyll
 - splits H₂O
 - O combines with another O to form O₂
 - O₂ released to atmosphere
 - and we breathe easier!

Experimental evidence

- Where did the O₂ come from?
 - ◆ radioactive tracer = O₁₈

Experiment 1



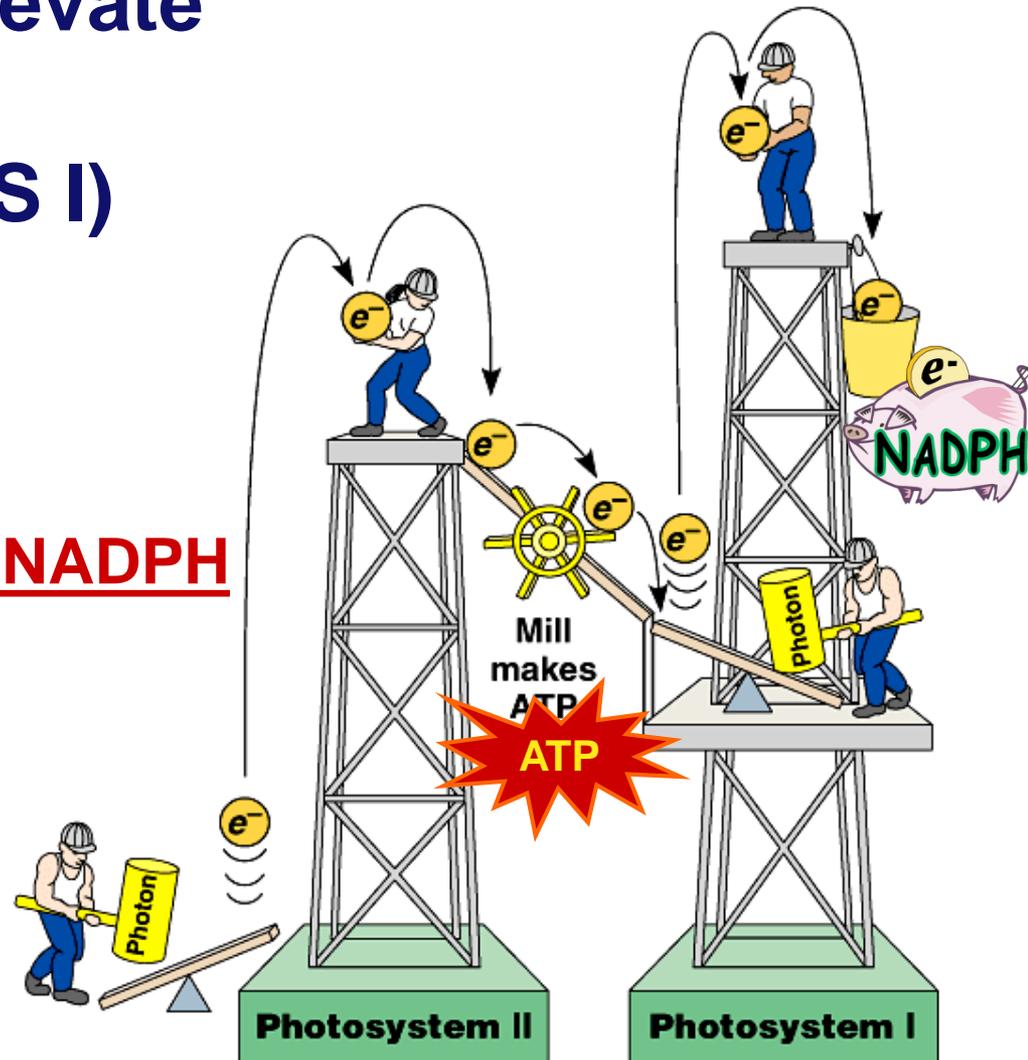
Experiment 2



Proved O₂ came from H₂O not CO₂ = plants split H₂O!

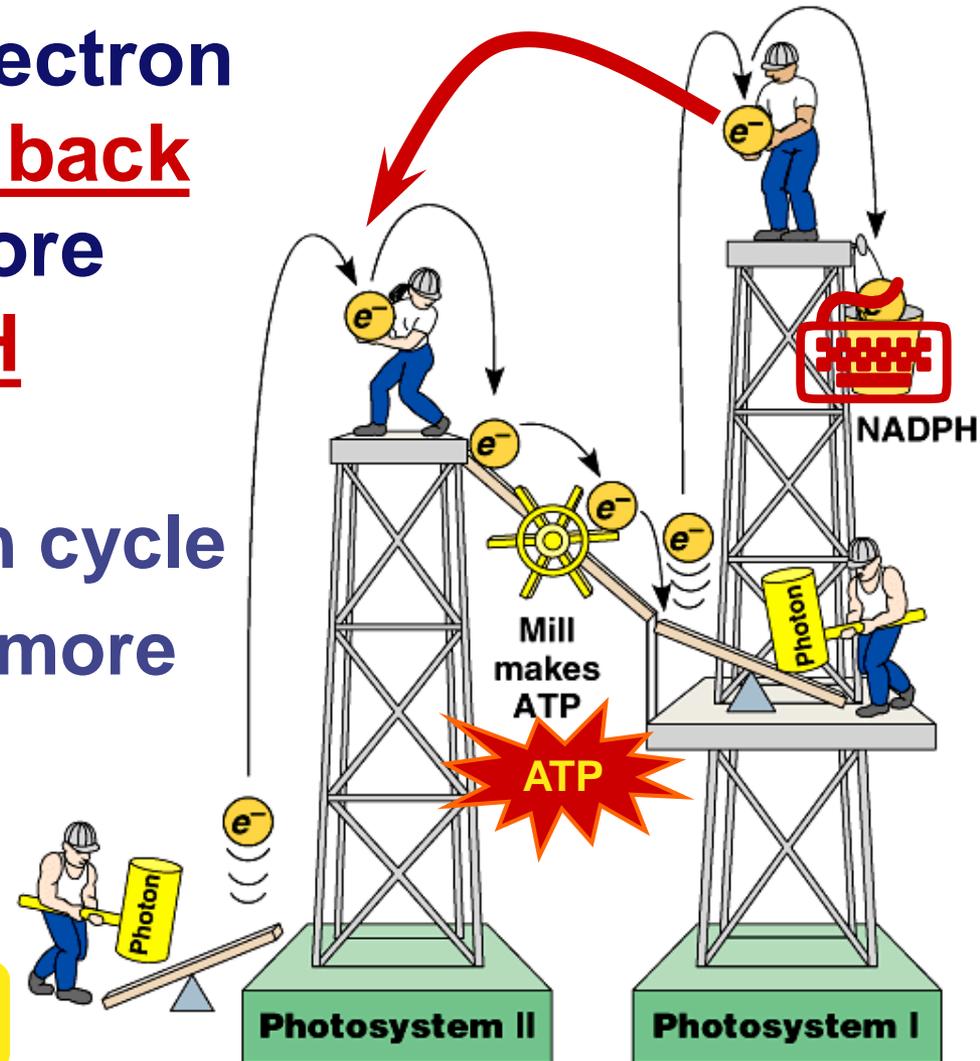
Noncyclic Photophosphorylation

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



Cyclic photophosphorylation

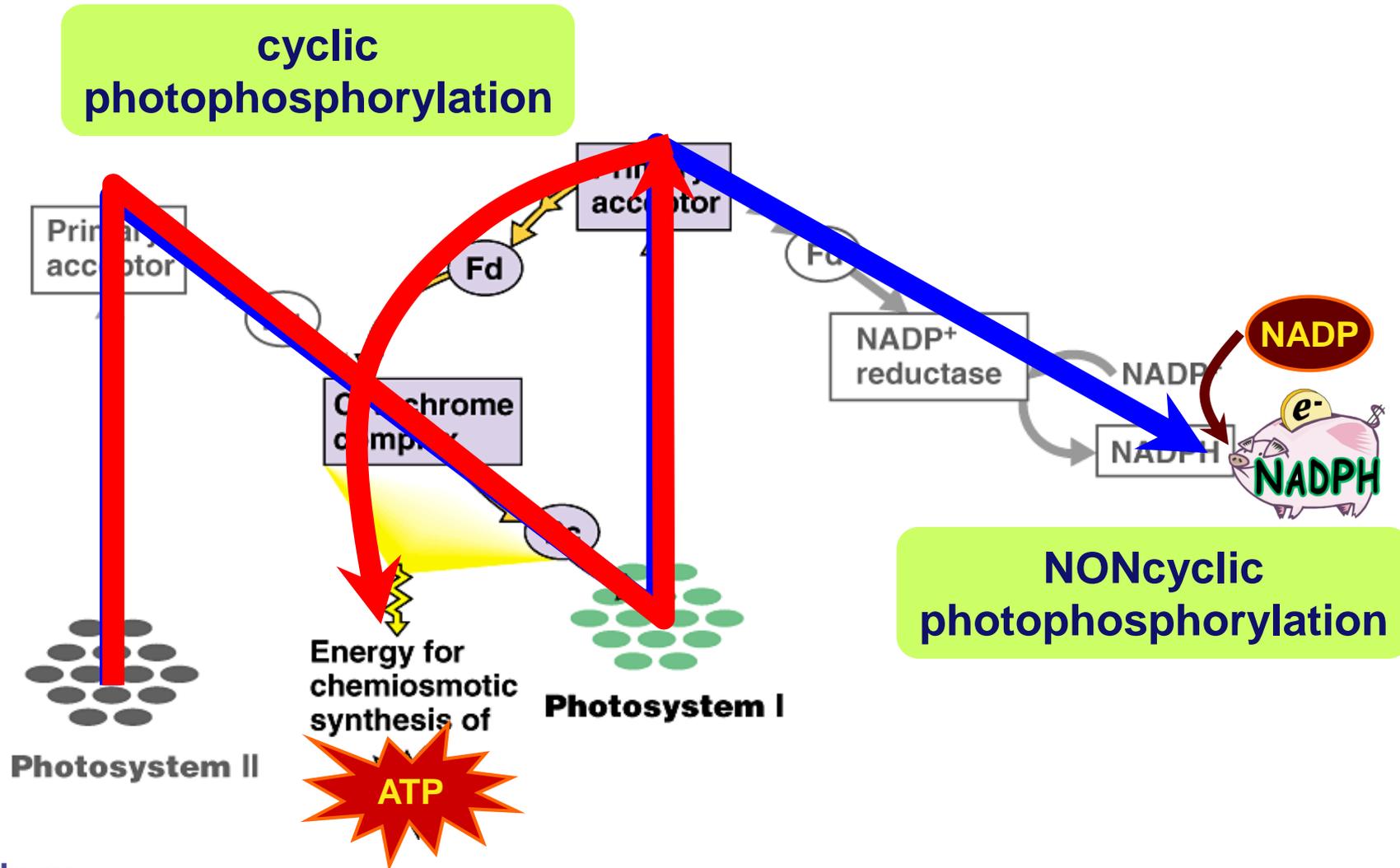
- If **PS I** can't pass electron to NADP...it **cycles back to PS II** & makes more **ATP**, but **no NADPH**
 - ◆ coordinates light reactions to Calvin cycle
 - ◆ Calvin cycle uses more ATP than NADPH



18 ATP +
12 NADPH

→ **1 C₆H₁₂O₆**

Photophosphorylation



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?

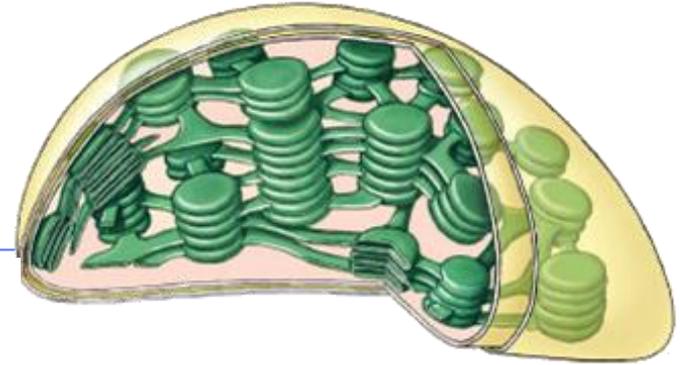
What will the ATP be used for?

Where did the NADPH come from?

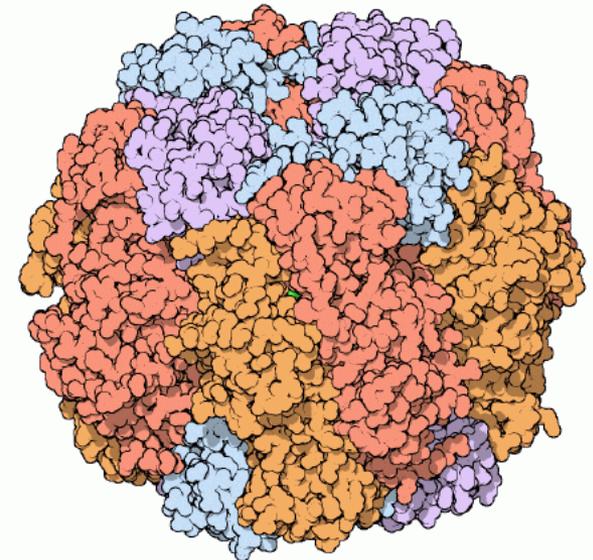
What will the NADPH be used for?

**You can grow if you
Ask Questions!**





Photosynthesis:
The Calvin Cycle
Life from Air



1950s | 1961

Whoops! Wrong Calvin...



Remember what it means to be a **plant**...

- Need to produce all organic molecules necessary for growth
 - ◆ carbohydrates, lipids, proteins, nucleic acids
- Need to store chemical energy (ATP) produced from light reactions
 - ◆ in a more stable form
 - ◆ that can be moved around plant
 - ◆ saved for a rainy day

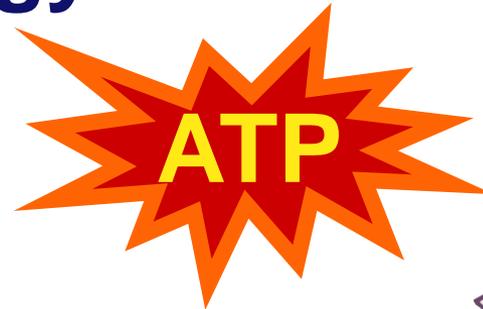
carbon + water + energy → glucose + oxygen
dioxide



Light reactions

- Convert solar energy to chemical energy

- ◆ **ATP** → energy



- ◆ **NADPH** → reducing power



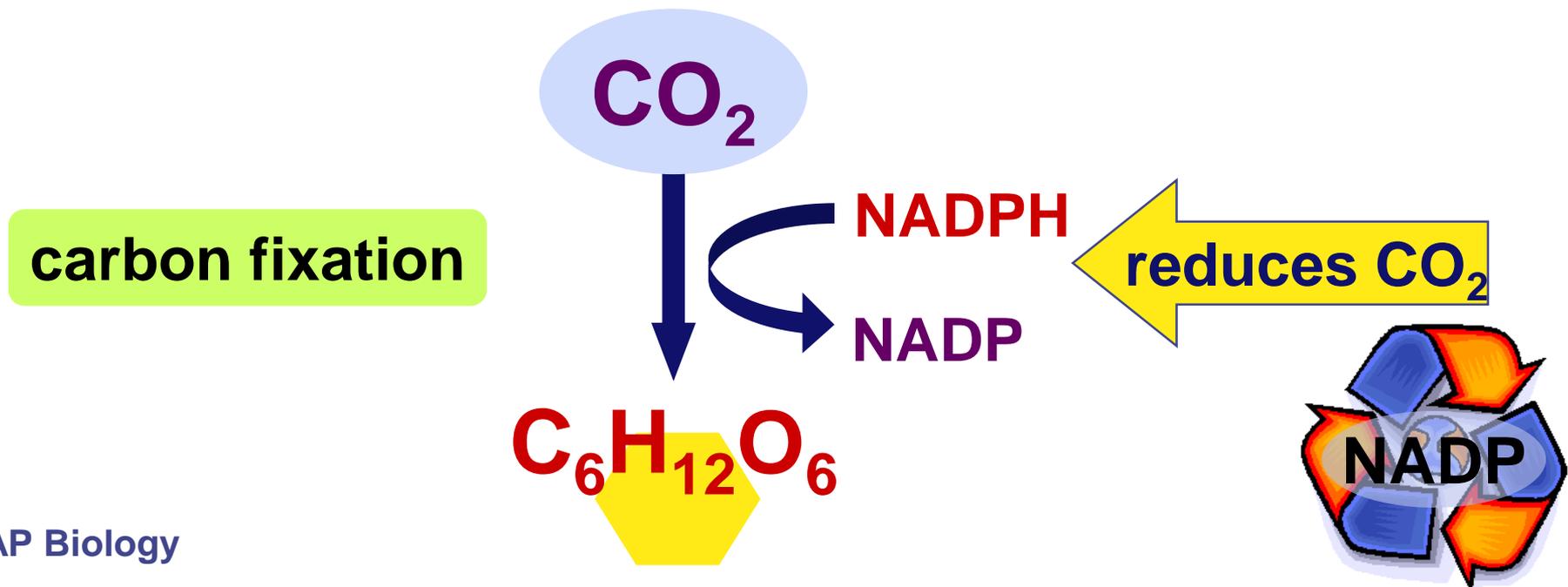
- What can we do now?

→ → **build stuff !!**

photosynthesis

How is that helpful?

- Want to make $C_6H_{12}O_6$
 - ◆ synthesis
 - ◆ How? From what?
What raw materials are available?



From $\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6$

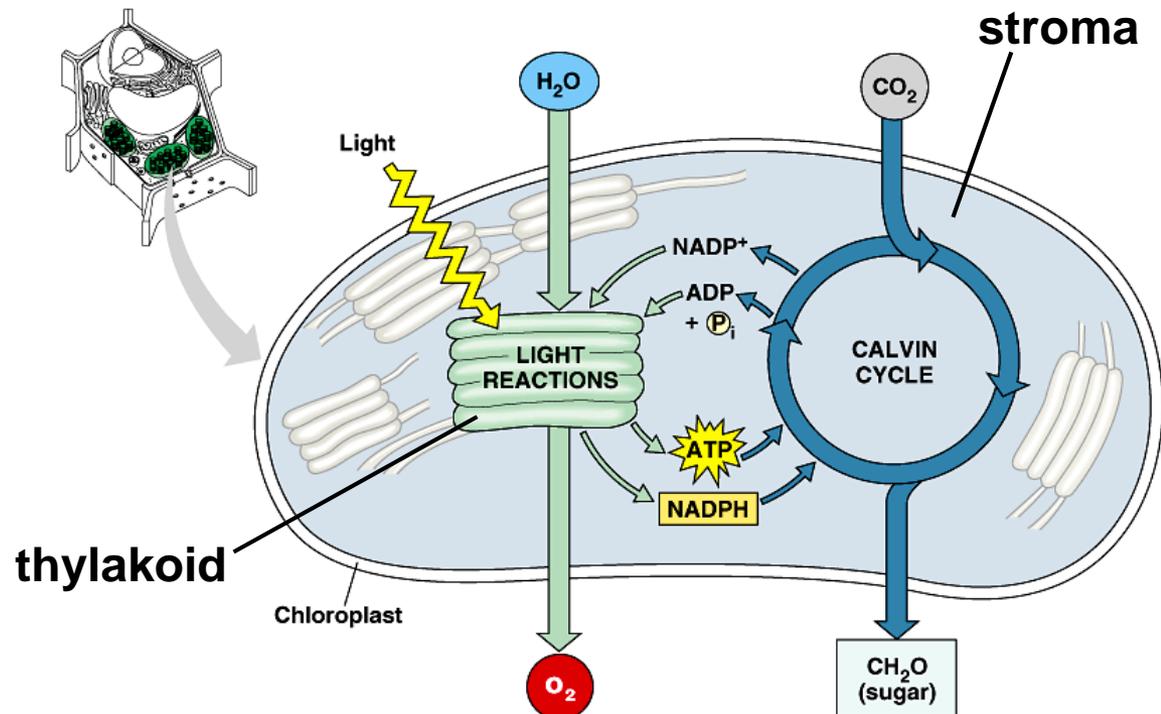
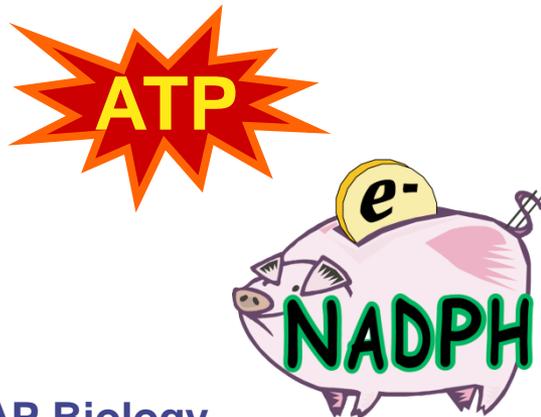
- CO_2 has very little chemical energy
 - ◆ fully oxidized
- $\text{C}_6\text{H}_{12}\text{O}_6$ contains a lot of chemical energy
 - ◆ highly reduced
- Synthesis = endergonic process
 - ◆ put in a lot of energy
- Reduction of $\text{CO}_2 \rightarrow \text{C}_6\text{H}_{12}\text{O}_6$ proceeds in many small uphill steps
 - ◆ each catalyzed by a specific enzyme
 - ◆ using energy stored in **ATP & NADPH**

From Light reactions to Calvin cycle

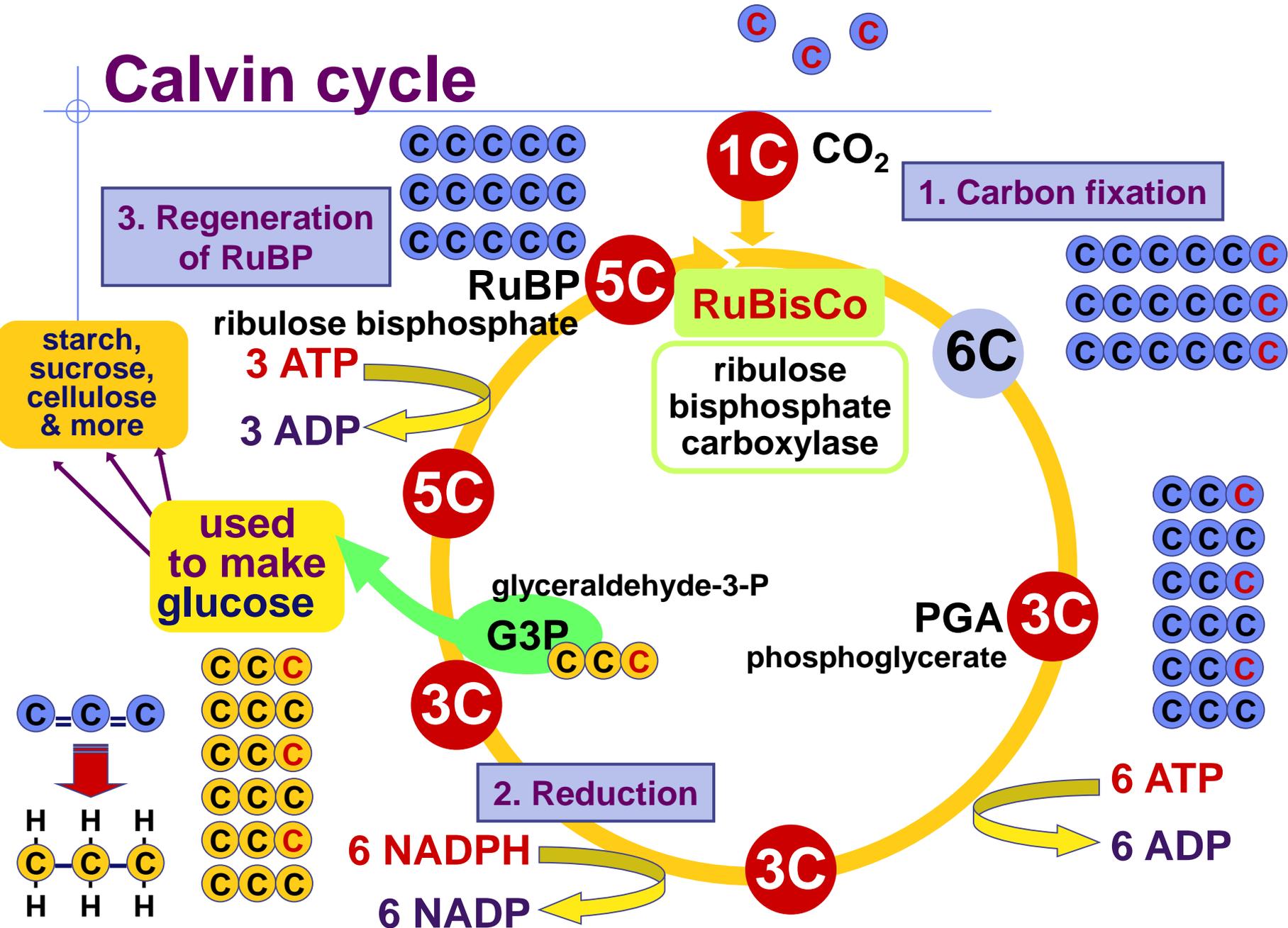
- Calvin cycle
 - ◆ chloroplast stroma
- Need products of light reactions to drive synthesis reactions

◆ ATP

◆ NADPH

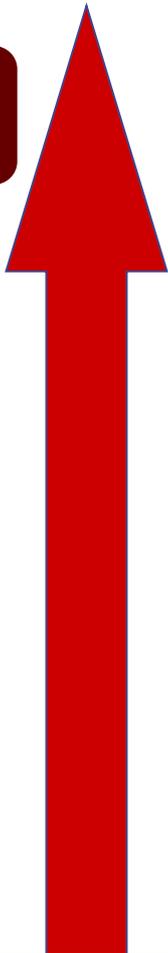


Calvin cycle

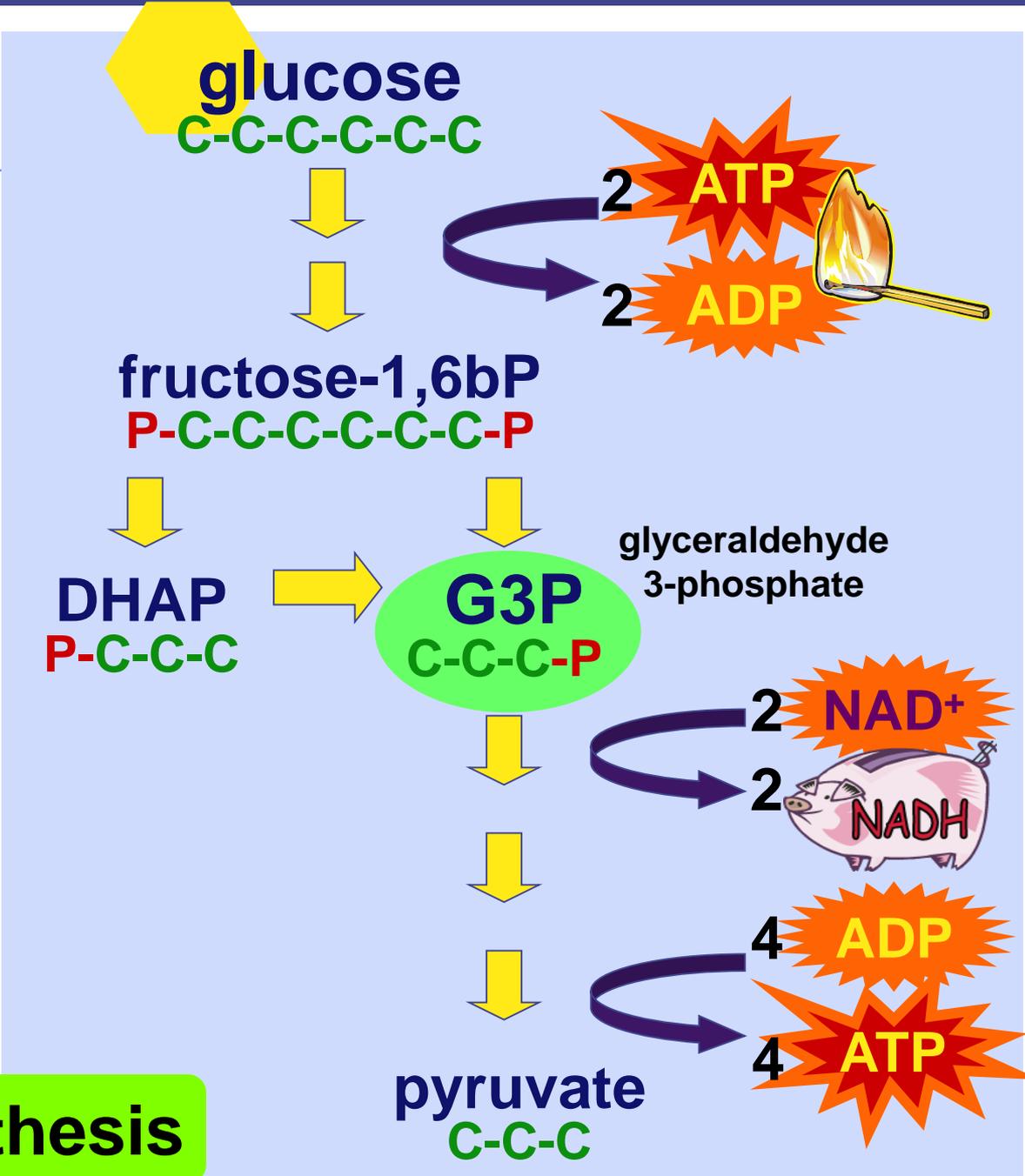


Remember
G3P?

glycolysis



Photosynthesis



To G3P
and beyond!

To G3P and Beyond!

- **Glyceraldehyde-3-P**

- ◆ end product of Calvin cycle
- ◆ energy rich 3 carbon sugar
- ◆ “C3 photosynthesis”

- **G3P** is an important intermediate

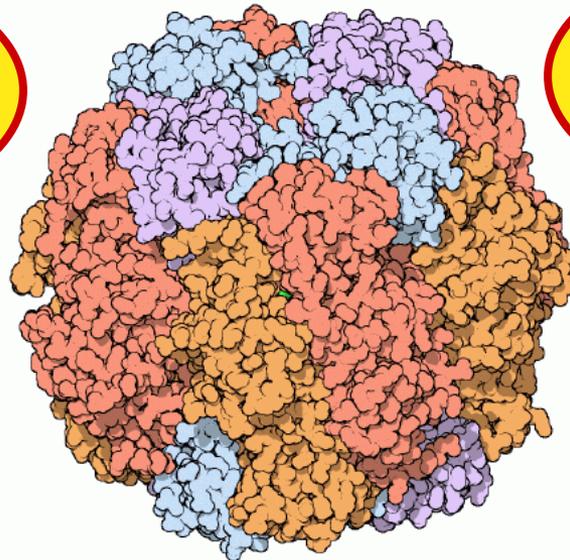
G3P → → glucose → → carbohydrates
→ → lipids → → phospholipids, fats, waxes
→ → amino acids → → proteins
→ → nucleic acids → → DNA, RNA



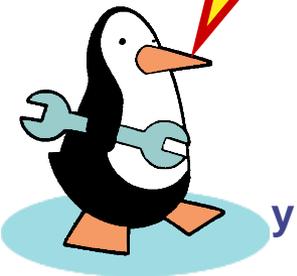
RuBisCo

- Enzyme which fixes carbon from air
 - ◆ ribulose biphosphate carboxylase
 - ◆ the most important enzyme in the world!
 - it makes life out of air!
 - ◆ definitely the most abundant enzyme

I'm green
with envy!



It's not easy
being green!



Accounting

- The accounting is complicated
 - ◆ 3 turns of Calvin cycle = **1 G3P**
 - ◆ **3 CO₂** → **1 G3P (3C)**
 - ◆ 6 turns of Calvin cycle = **1 C₆H₁₂O₆ (6C)**
 - ◆ **6 CO₂** → **1 C₆H₁₂O₆ (6C)**
 - ◆ **18 ATP + 12 NADPH** → **1 C₆H₁₂O₆**
 - ◆ any **ATP** left over from light reactions will be used elsewhere by the cell

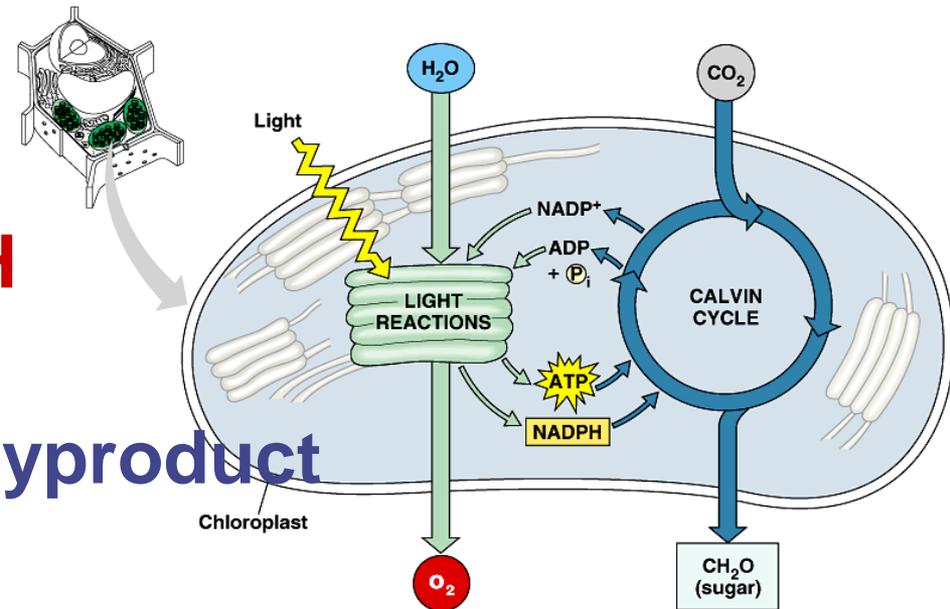
Photosynthesis summary

■ Light reactions

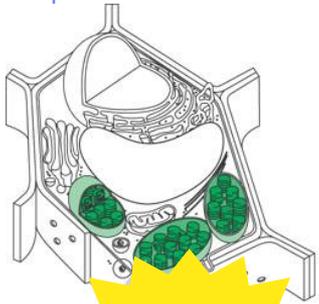
- ◆ produced **ATP**
- ◆ produced **NADPH**
- ◆ consumed **H₂O**
- ◆ produced **O₂** as byproduct

■ Calvin cycle

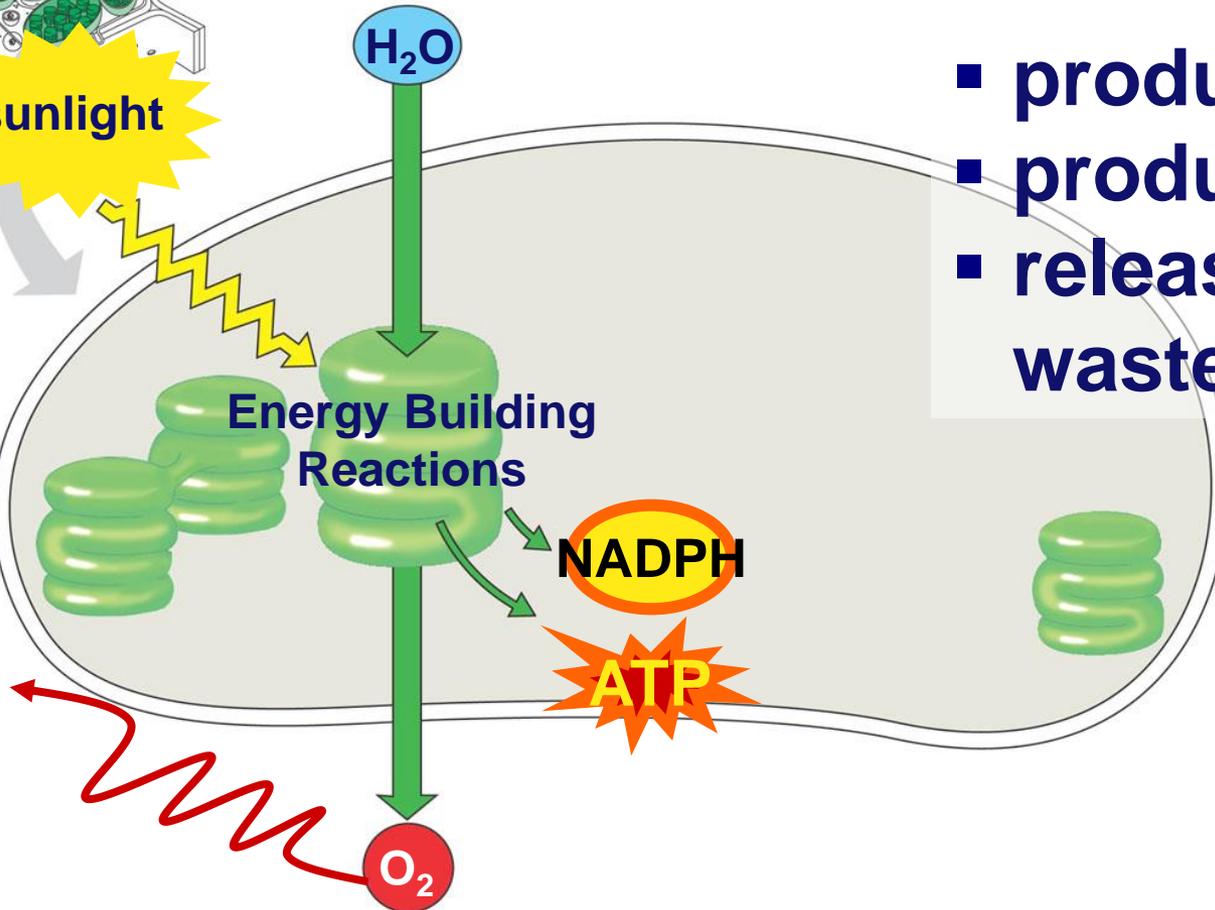
- ◆ consumed **CO₂**
- ◆ produced **G3P (sugar)**
- ◆ regenerated **ADP**
- ◆ regenerated **NADP**



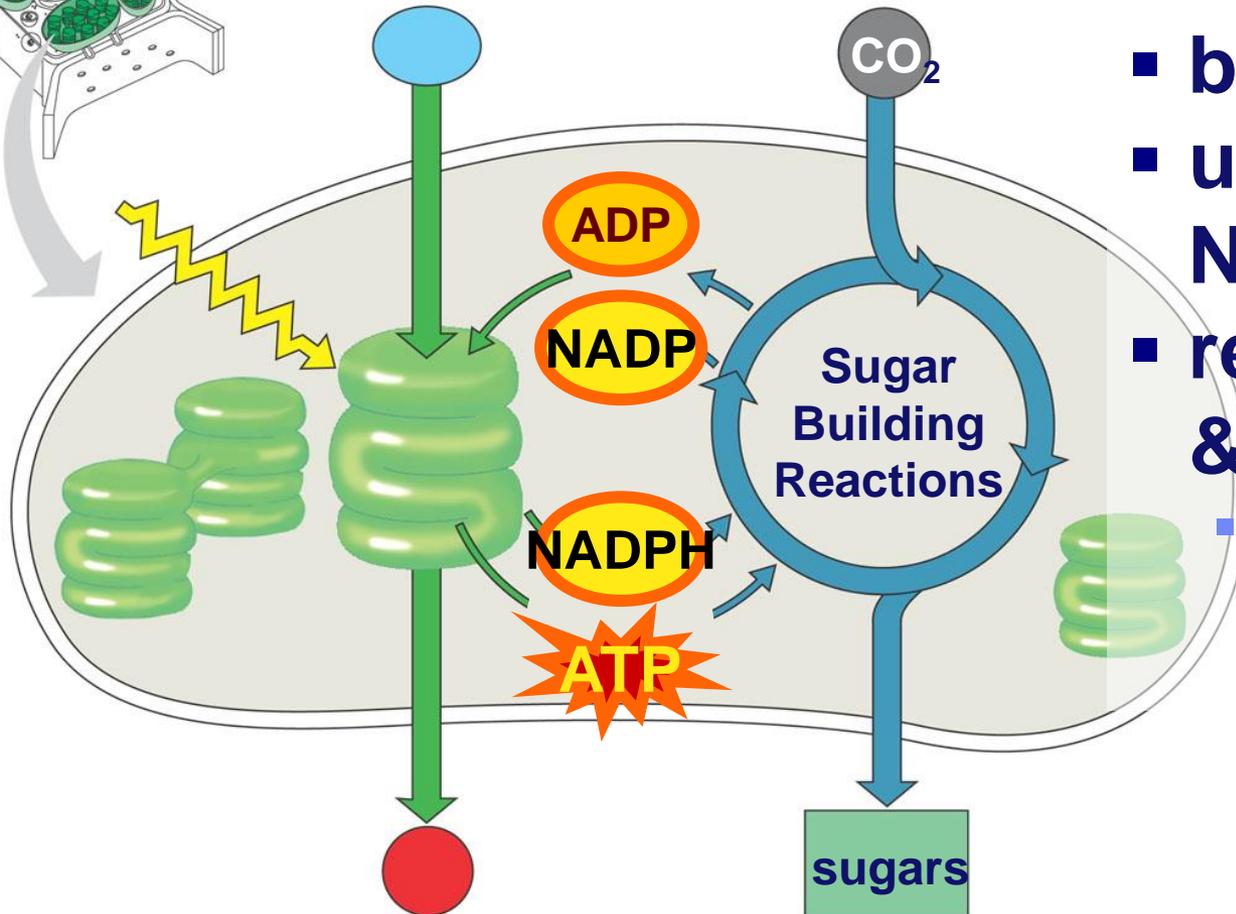
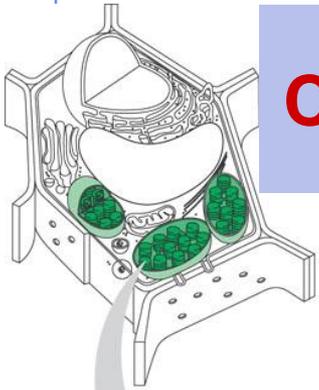
Light Reactions



- produces ATP
- produces NADPH
- releases O_2 as a waste product

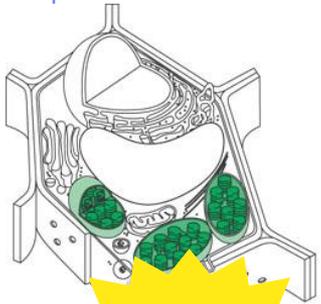


Calvin Cycle



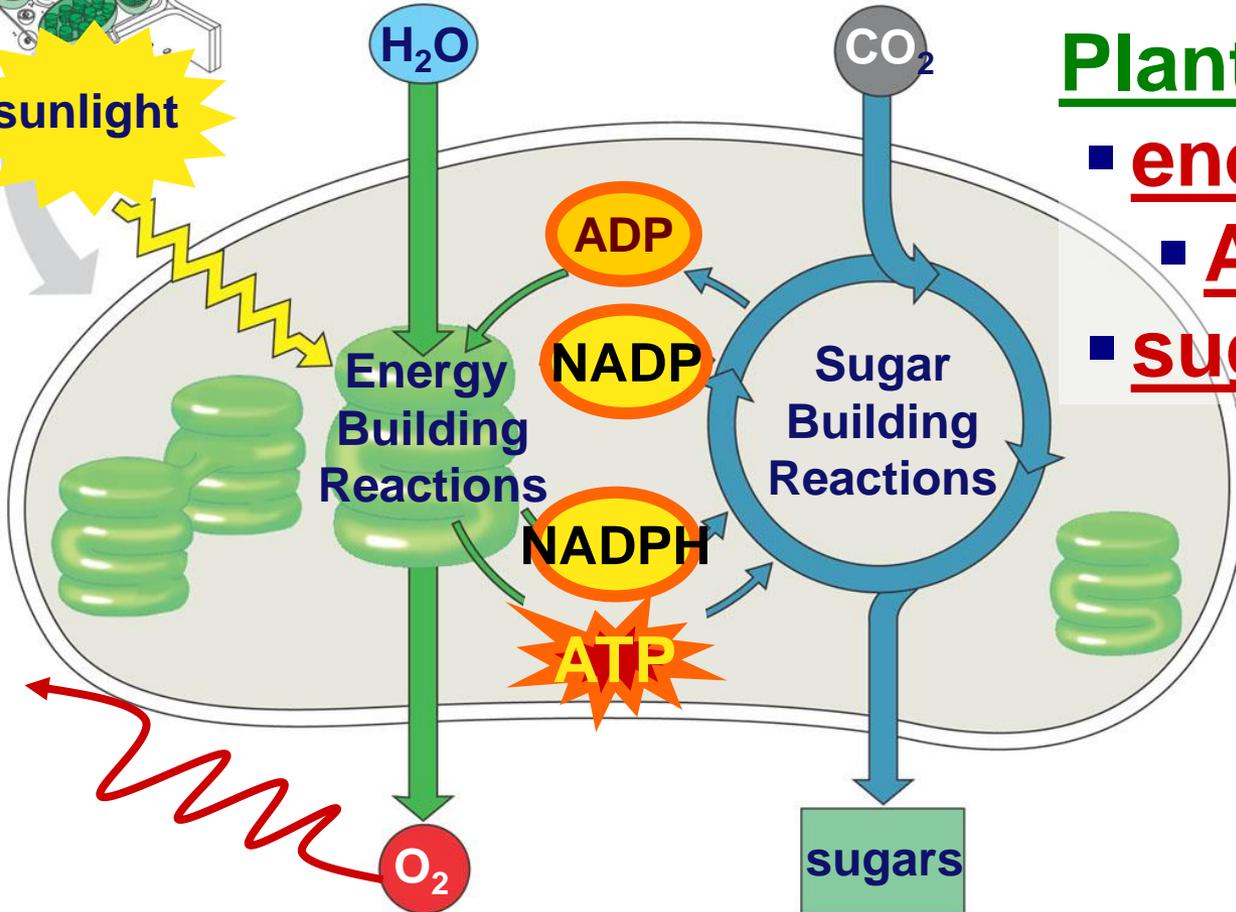
- builds sugars
- uses ATP & NADPH
- recycles ADP & NADP
- back to make more ATP & NADPH

Putting it all together

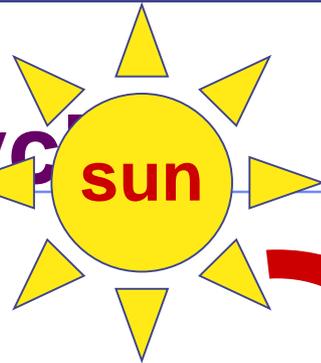


Plants make both:

- **energy**
- **ATP & NADPH**
- **sugars**



Energy cycle



even though this equation is a bit of a lie... it makes a better story

Photosynthesis



glucose



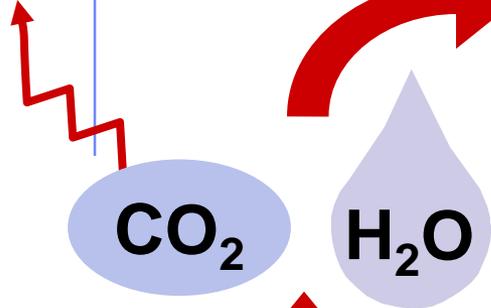
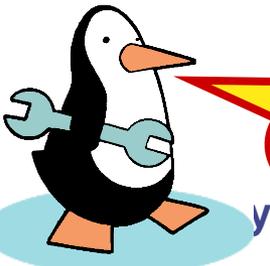
animals, plants



Cellular Respiration



The Great Circle of Life, Mufasa!



Summary of photosynthesis



- Where did the CO_2 come from?
- Where did the CO_2 go?
- Where did the H_2O come from?
- Where did the H_2O go?
- Where did the energy come from?
- What's the energy used for?
- What will the $\text{C}_6\text{H}_{12}\text{O}_6$ be used for?
- Where did the O_2 come from?
- Where will the O_2 go?
- What else is involved...not listed in this equation?

Supporting a biosphere



- On global scale, photosynthesis is the most important process for the continuation of life on Earth
 - ◆ each year photosynthesis...
 - captures 121 billion tons of CO_2
 - synthesizes 160 billion tons of carbohydrate
 - ◆ heterotrophs are dependent on plants as food source for fuel & raw materials

The poetic perspective...

- All the solid material of every plant was built by sunlight out of thin air
- All the solid material of every animal was built from plant material



air

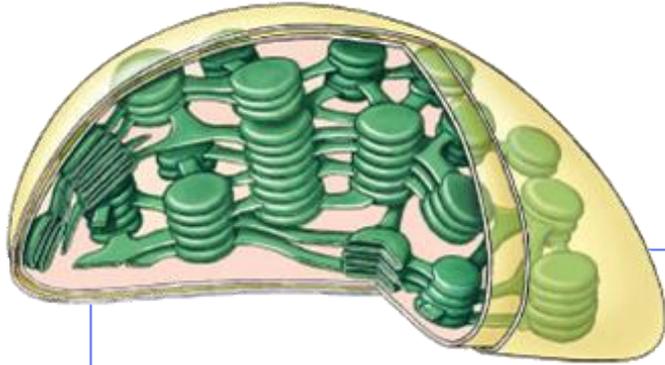


sun

Then all the plants, cats, dogs, elephants & people ... are really particles of air woven together by strands of sunlight!

**If plants can do it...
You can learn it!
Ask Questions!!**

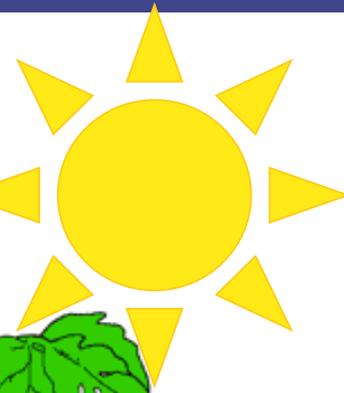




Photosynthesis: Variations on the Theme



Remember what plants need...



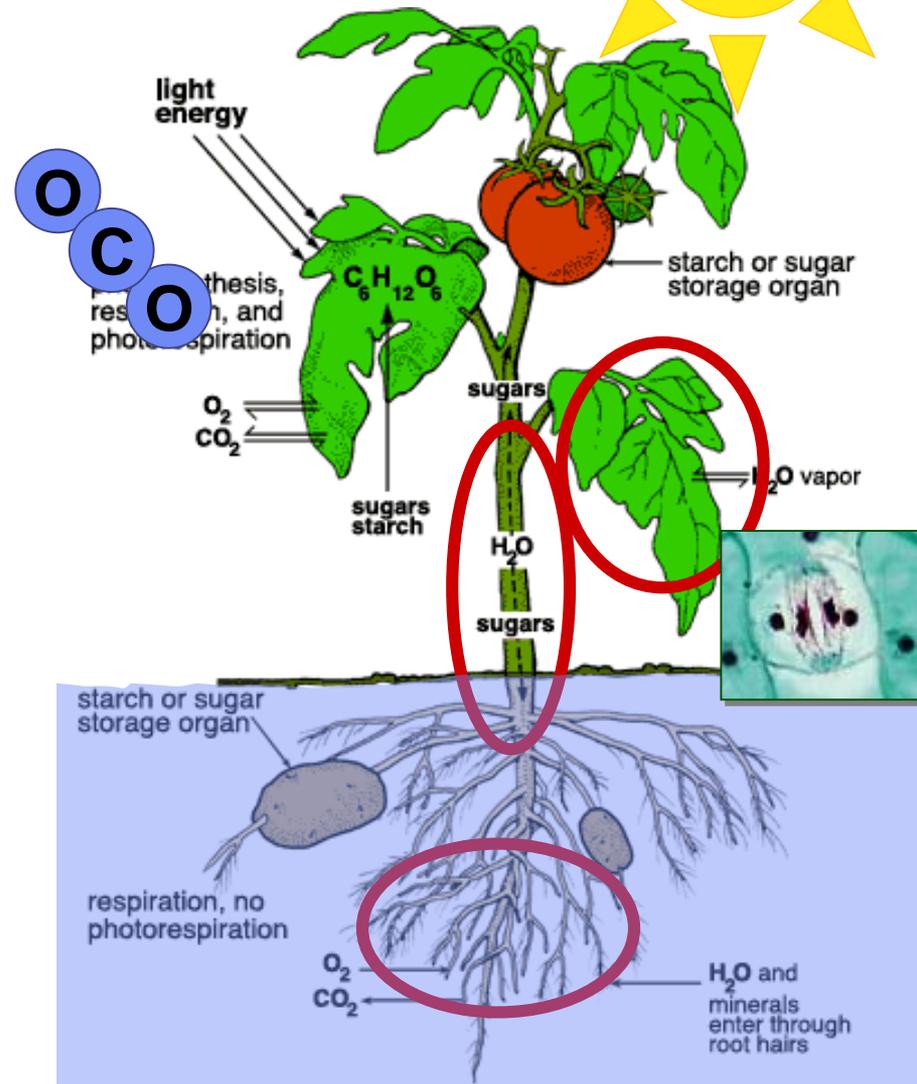
■ Photosynthesis

◆ light reactions

- light ← sun
- H_2O ← ground

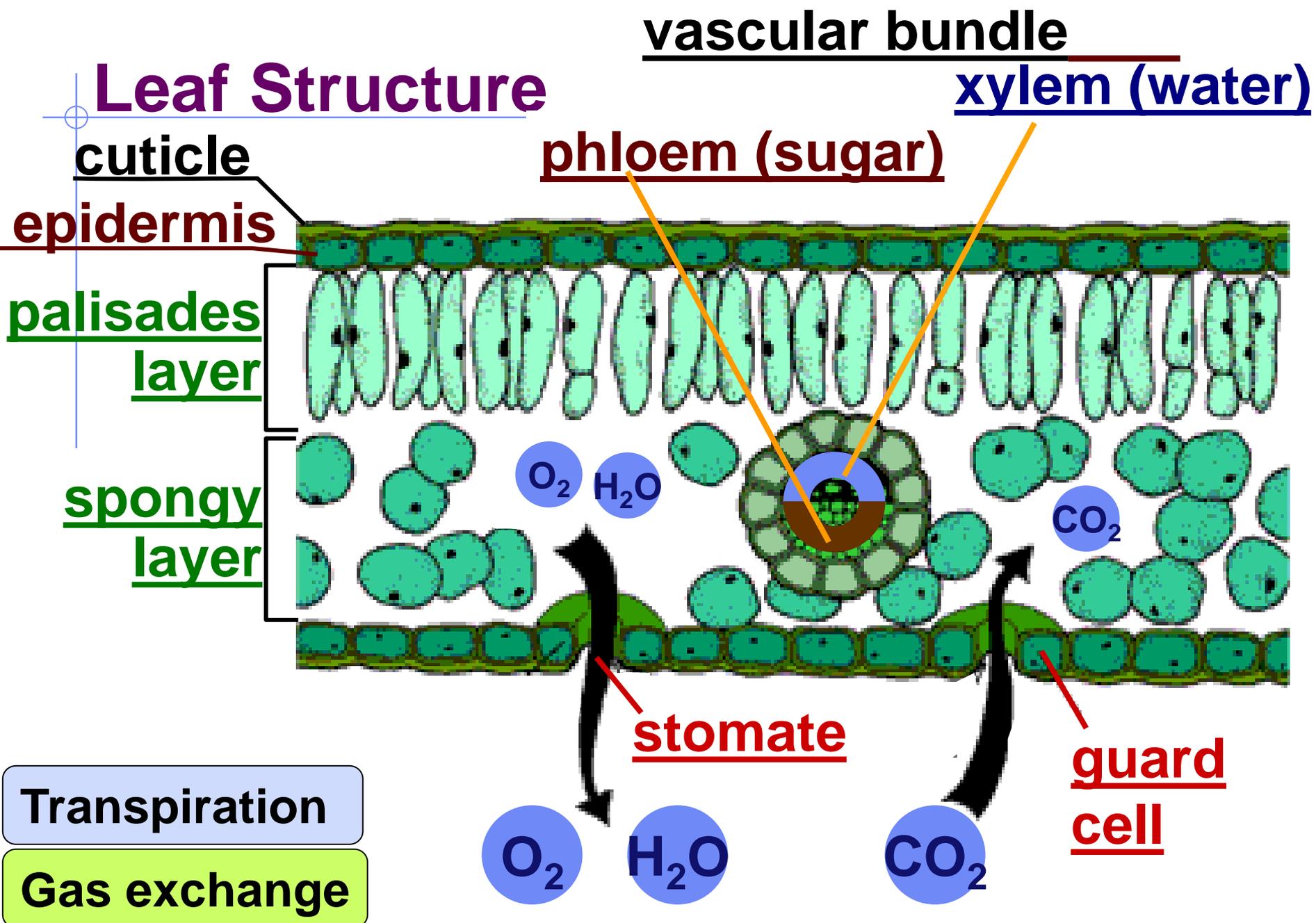
◆ Calvin cycle

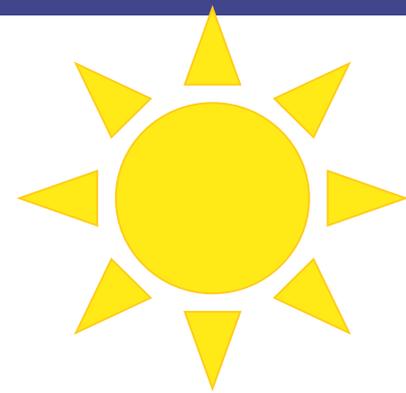
- CO_2 ← air



What structures have plants evolved to supply these needs?

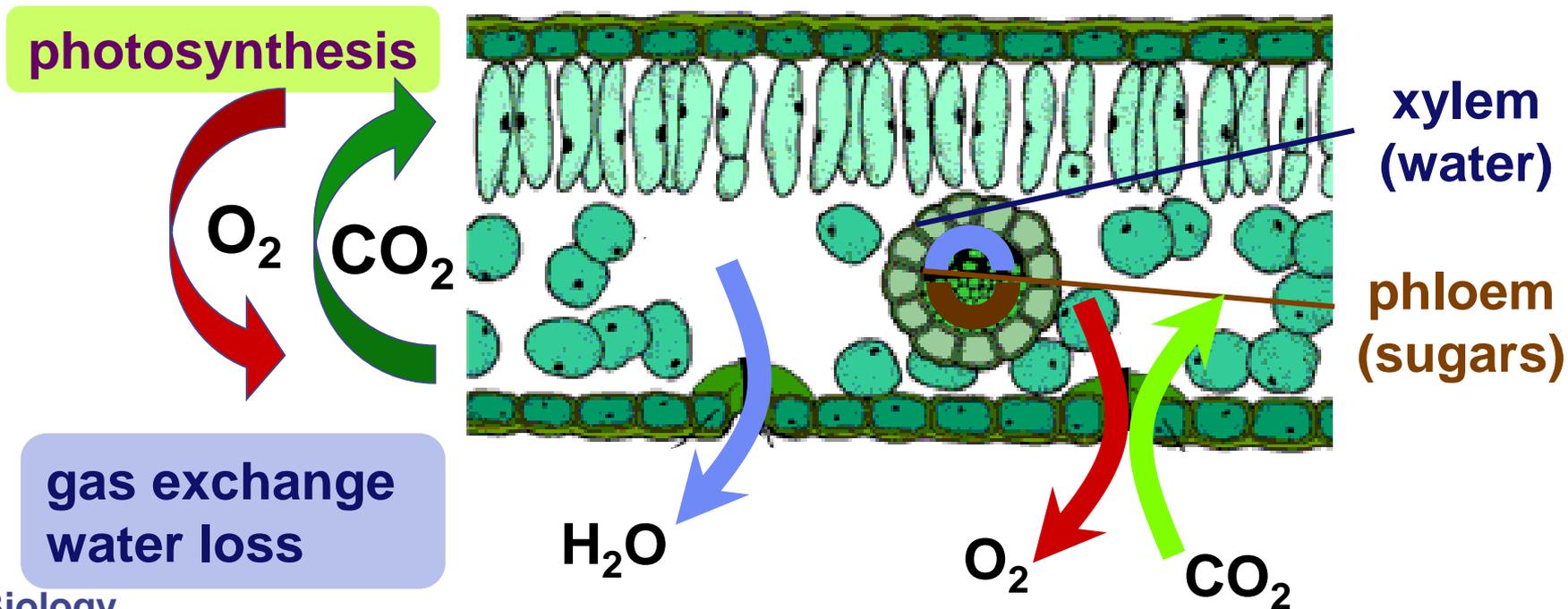
Leaf Structure





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**



Controlling water loss from leaves

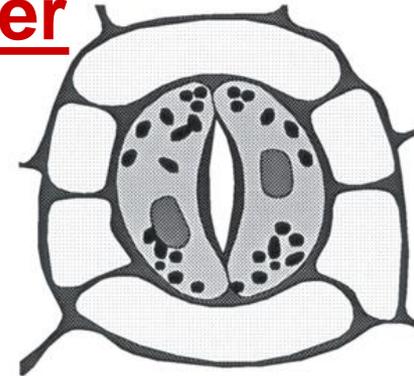
- Hot or dry days

- ◆ stomates close to conserve water

- ◆ guard cells

- gain H_2O = stomates open

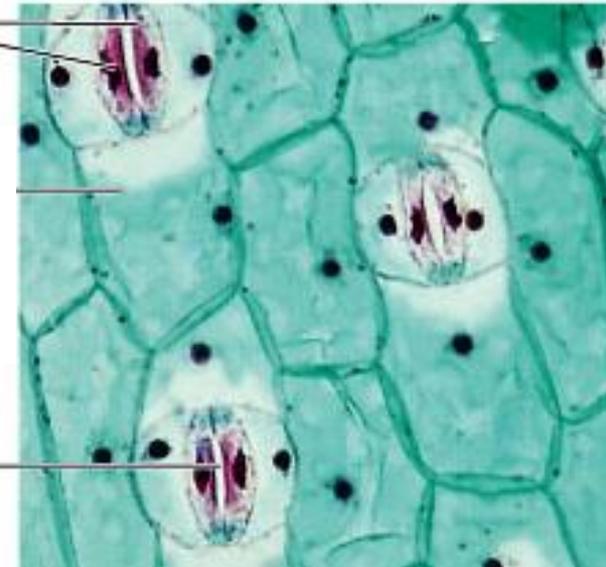
- lose H_2O = stomates close



- ◆ adaptation to living on land, but...

creates PROBLEMS!

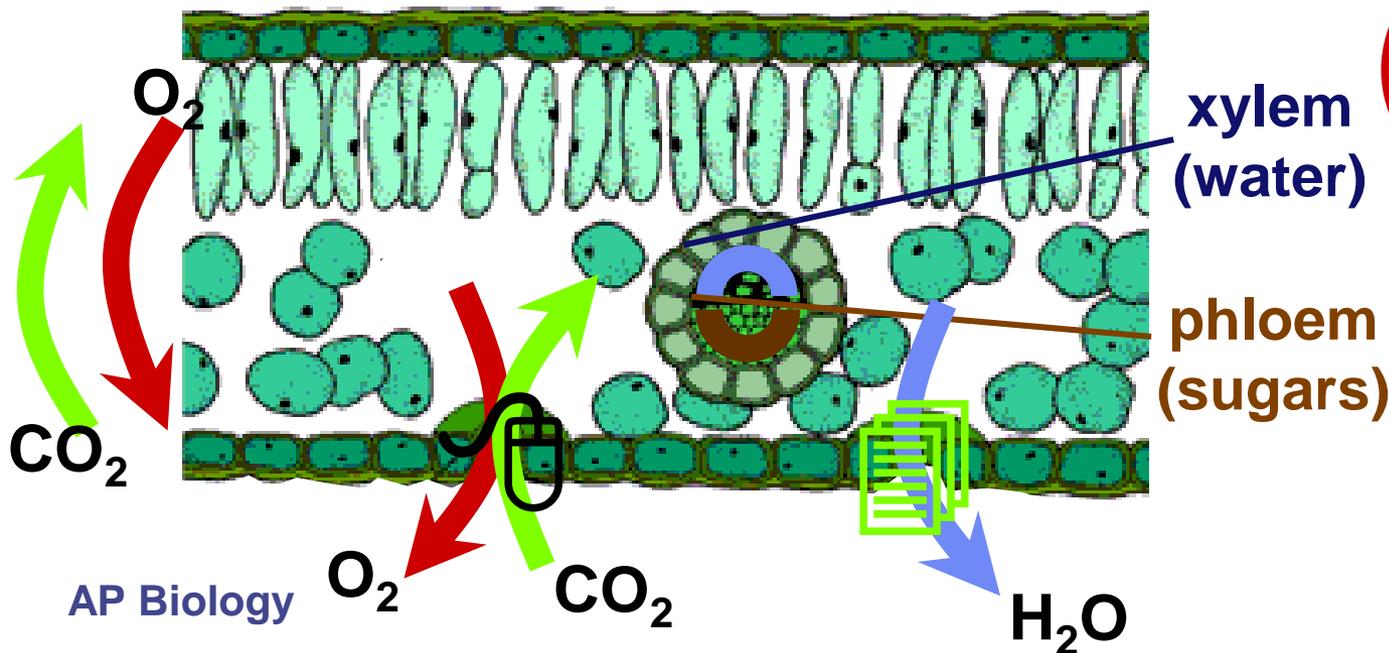
Guard cells



Stoma

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



The best laid schemes of mice and men... and plants!

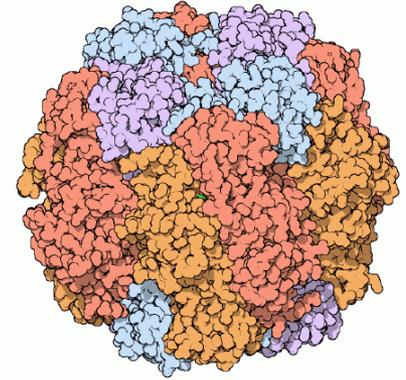


Inefficiency of RuBisCo: CO_2 vs O_2

■ RuBisCo in Calvin cycle

◆ carbon fixation enzyme

- normally bonds C to RuBP
- CO_2 is the optimal substrate
- reduction of RuBP
- building sugars



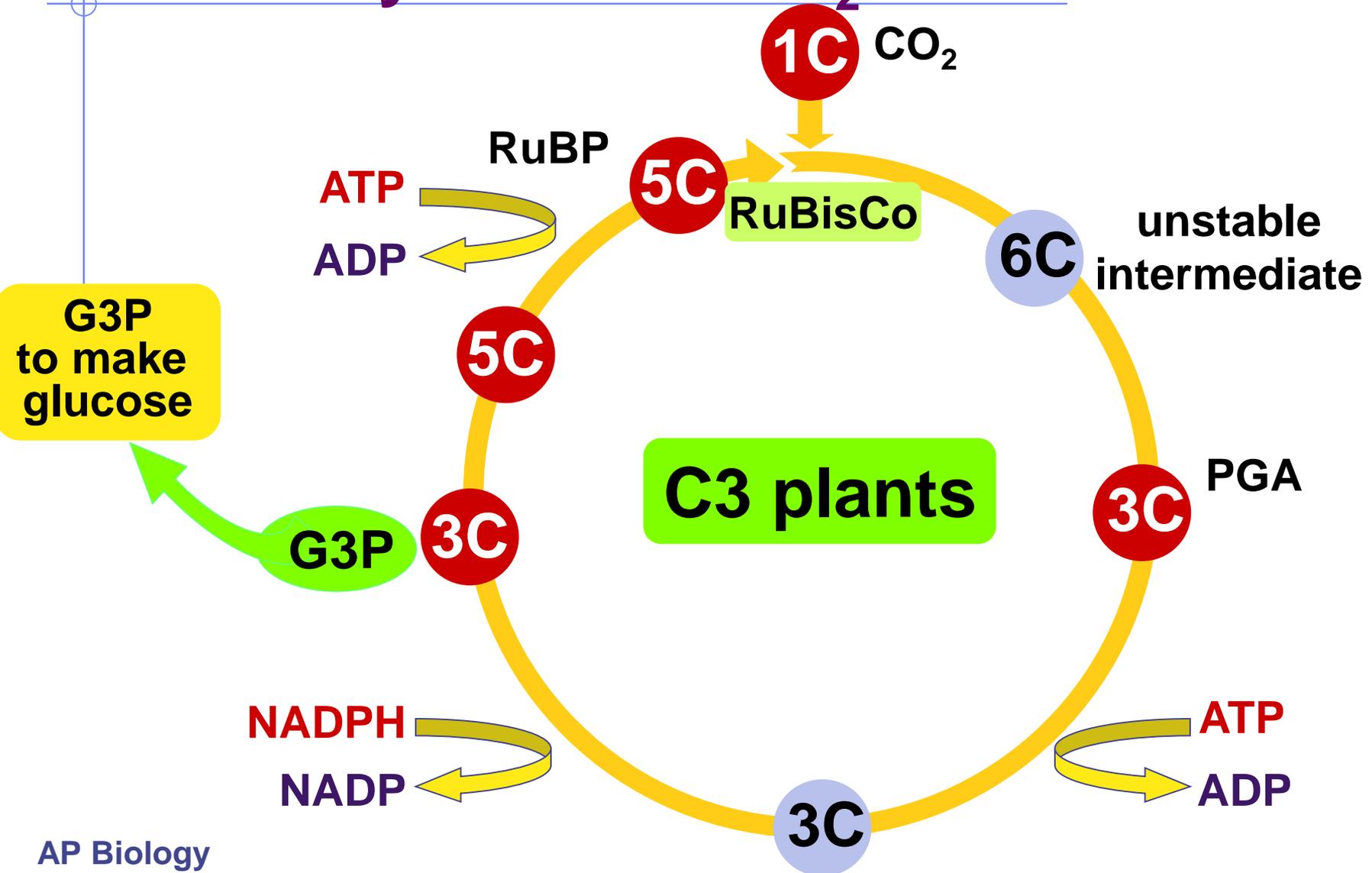
photosynthesis

◆ when O_2 concentration is high

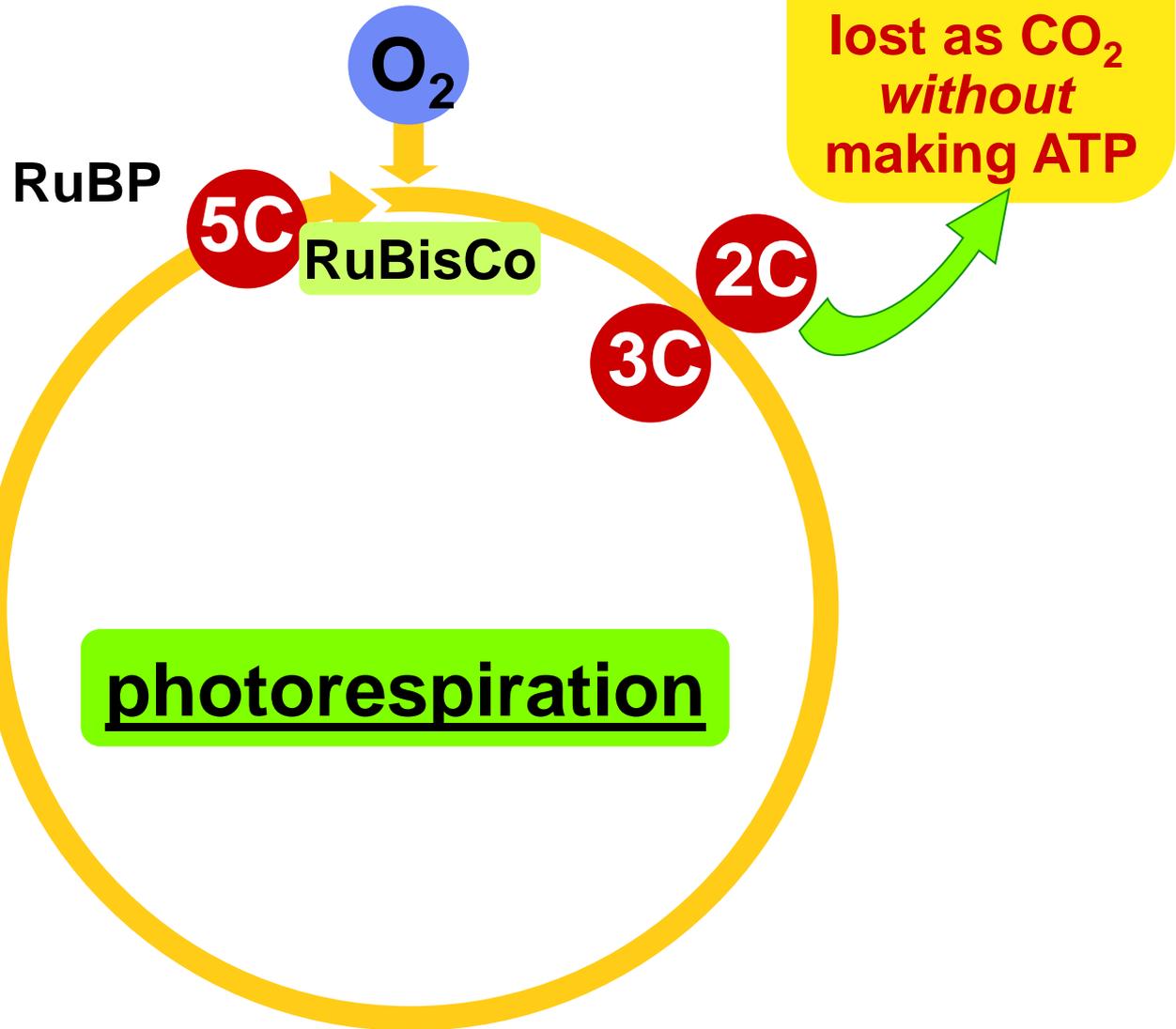
- RuBisCo bonds O to RuBP
- O_2 is a competitive substrate
- oxidation of RuBP
- breakdown sugars

photorespiration

Calvin cycle when CO₂ is abundant

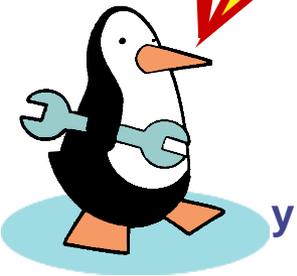


Calvin cycle when O₂ is high



Hey Dude,
are you high
on oxygen!

It's so
sad to see a
good enzyme,
go BAD!



Impact of Photorespiration

- **Oxidation of RuBP**
 - ◆ short circuit of Calvin cycle
 - ◆ **loss of carbons to CO₂**
 - can lose 50% of carbons fixed by Calvin cycle
 - ◆ reduces production of photosynthesis
 - **no ATP** (energy) produced
 - **no C₆H₁₂O₆** (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 CO₂ (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

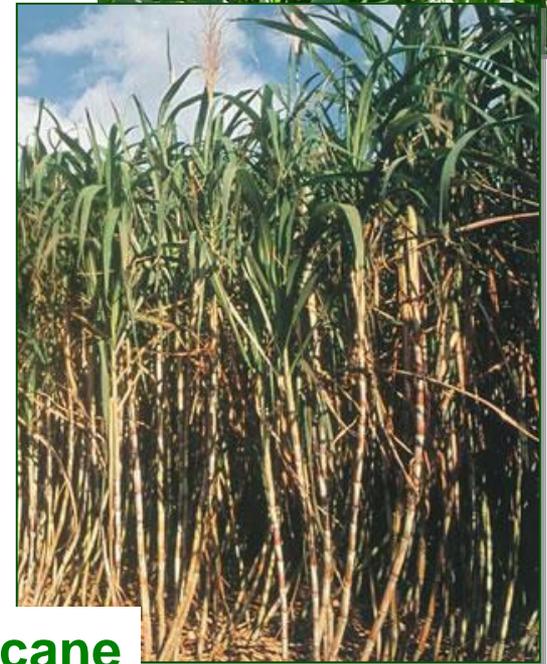


C4 plants

- 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...



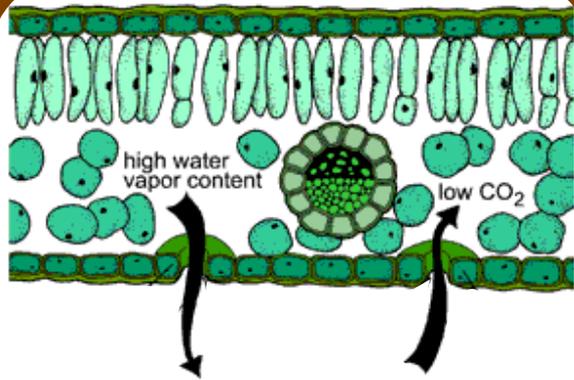
corn



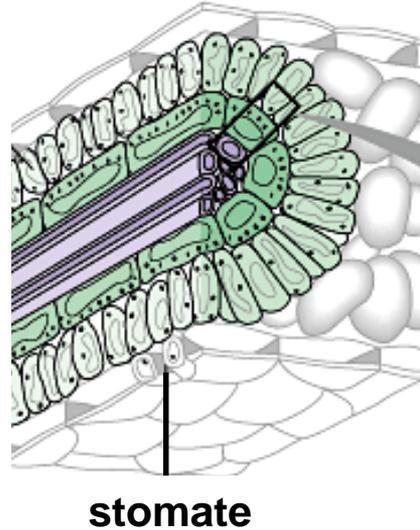
sugar cane

PEP (3C) + CO₂ → oxaloacetate (4C)

C4 leaf anatomy



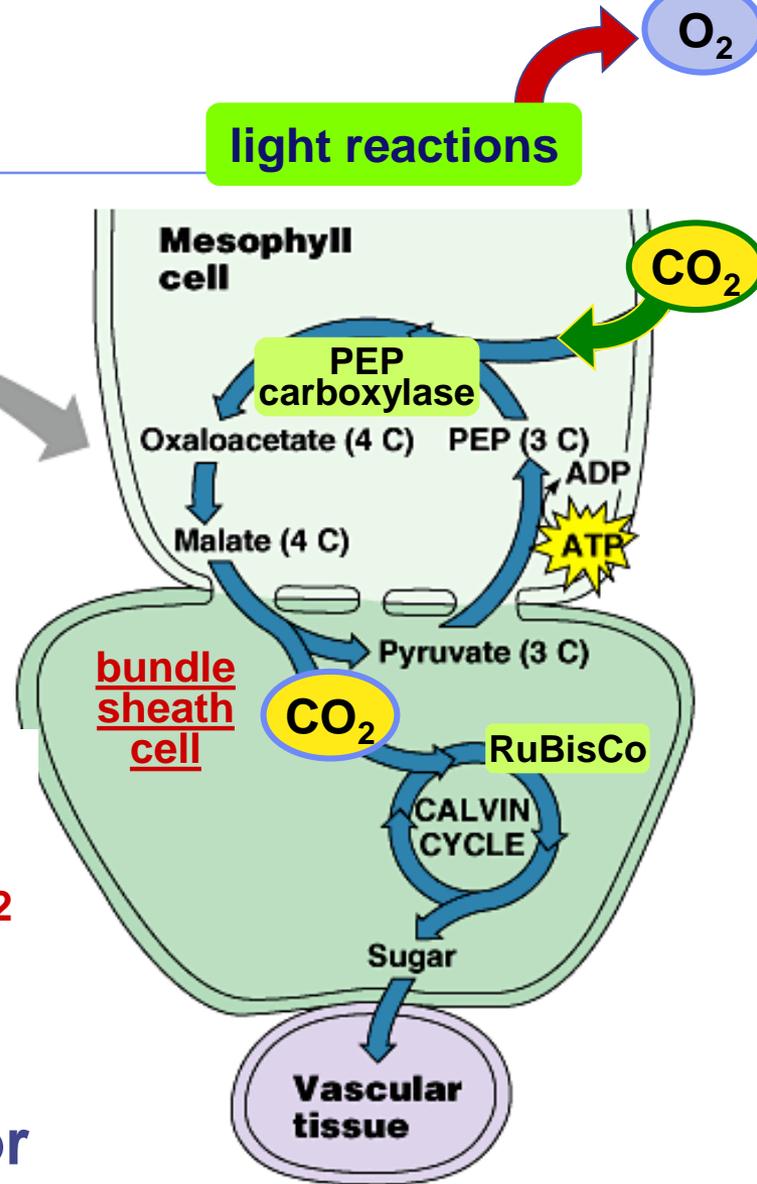
C3 anatomy



stomate

PEP carboxylase enzyme

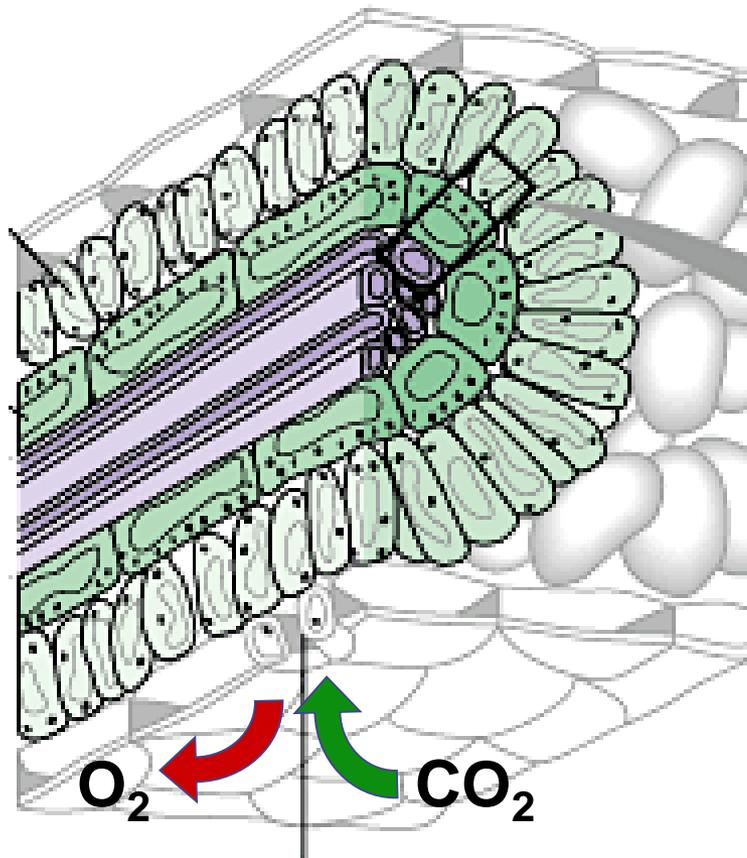
- ◆ higher attraction for CO₂ than O₂
 - better than RuBisCo
- ◆ fixes CO₂ in 4C compounds
- ◆ regenerates CO₂ in inner cells for RuBisCo
 - keeping O₂ away from RuBisCo



C4 anatomy

C4 photosynthesis

PHYSICALLY separated C fixation from Calvin cycle



■ Outer cells

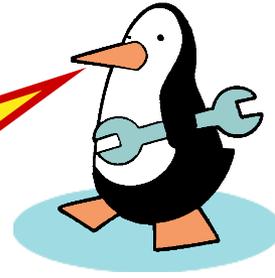
- ◆ light reaction & carbon fixation
- ◆ pumps CO₂ to inner cells
- ◆ keeps O₂ away from inner cells
 - away from RuBisCo

■ Inner cells

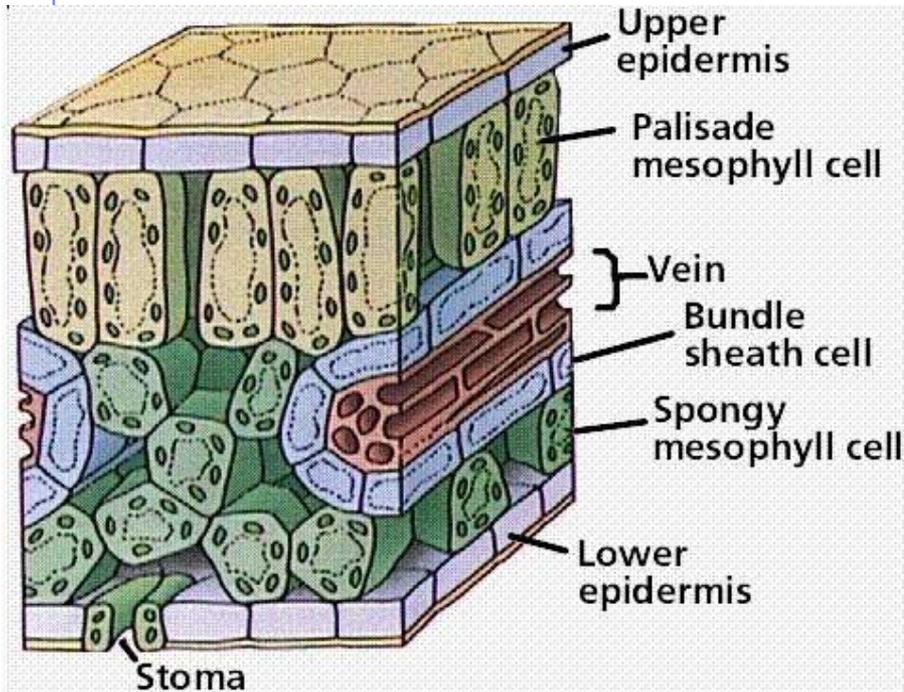
- ◆ Calvin cycle
- ◆ glucose to veins

Comparative anatomy

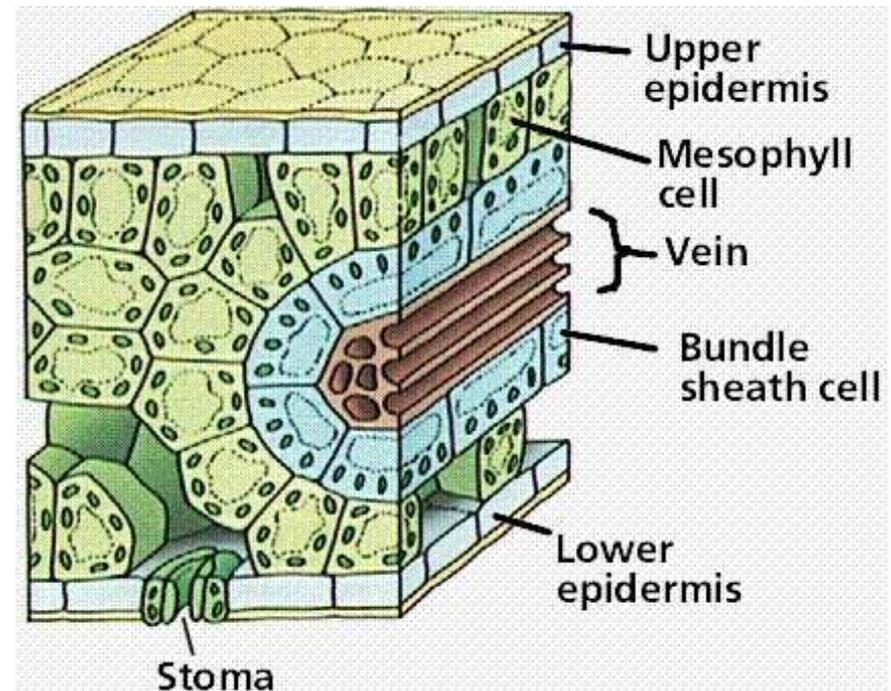
Location,
location, location!



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 CO₂ from 4C acids to Calvin cycle
 - increases concentration of CO₂ in cells
 - ◆ succulents, some cacti, pineapple

It's all in the timing!



CAM plants

cacti



succulents



pineapple

C4 vs CAM Summary

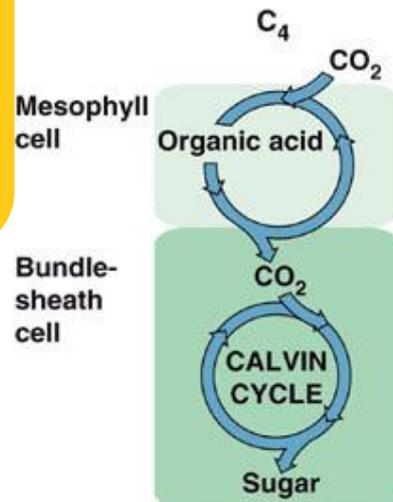
solves CO_2 / O_2 gas exchange vs. H_2O loss challenge



Sugarcane

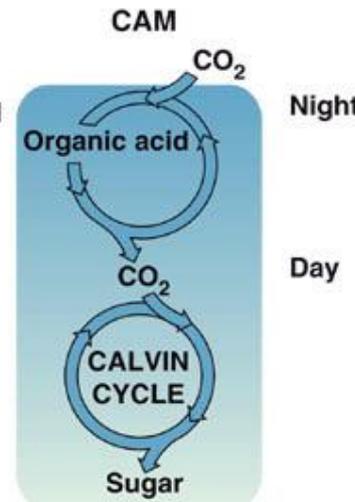


Pineapple



1 CO_2 incorporated into four-carbon organic acids (carbon fixation)

2 Organic acids release CO_2 to Calvin cycle



Night

Day

CAM plants

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

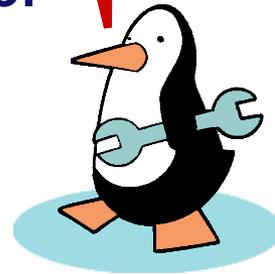
C4 plants

separate 2 steps of C fixation anatomically in 2 different cells

Why the C3 problem?

- **Possibly evolutionary baggage**
 - ◆ Rubisco evolved in high CO₂ atmosphere
 - there wasn't strong selection against active site of Rubisco accepting both CO₂ & O₂
- **Today it makes a difference**
 - ◆ 21% O₂ vs. 0.03% CO₂
 - ◆ 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

We've all got baggage!



**It's not so easy as it looks...
Any Questions??**

