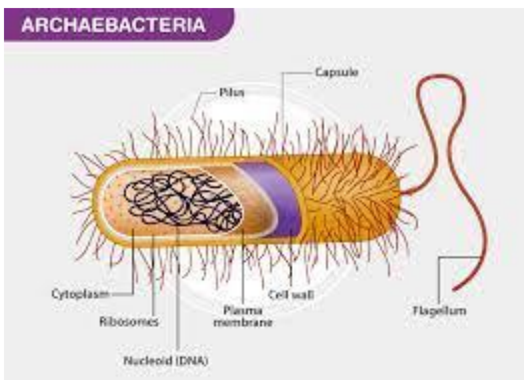
Plant Physiology

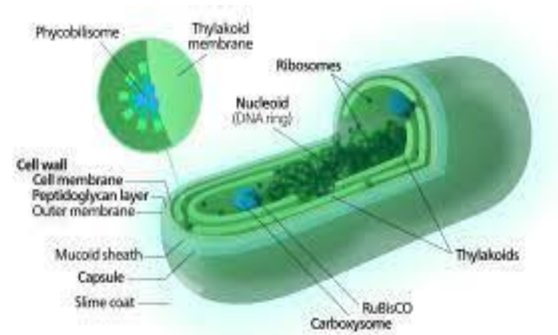
Unite III

Photosynthesis

Carbon Utilization and Dry Matter Production

In the earliest geological period, as the first prokaryotes (archaebacteria, Sulphur bacteria, cyanobacteria) developed photosynthetically active membranes, the environment was strongly anoxic. The primaeval atmosphere was a reducing one, and even the hydrosphere contained very little free oxygen.





1. Biotic producers; photoautotrophs; chemoautotrophs; obtains organic food without eating other organisms.

2. Biotic consumers; obtains organic food by eating other organisms or their by-products (includes decomposers).

Heterotrophic

Making energy & organic molecules from ingesting organic molecules

glucose + oxygen → carbon dioxide + water + energy

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

oxidation = exergonic

Autotrophic

Making energy & organic molecules from light energy

carbon dioxide + water + energy → glucose + oxygen

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

reduction = endergonic

- Photoautotrophic organisms through their ability to carry on photosynthesis created

1. Energy
2. Material Basis for the evolution of life on earth.

The two end products of photosynthesis

Oxygen evolved & Carbon assimilated (Carbohydrates) are equally important to all living organisms.

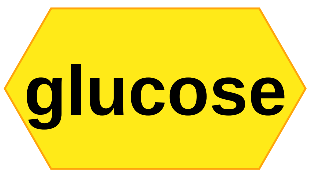
- O2 :- is requested for respiration –which is the most efficient form of biological oxidation, providing energy for metabolism and for maintaining cellular structure.
- Carbohydrates :- the universal substrate for respiration and the starting point for wide diversity of biosynthesis.

What does it mean to be a plant.

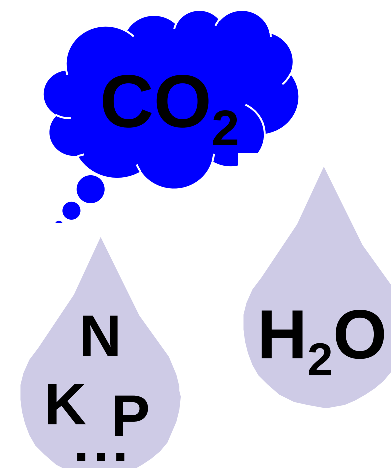
Need to…

- 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 <u>building block atoms</u> from the environment
  - C,H,O,N,P,K,S,Mg
- produce all <u>organic molecules</u> needed for growth
  - carbohydrates, proteins, lipids, nucleic acids



❖ Characteristics of light

- Certain wavelengths of visible light drive the light reactions of photosynthesis

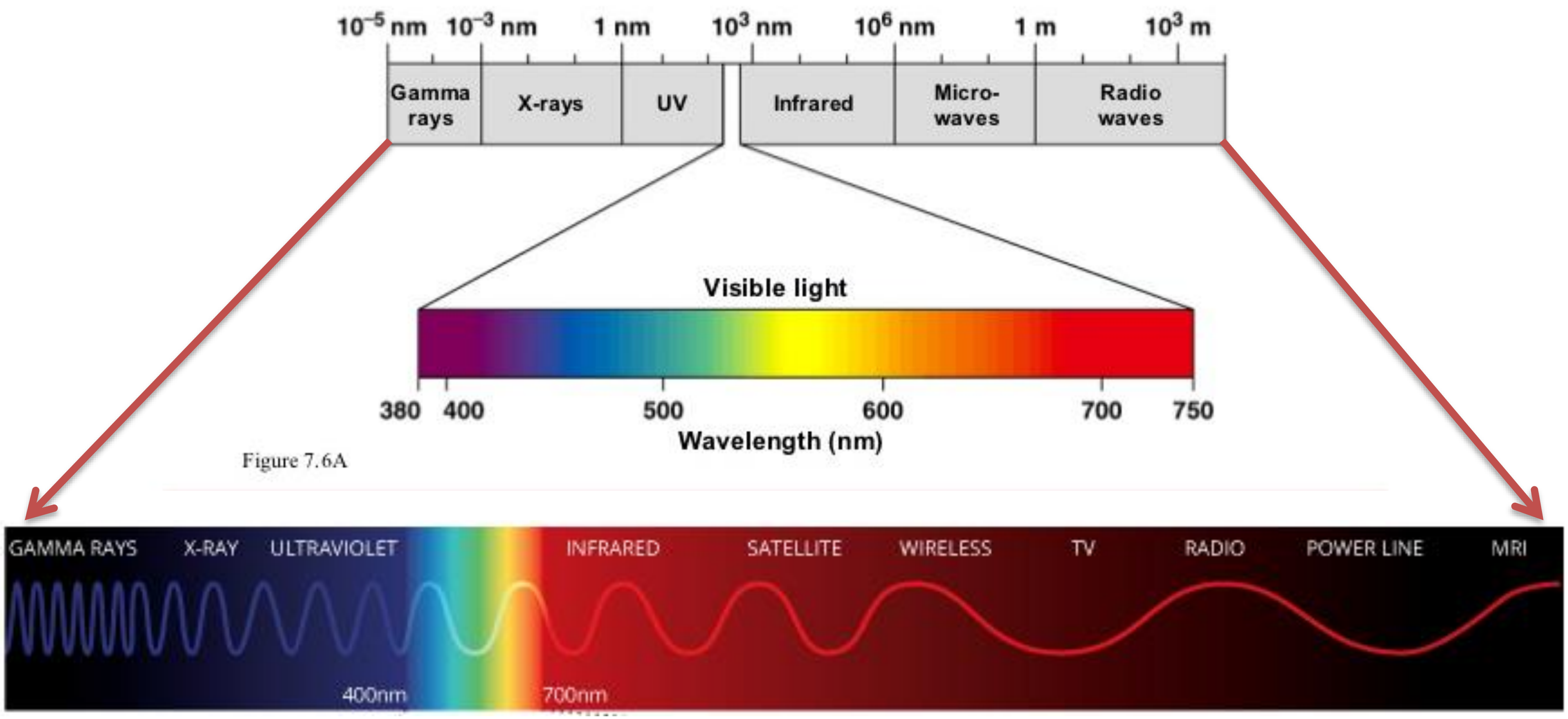
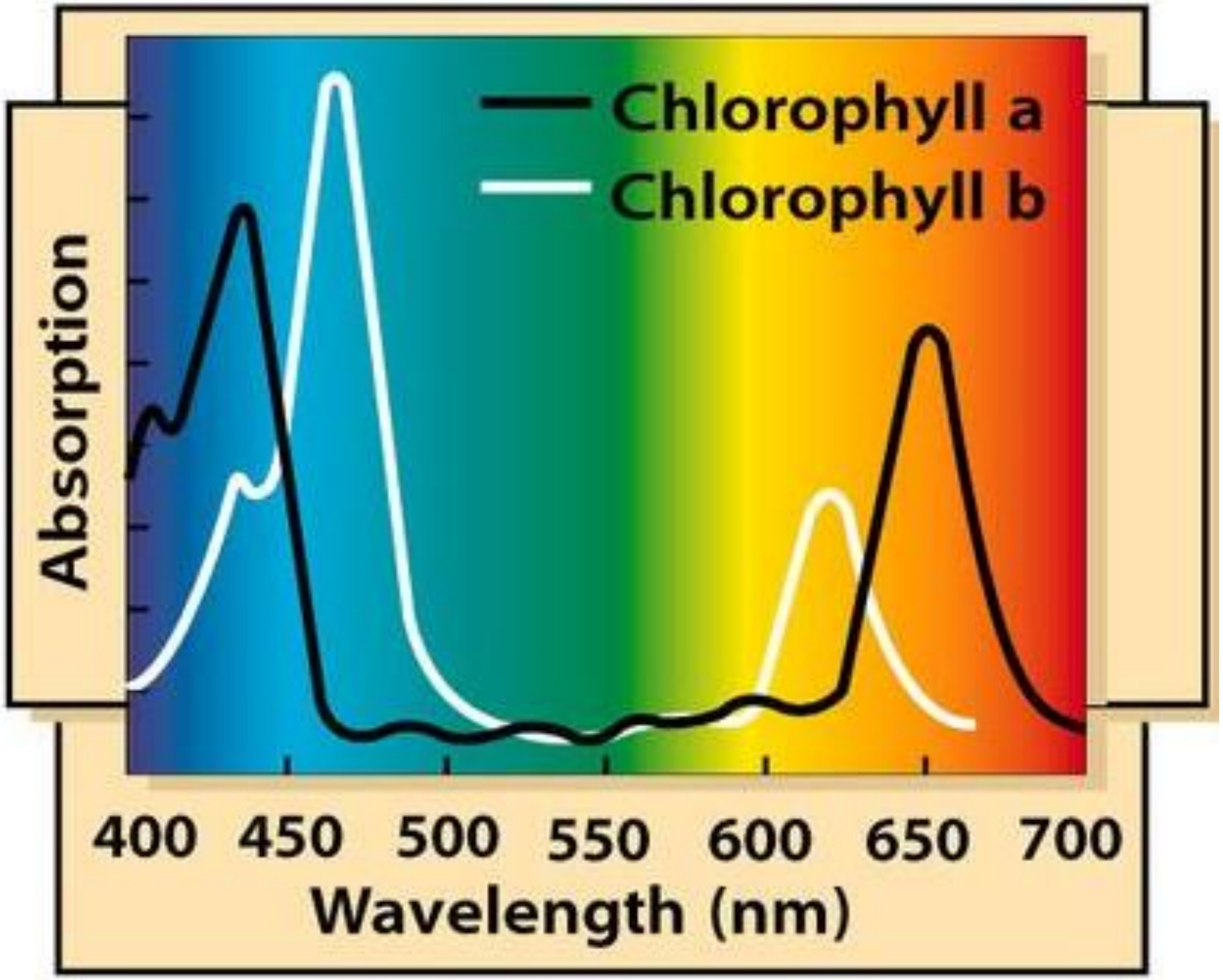
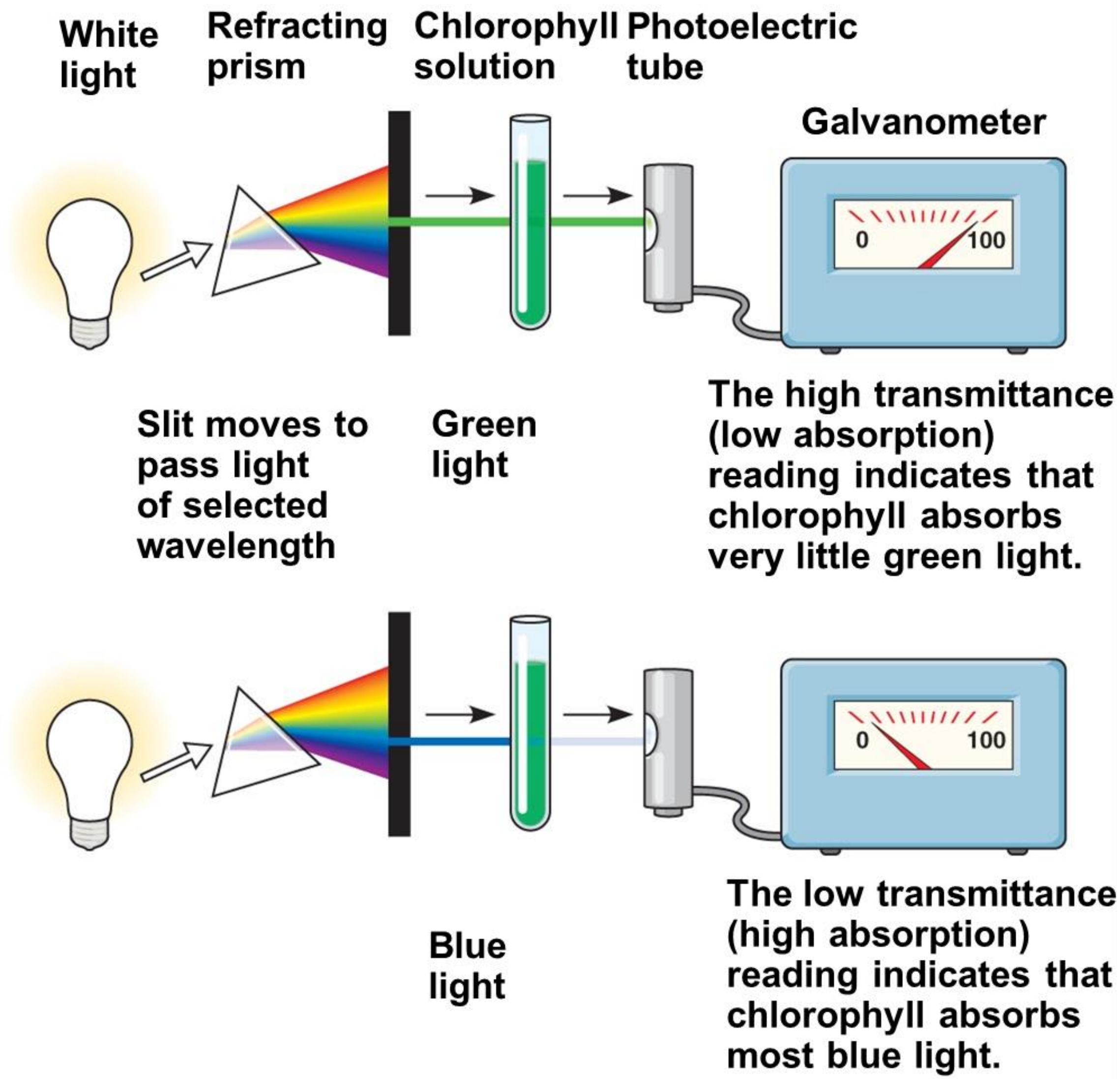


Figure 7.6A

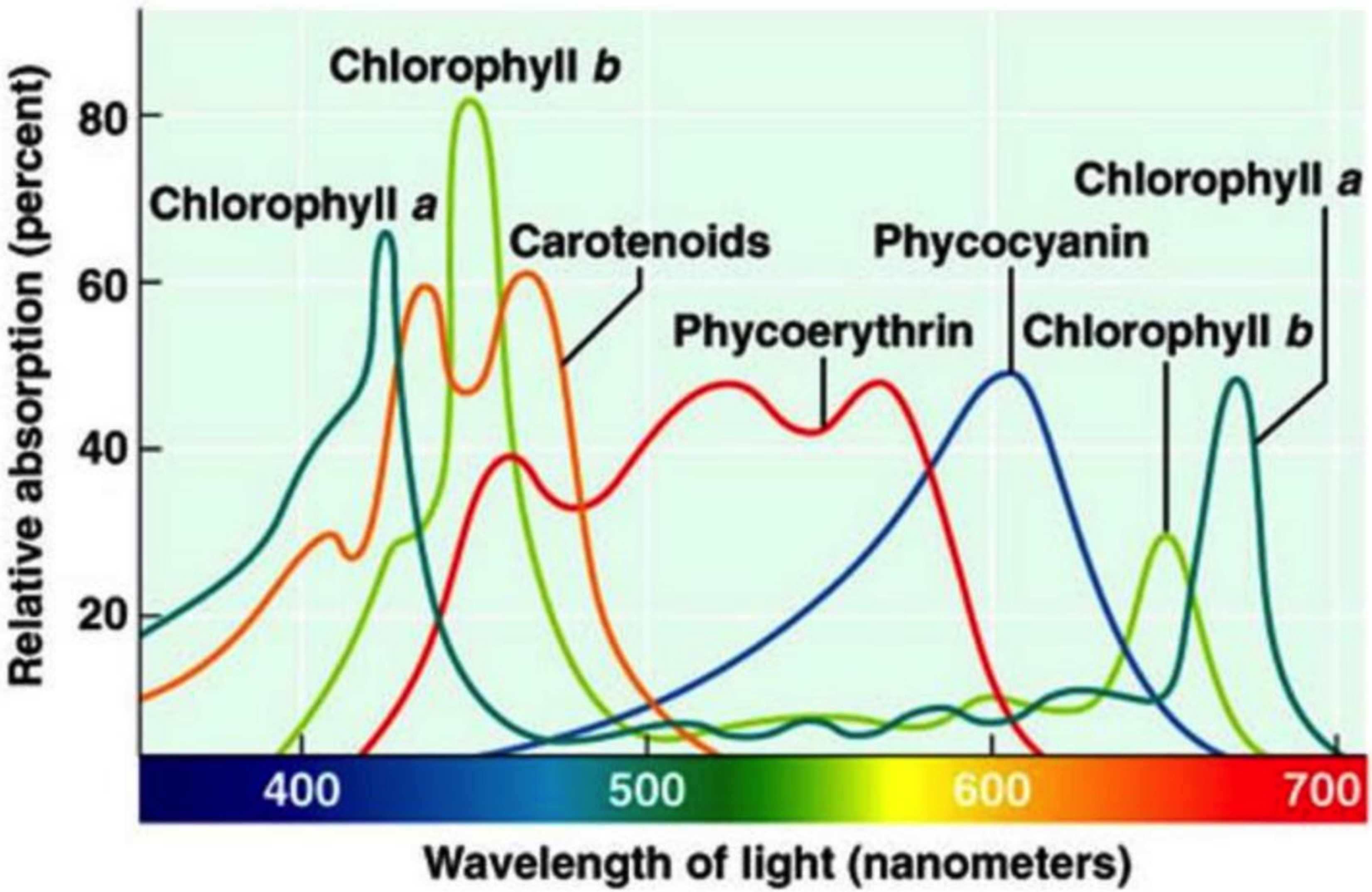
❖ Absorption of light

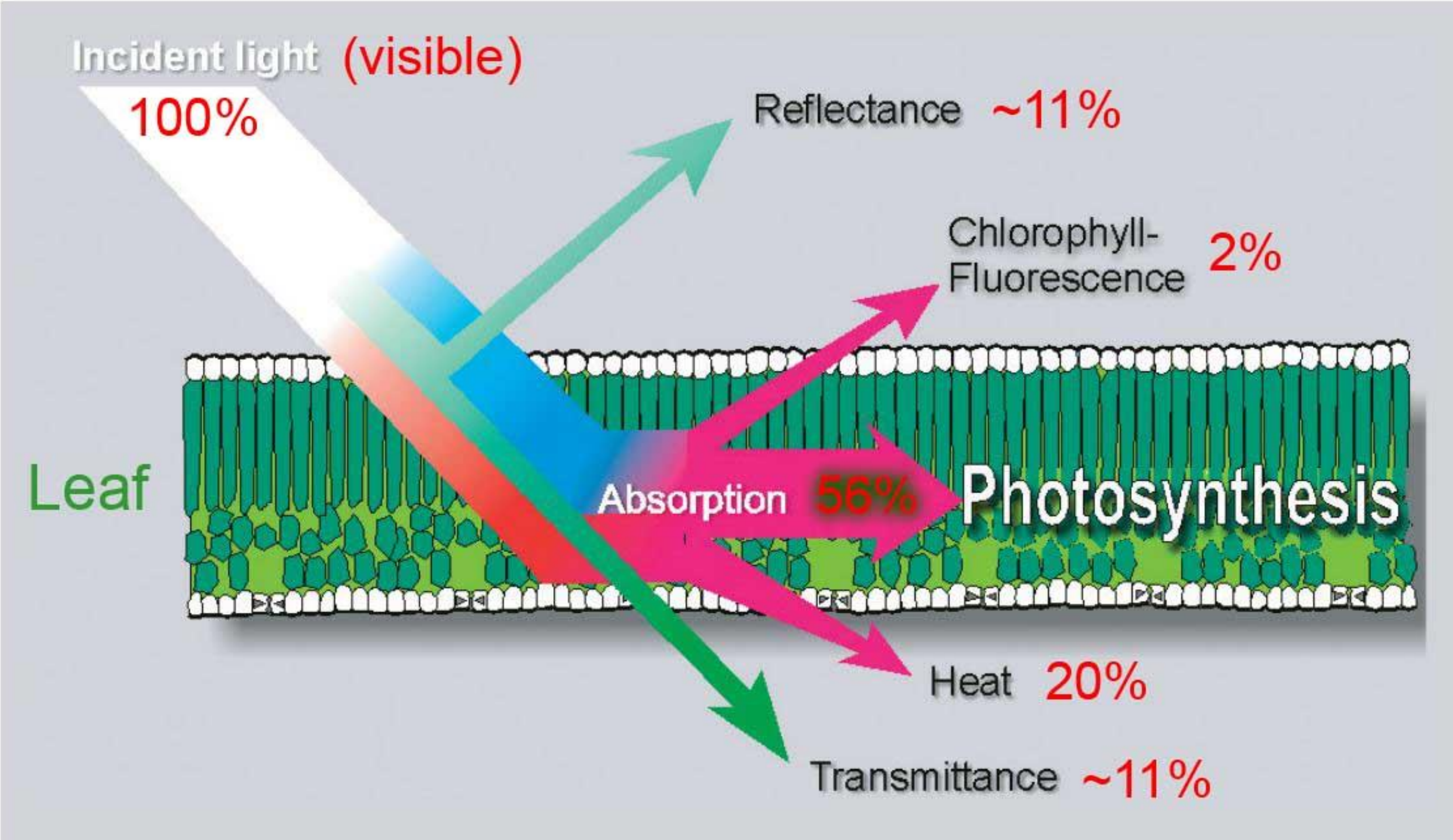
Chlorophyll only absorbs light of specific wavelengths




White light
Refracting prism
Chlorophyll solution
Photoelectric tube
Galvanometer
0
100
Slit moves to pass light of selected wavelength
Green light
The high transmittance (low absorption) reading indicates that chlorophyll absorbs very little green light.
0
100
Blue light
The low transmittance (high absorption) reading indicates that chlorophyll absorbs most blue light.

Absorption of light by plant / all pigments

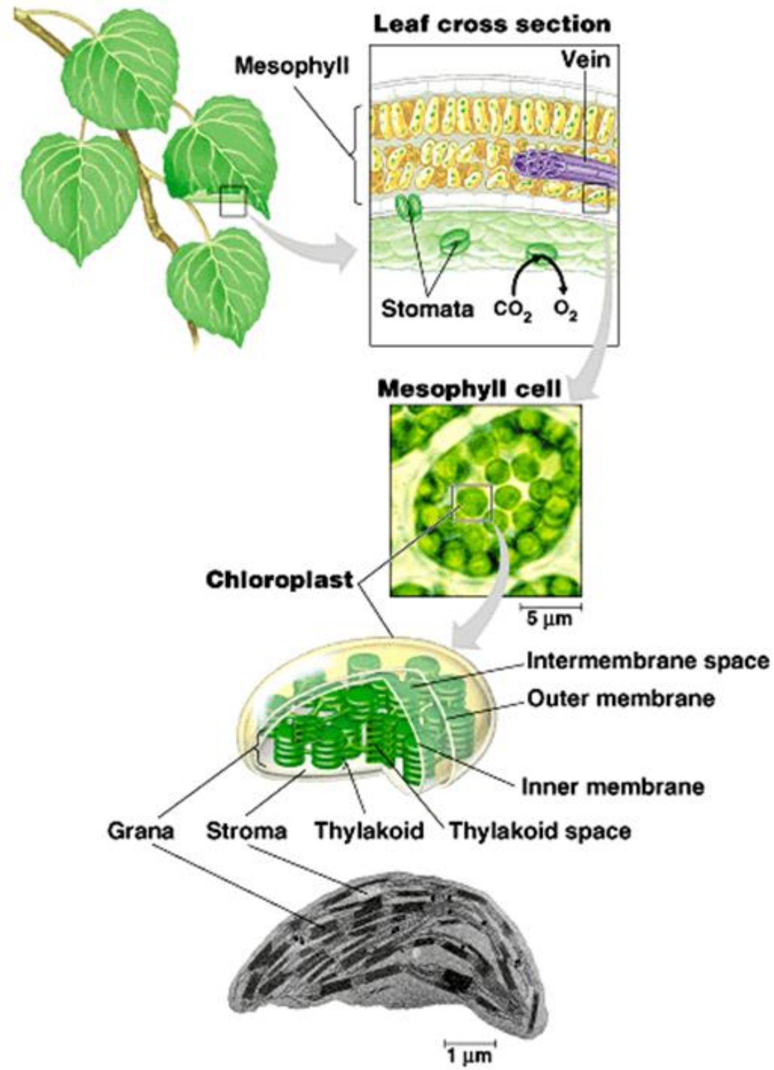




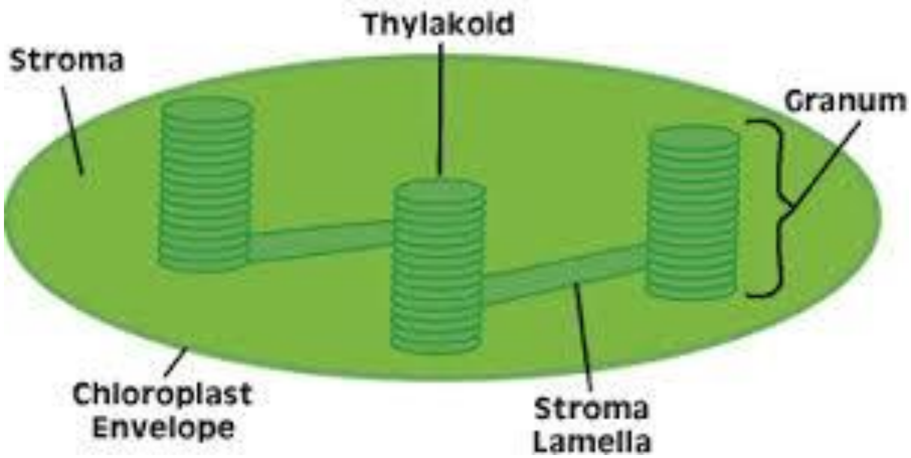
How light energy falling on a leaf is partitioned. About 78% of the incident radiation is absorbed, while the rest is either transmitted or reflected at the leaf's surface. About 20% is dissipated through heat and only 2% emitted as fluorescence, as a by-product of photosynthetic reactions occurring within the leaf itself.

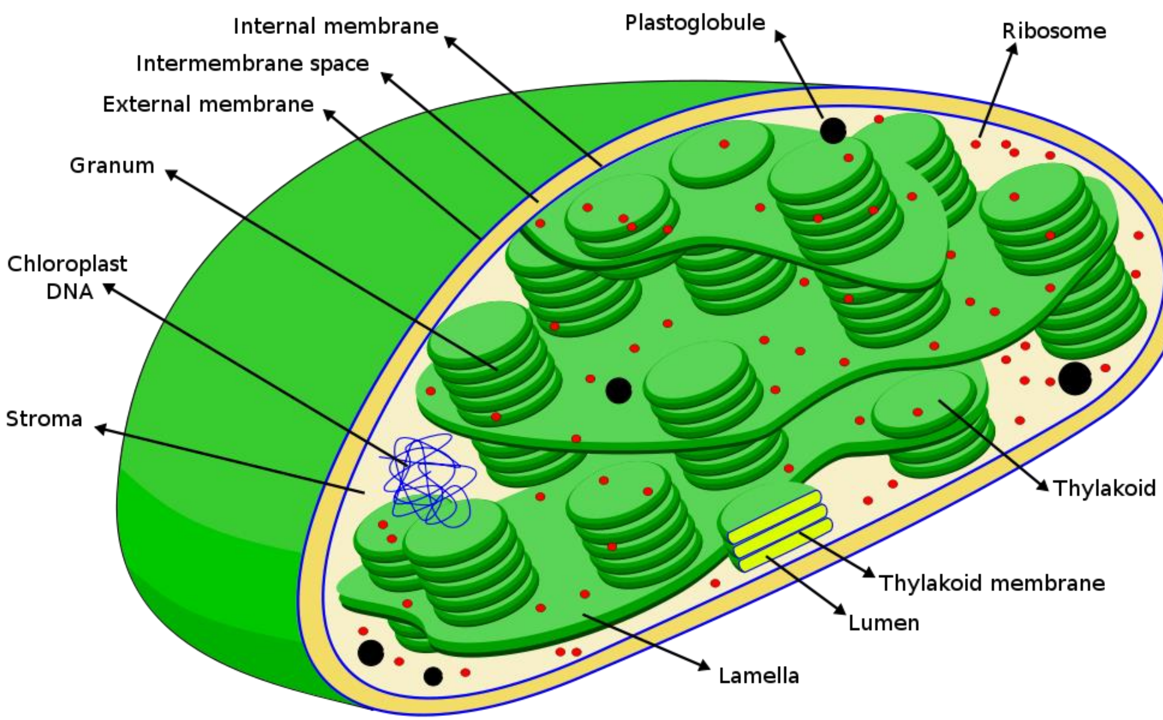
❖ The chloroplast

- Sites of photosynthesis
- Pigment: chlorophyll
- Plant cell: mesophyll
- Gas exchange: stomata
- Double membrane
- Thylakoids, stack-granum
- Thylakoid membrane contains
  - chlorophyll molecules
  - electron transport chain
  - ATP synthase
- Stroma-fluid-filled interior

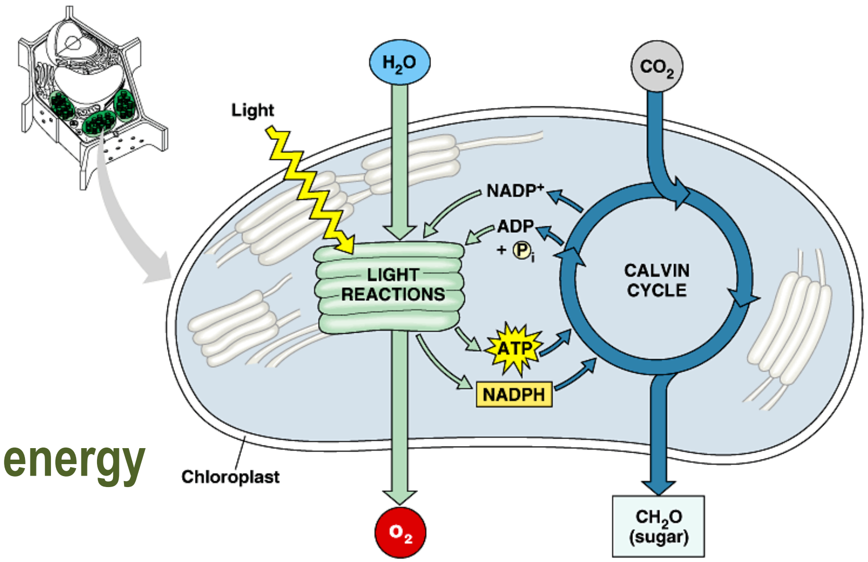


❖ The chloroplast structure





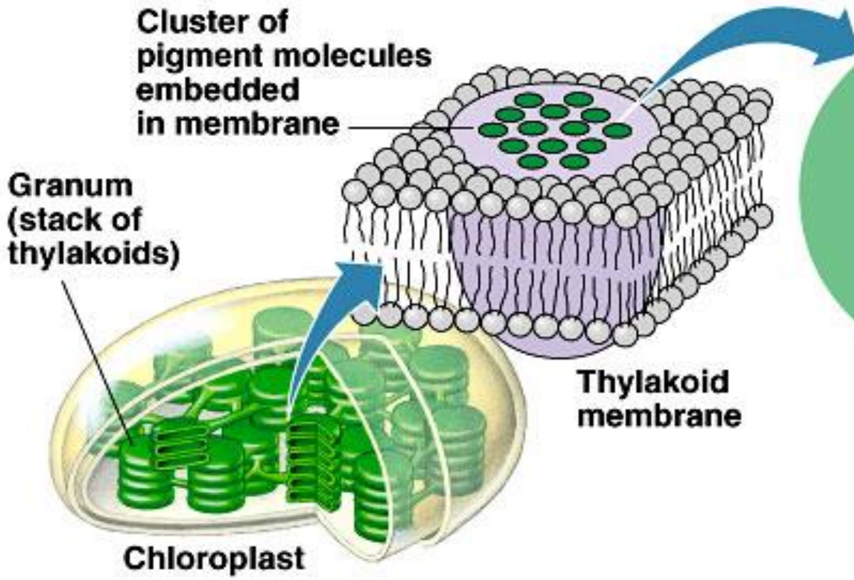
❖ Photosynthesis

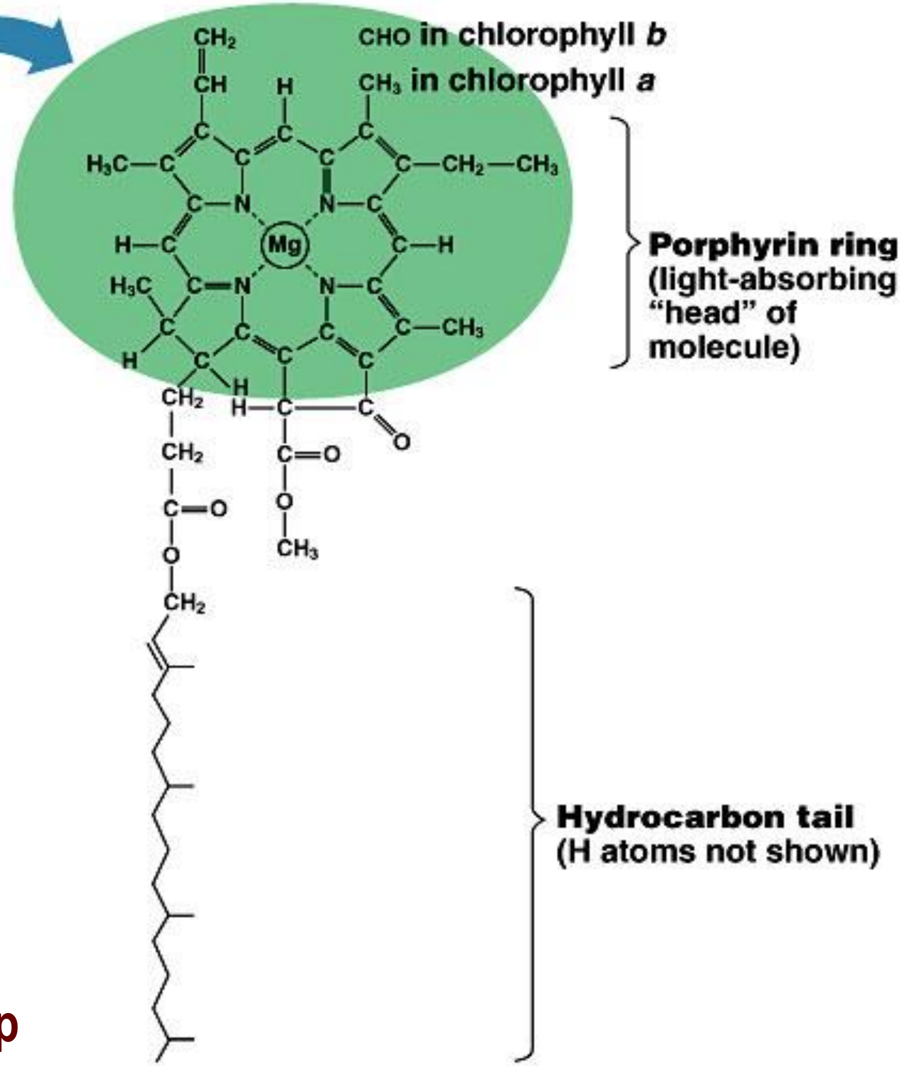


- Light reactions
  - light-dependent reactions
  - energy conversion reactions
    - convert solar energy to chemical energy
    - ATP & NADPH
- Calvin cycle
  - light-independent reactions
  - sugar building reactions
    - uses chemical energy (ATP & NADPH) to reduce CO_2 & synthesize $C_6H_{12}O_6$

Q What is the role of the light-dependent and independent reactions in photosynthesis ?

❖ Pigments of photosynthesis





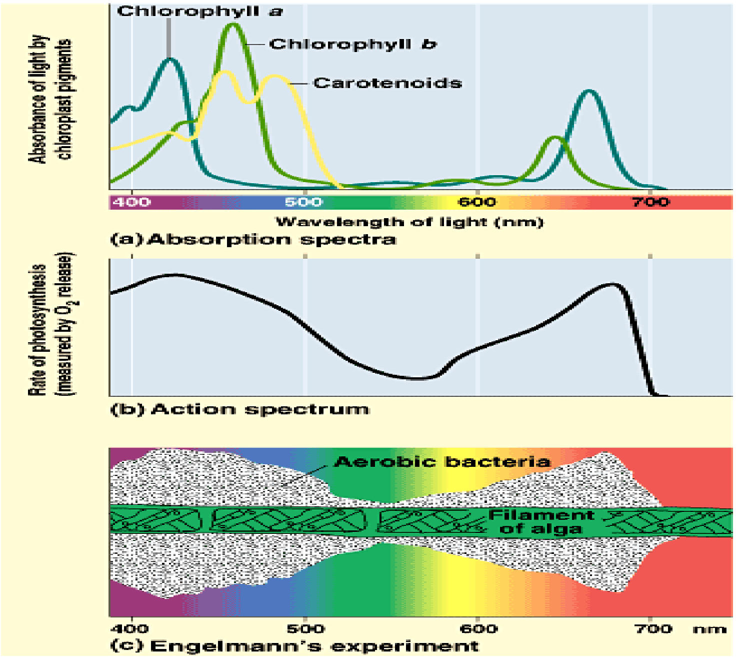
- **Chlorophylls & other pigments**
  - **embedded in thylakoid membrane**
  - **arranged in a "photosystem"**
    - **collection of molecules**
  - **structure-function relationship**

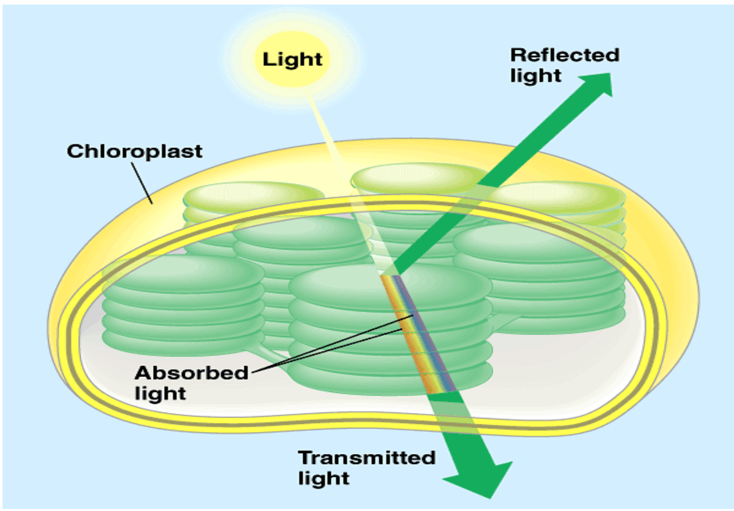
❖ Photosynthetic pigments

- Pigment ~substance that absorbs light
- Absorption spectrum~ measures the wavelength of light that absorbed by particular pigment
- Accessory pigments~ absorbs energy that chlorophyll a does not absorb

ensures that a greater % of incoming photons will stimulate photosynthesis

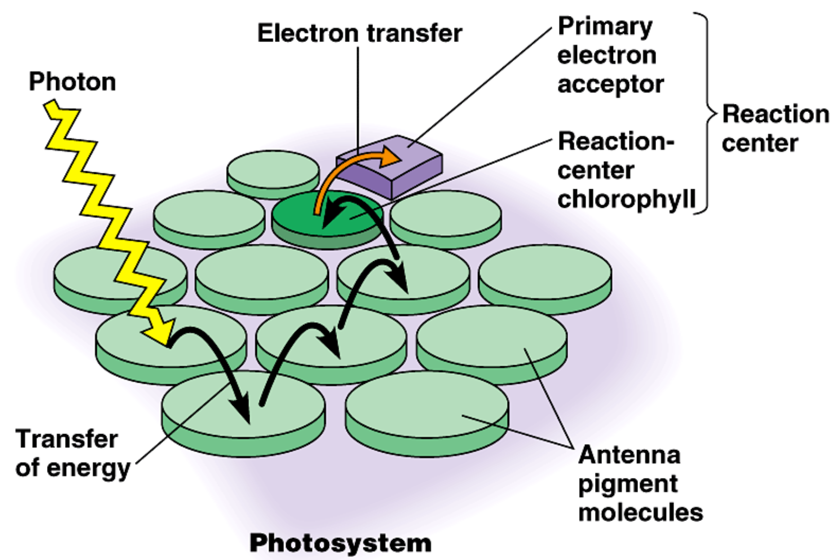
Action spectrum ~plots the efficiency of photosynthesis at various wavelengths



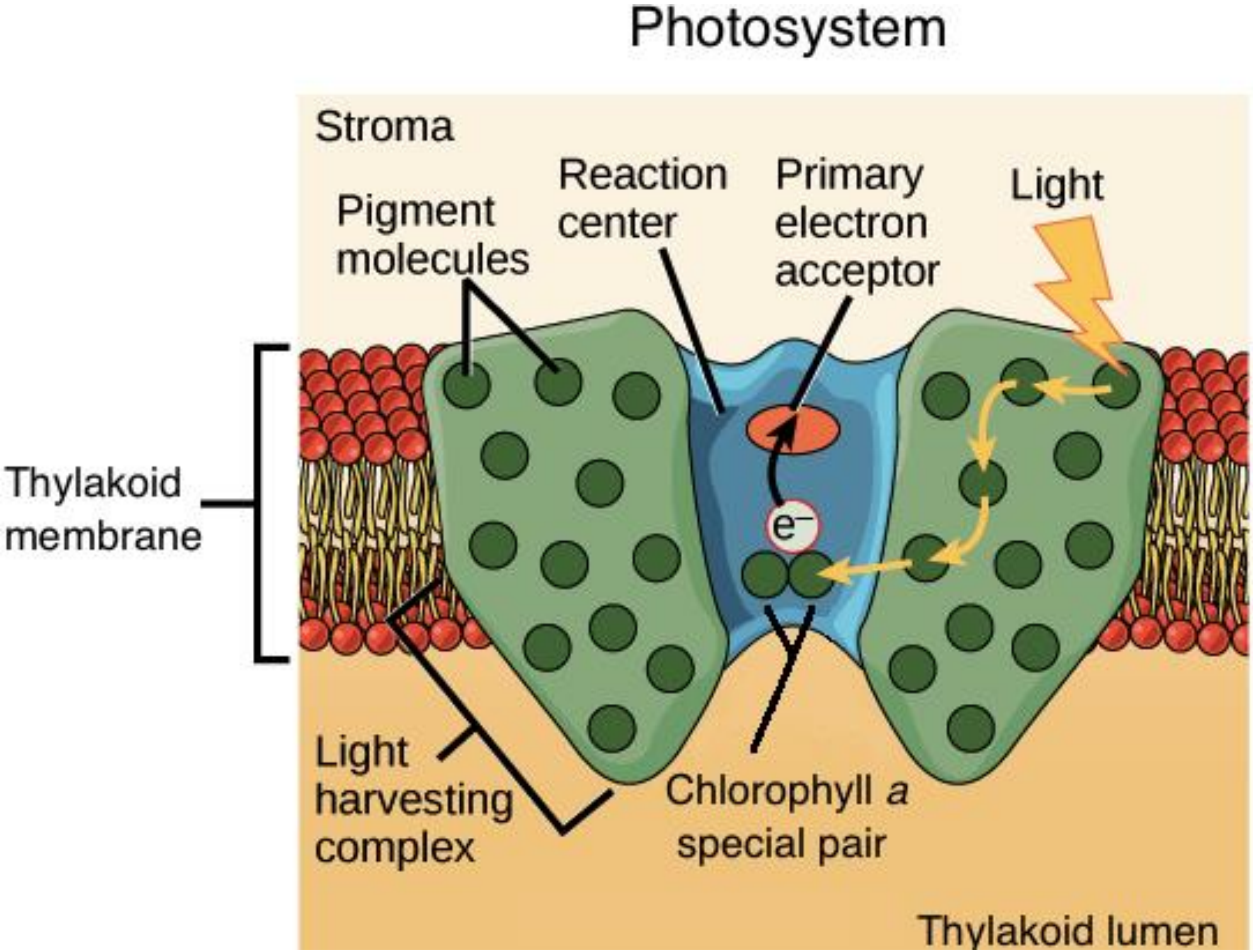


❖ Photosystems

- Light harvesting units of the thylakoid membrane
- Composed mainly of protein and pigment antenna complexes
- Antenna pigment molecules are struck by photons
- Energy is passed to reaction centers (redox location)
- Excited e- from chlorophyll is trapped by a primary e- acceptor

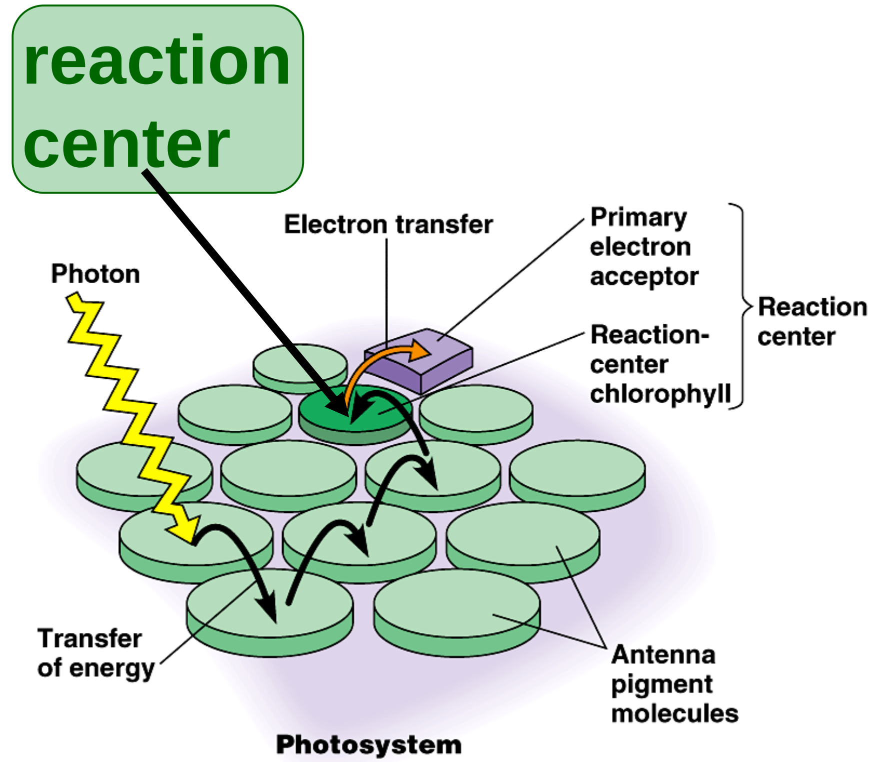


The light dependent reaction of photosynthesis



❖ Photosystems of photosynthesis

- Two photosystems in thylakoid membrane
  - collections of chlorophyll molecules
  - **Photosystem II**
    - chlorophyll *a*
    - P_{680} = absorbs 680nm wavelength red light
  - **Photosystem I**
    - chlorophyll *b*
    - P_{700} = absorbs 700nm wavelength red light



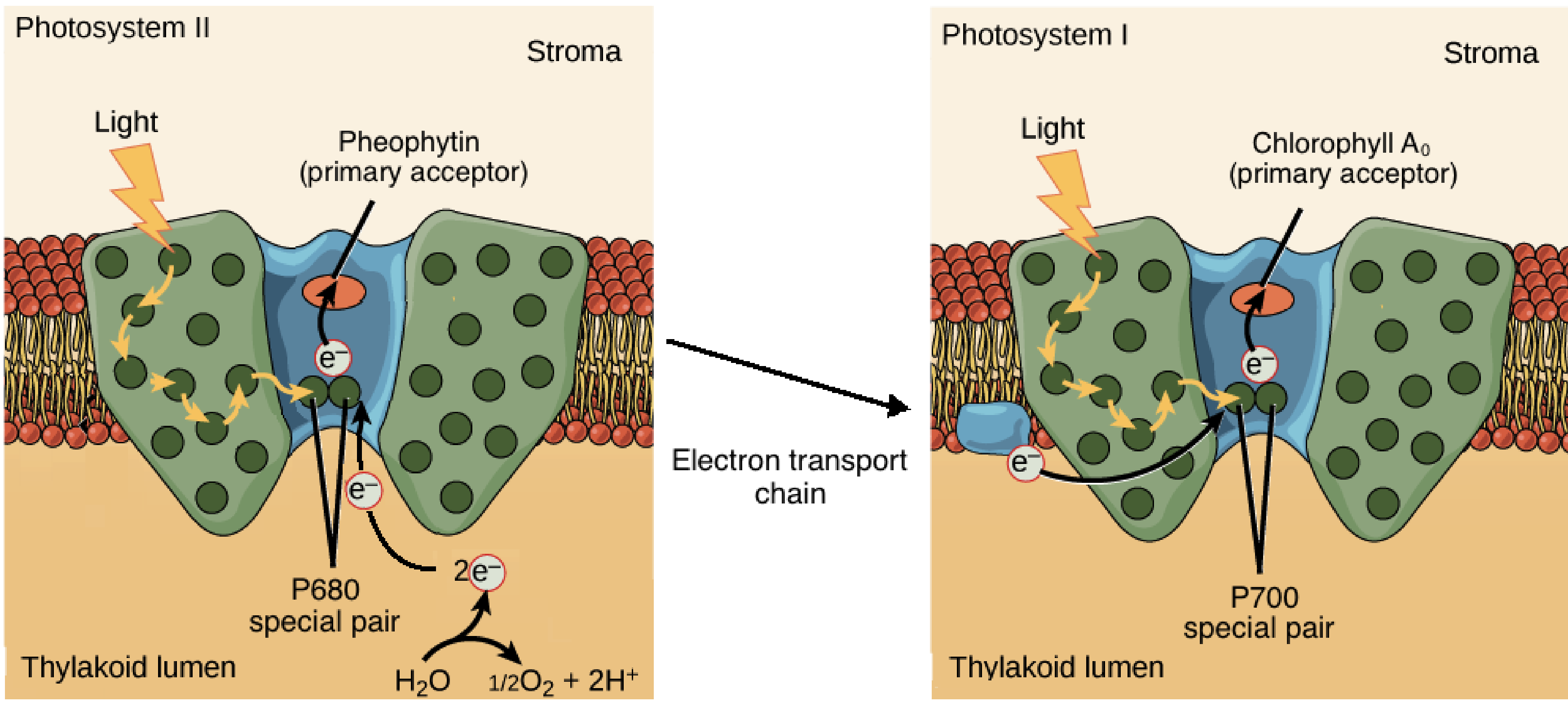
Photons are absorbed by clusters of pigment molecules (antenna molecules) in the thylakoid membrane.

When any antenna molecule absorbs a photon, it is transmitted from molecule to molecule until it reaches a particular chlorophyll *a* molecule = the **reaction center**.

At the reaction center is a **primary electron acceptor** which removes an excited electron from the reaction center chlorophyll a.

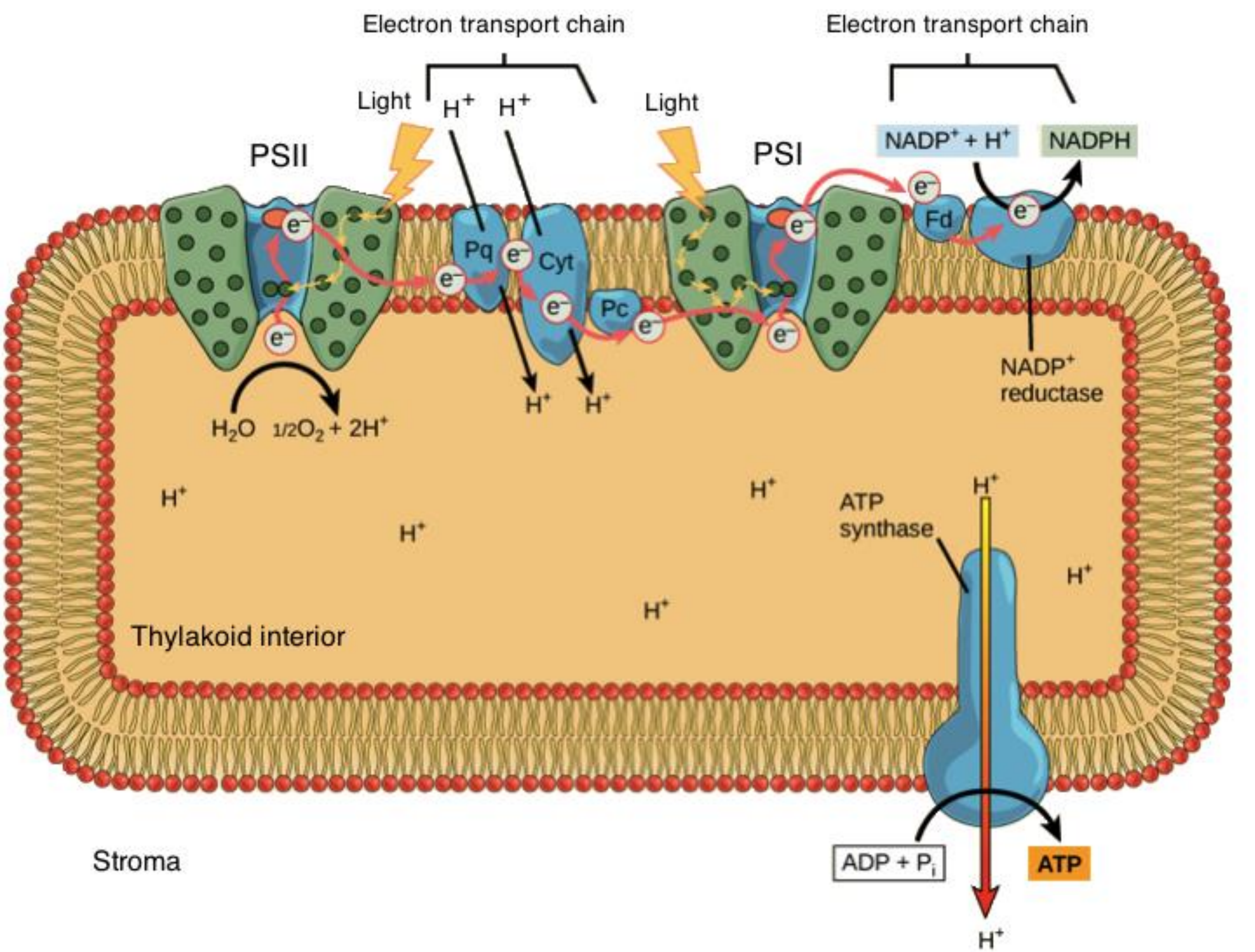
This starts the light reactions.

Photosystem II Vs. Photosystem I

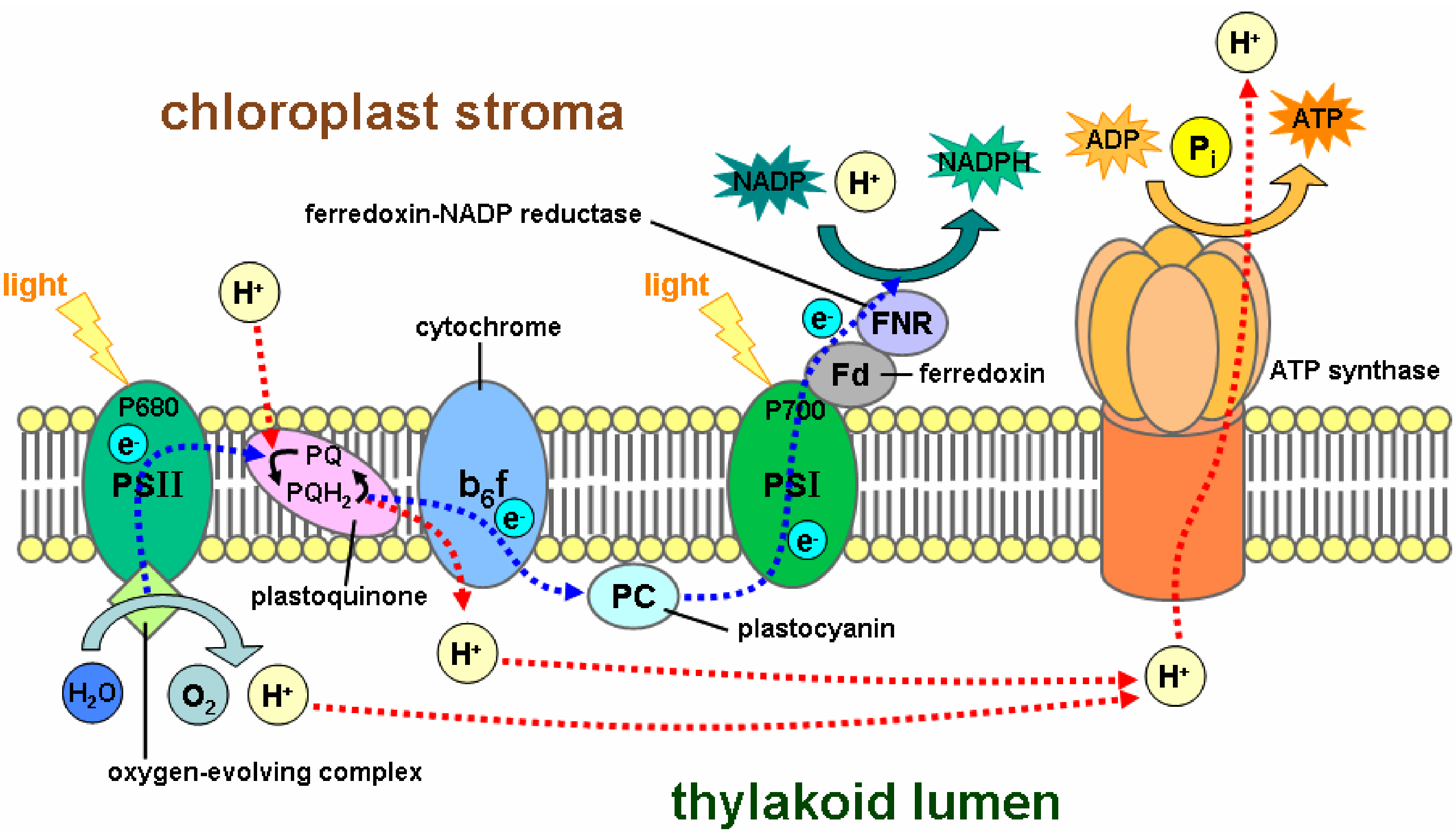


Electron transport chain

PSII and PSI



❖ Electron-chain cycle (ETC)

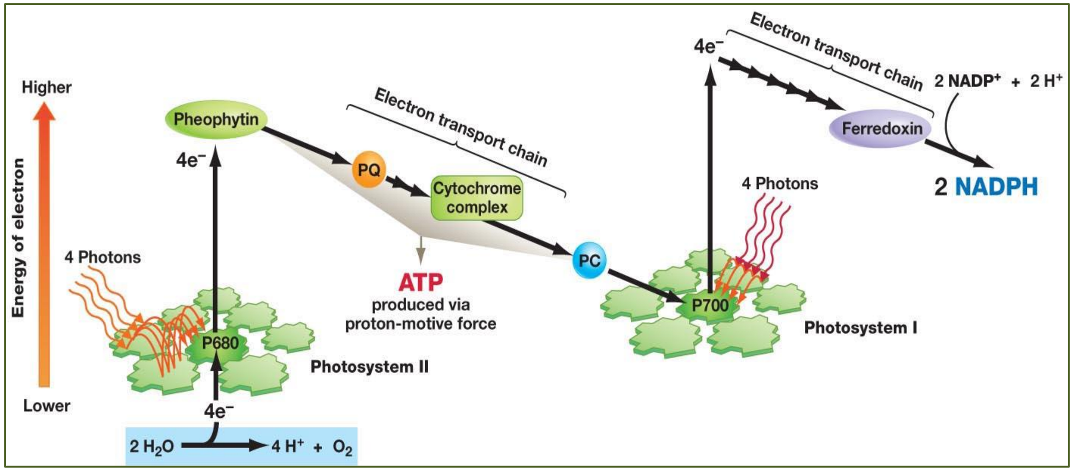


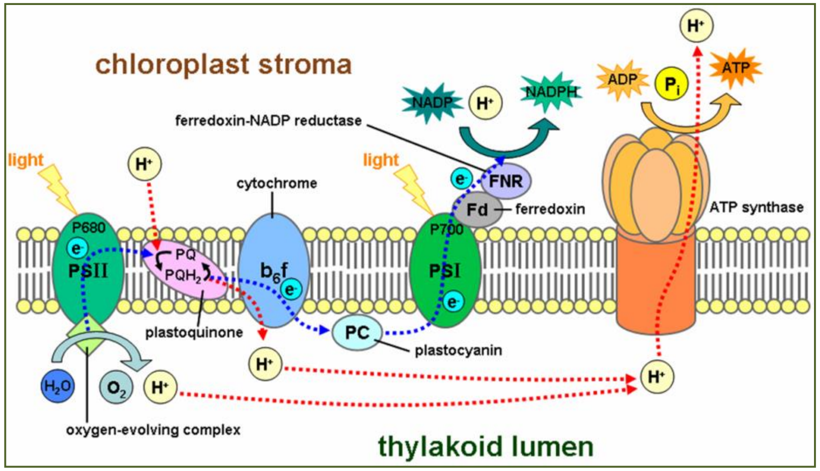
Two places where light comes in.

Remember photosynthesis is endergonic -- the electron transport chain is driven by light energy.

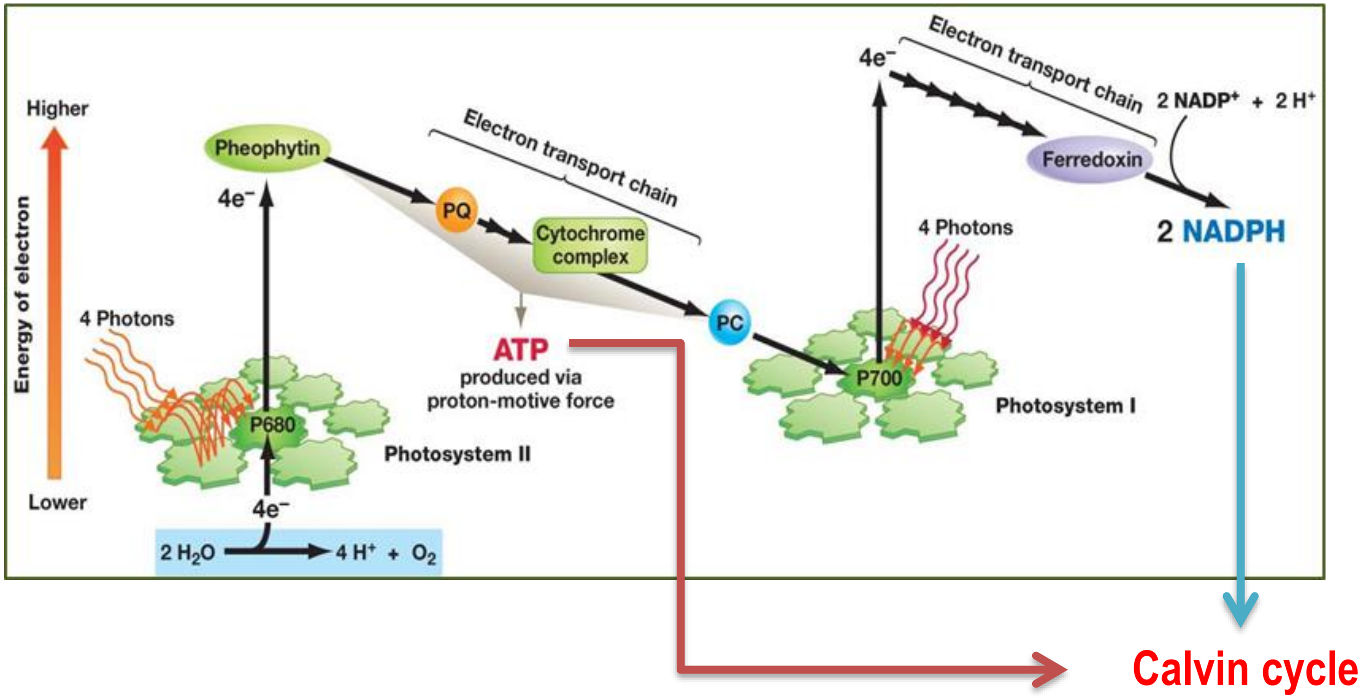
❖ Electron-chain cycle (ETC)

- **PS II absorbs light**
  - Excited electron passes from chlorophyll to the primary electron acceptor
  - Need to replace electron in chlorophyll
  - An enzyme extracts electrons from H_2O & supplies them to the chlorophyll
    - This reaction splits H_2O into 2 H^+ & O^- which combines with another O^- to form O_2
    - O_2 released to atmosphere
- **Chlorophyll absorbs light energy** (photon) and this moves an electron to a higher energy state
  - Electron is handed off down chain from electron acceptor to electron acceptor
  - In process has collected H^+ ions from H_2O & also pumped by Plastoquinone within thylakoid sac.
    - Flow back through ATP synthase to generate ATP.





❖ Electron-chain cycle (ETC)



- Need a 2nd photon -- shot of light energy to excite electron back up to high energy state.

    2nd ETC drives reduction of NADP to NADPH.

- Light comes in at 2 points.

    Produce ATP & NADPH

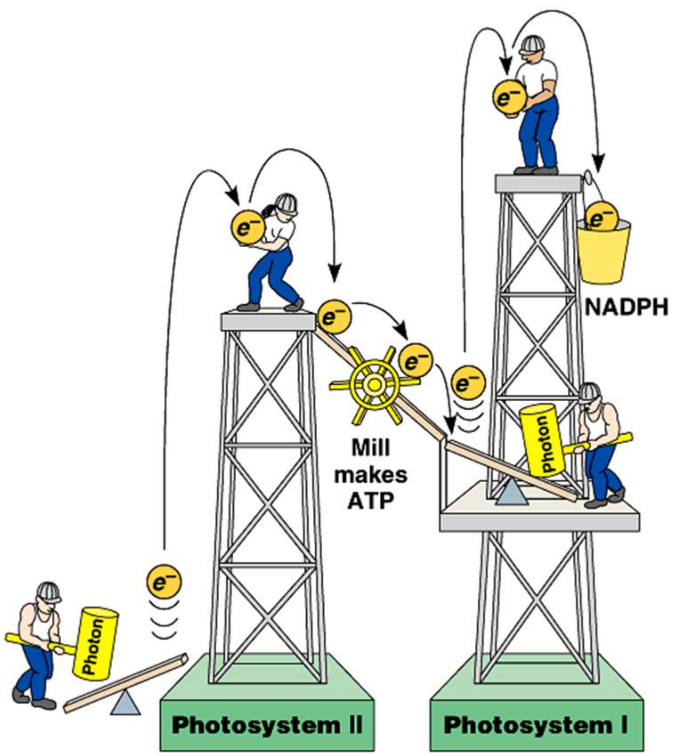
❖ETC of photosynthesis

- 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!

❖ Non-cyclic and cyclic photophosphorylation

1. Non-cyclic

- Light reactions elevate electrons
- 2 steps (PS II and PS I)



- PS II generates
  energy as ATP
- PS I generates
  reducing power as NADPH

1 photosystem is not enough.

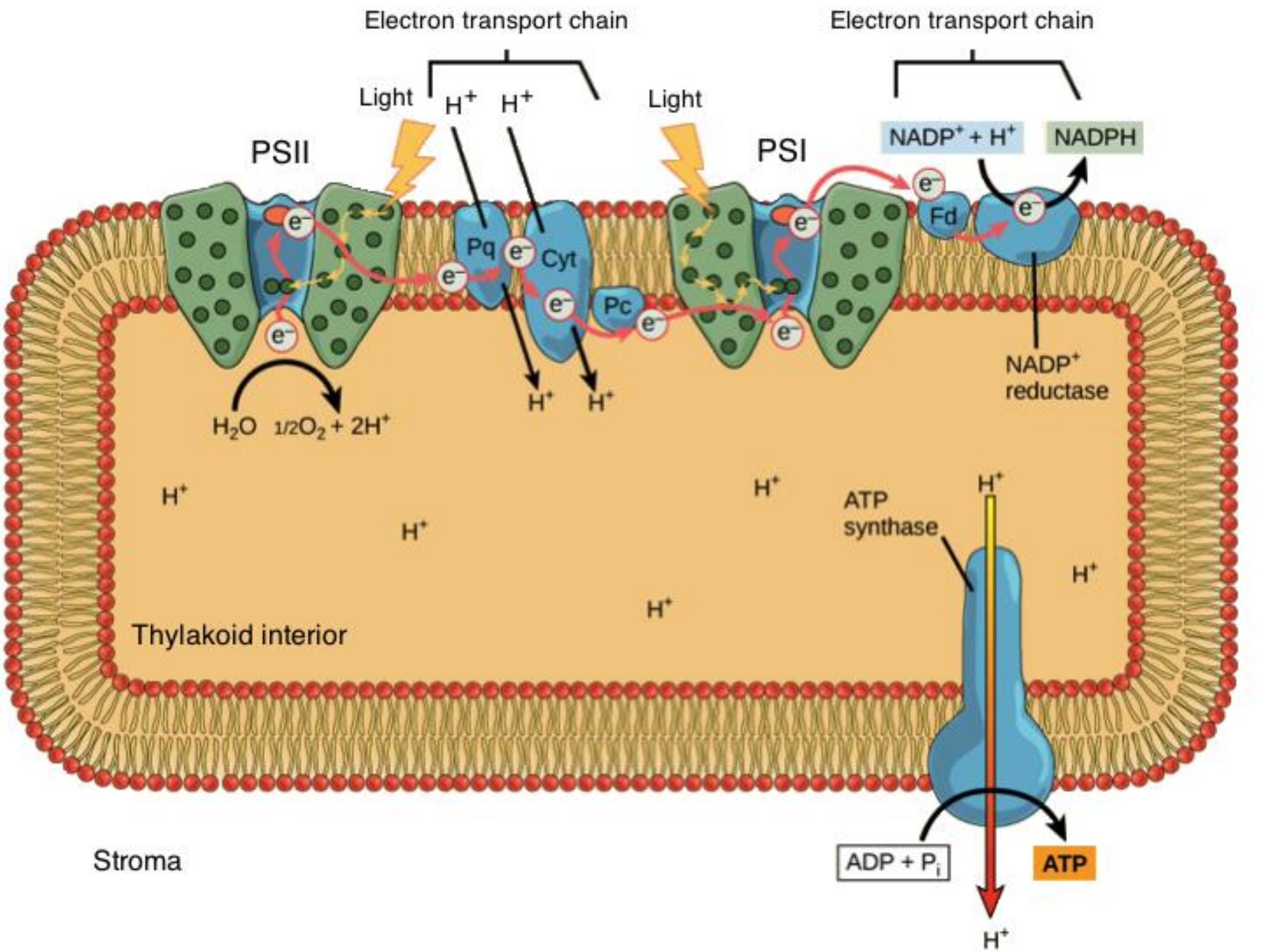
Have to lift electron in 2 stages to a higher energy level. Does work as it falls.

First, produce ATP -- but producing ATP is not enough.

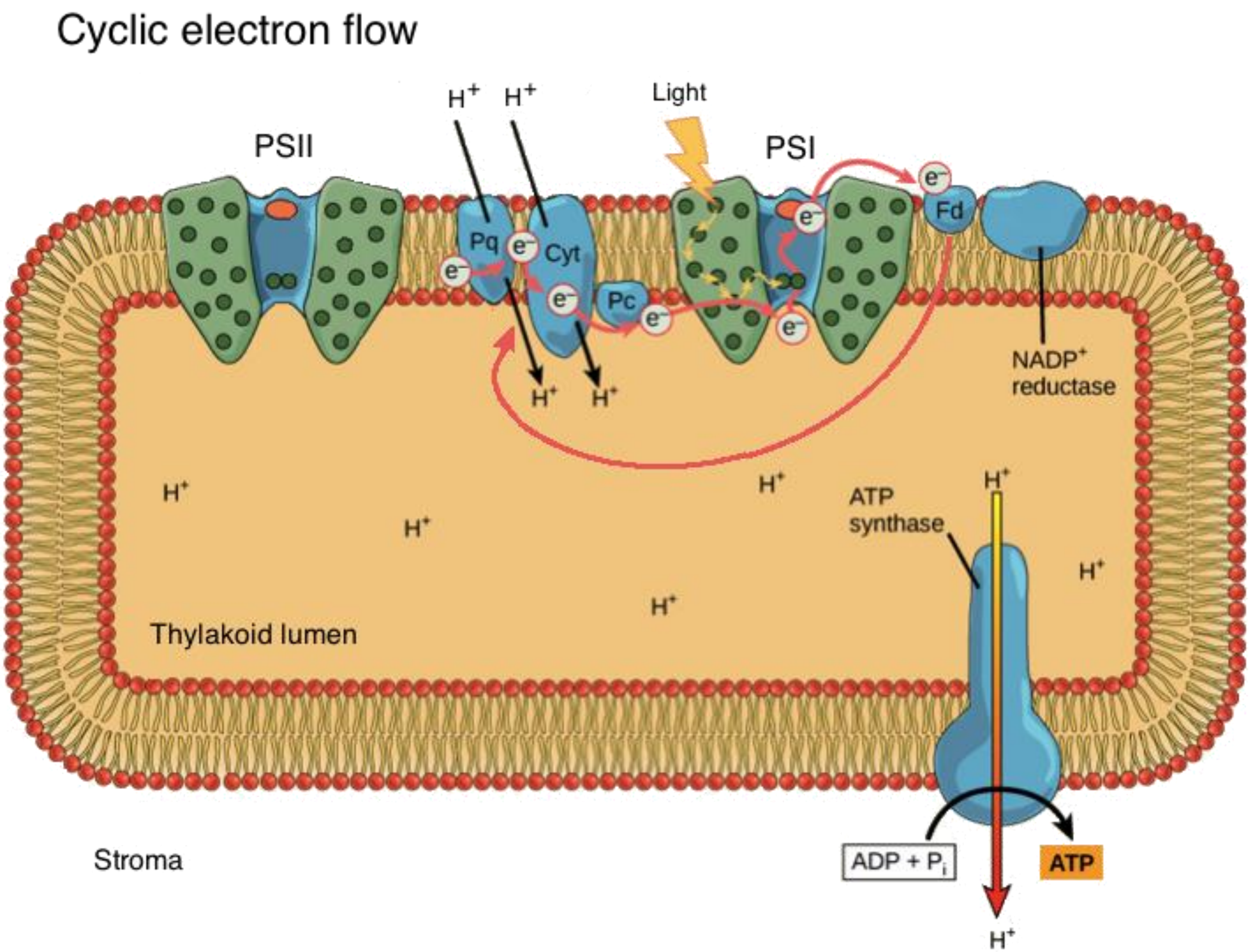
Second, need to produce organic molecules for other uses & also need to produce a stable storage molecule for a rainy day (sugars). This is done in Calvin Cycle!

Electron transport chain / non-cyclic

Non- cyclic electron flow



Electron transport chain / cyclic



❖ Non-cyclic and cyclic photophosphorylation

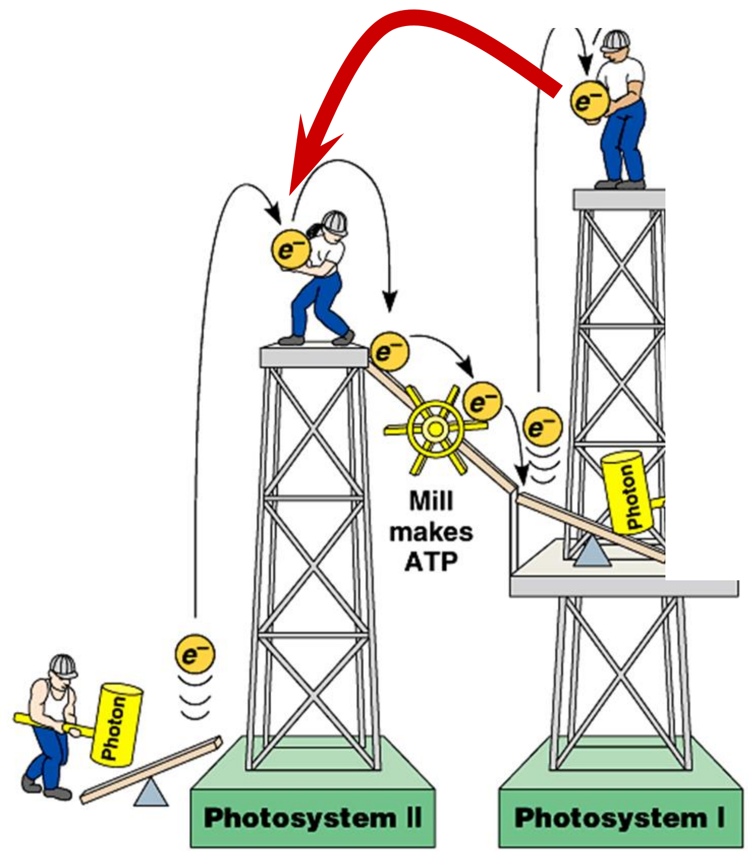
2. Cyclic

- If PS I can't pass electron to NADP…it cycles back to PS II & makes more ATP, but no NADPH

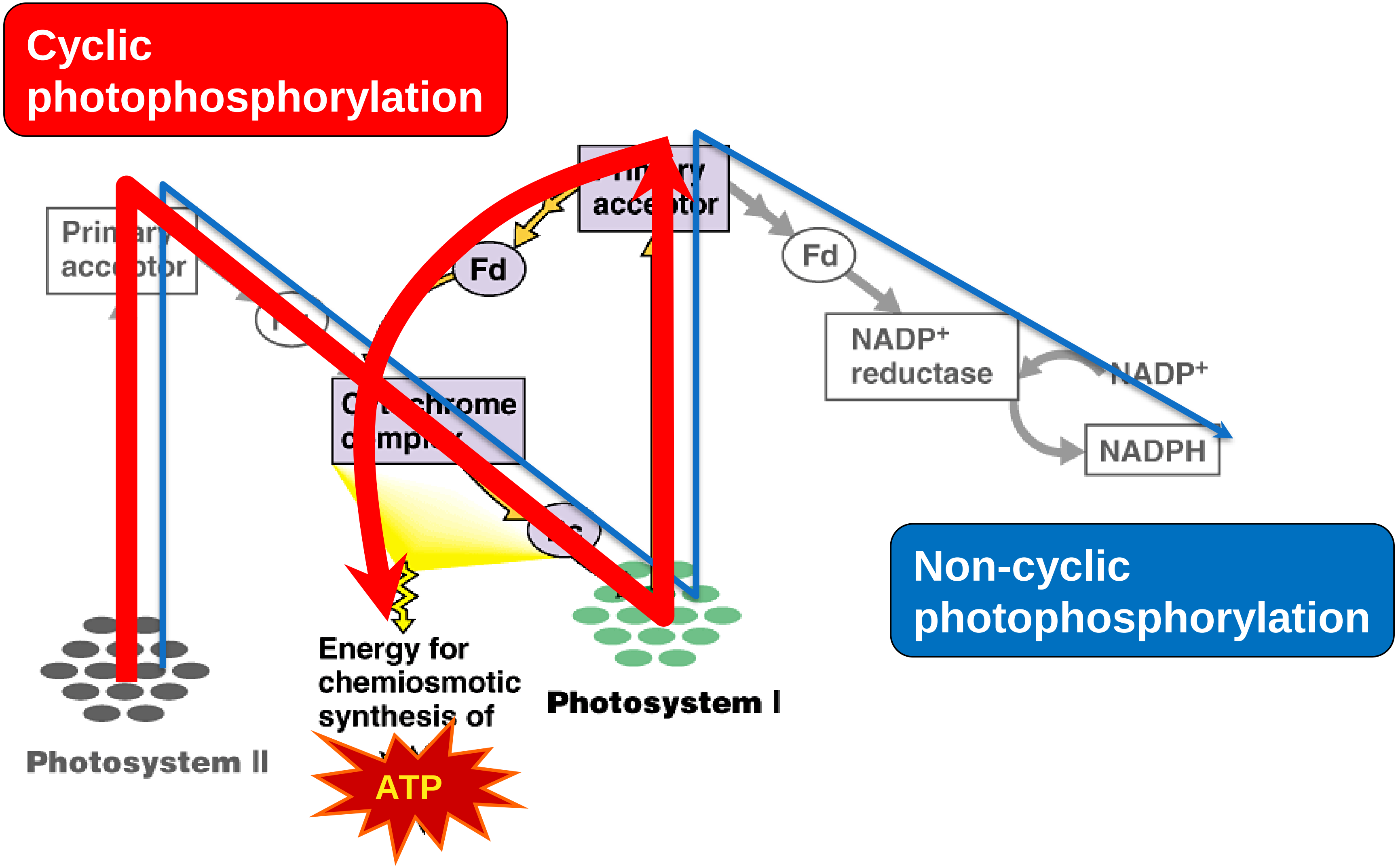
- coordinates light reactions to Calvin cycle
- Calvin cycle uses more ATP than NADPH

18 ATP + 12 NADPH

$\underline{1}\ C_6H_{12}O_6$



❖ Non-cyclic and cyclic photophosphorylation



Whoops! Wrong Calvin… 1950s 1961

❖ Light reactions

- Convert solar energy to chemical energy
  - ATP → **energy**

  - NADPH → **reducing power**

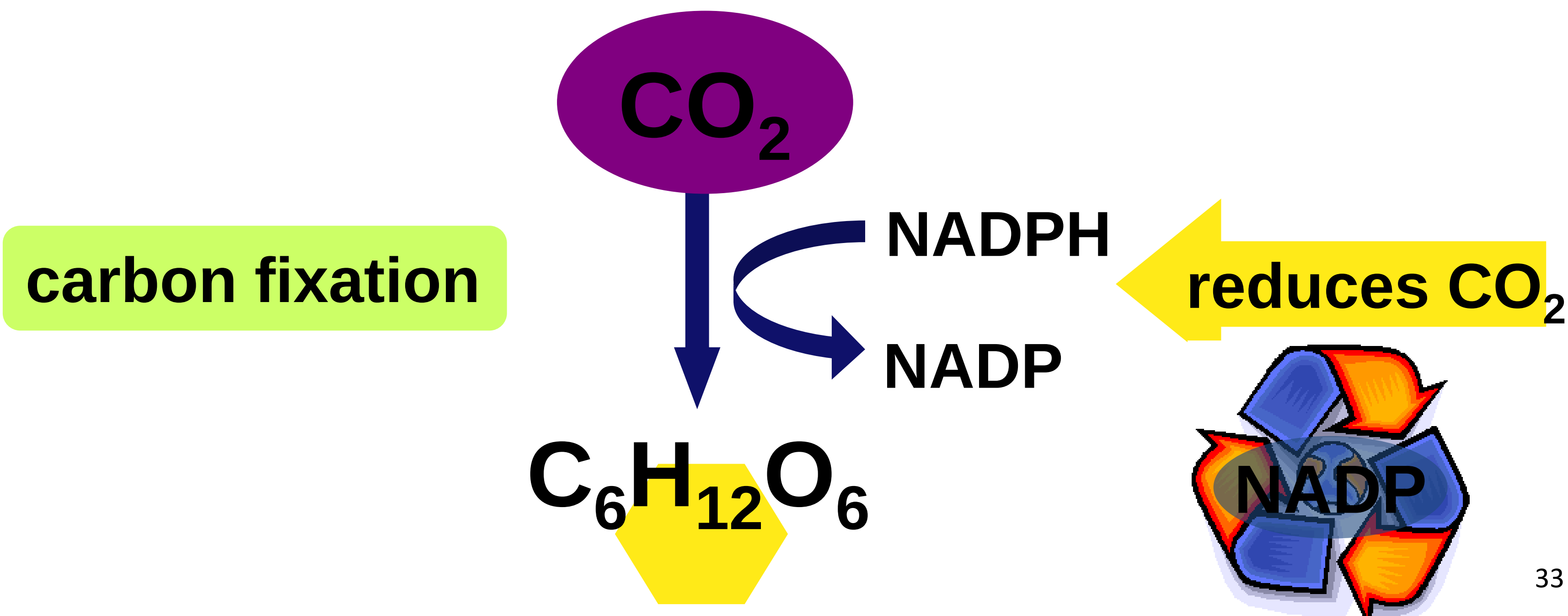
- What can we do now?

→ build stuff *!!*

→ *Photosynthesis*

How is that helpful?

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

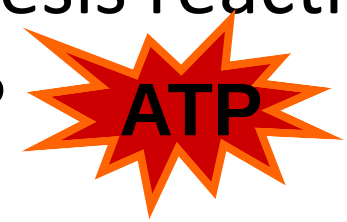


❖ From $CO_2 \rightarrow C_6H_{12}O_6$

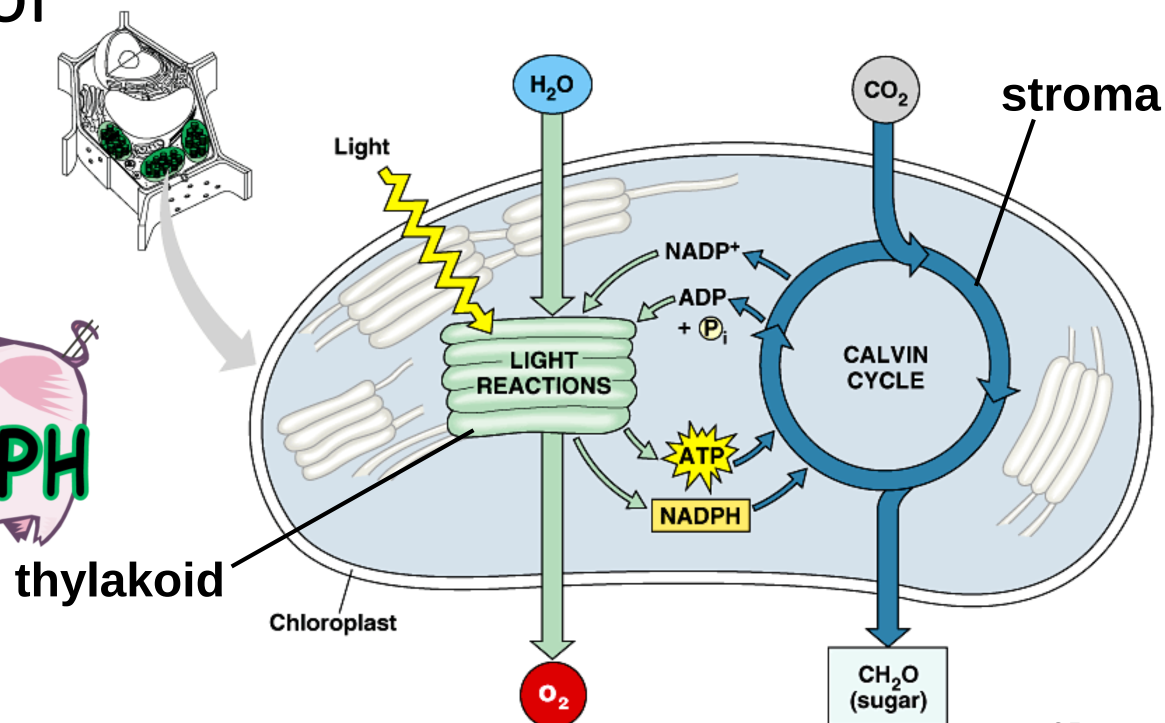
- CO_2 has very little chemical energy
  - fully oxidized
- $C_6H_{12}O_6$ contains a lot of chemical energy
  - highly reduced
- Synthesis = endergonic process
  - put in a lot of energy
- Reduction of $CO_2 \rightarrow C_6H_{12}O_6$ proceeds in many small uphill steps
  - each catalyzed by a specific enzyme
  - using energy stored in ATP & NADPH

❖ From Light reactions to Calvin cycle

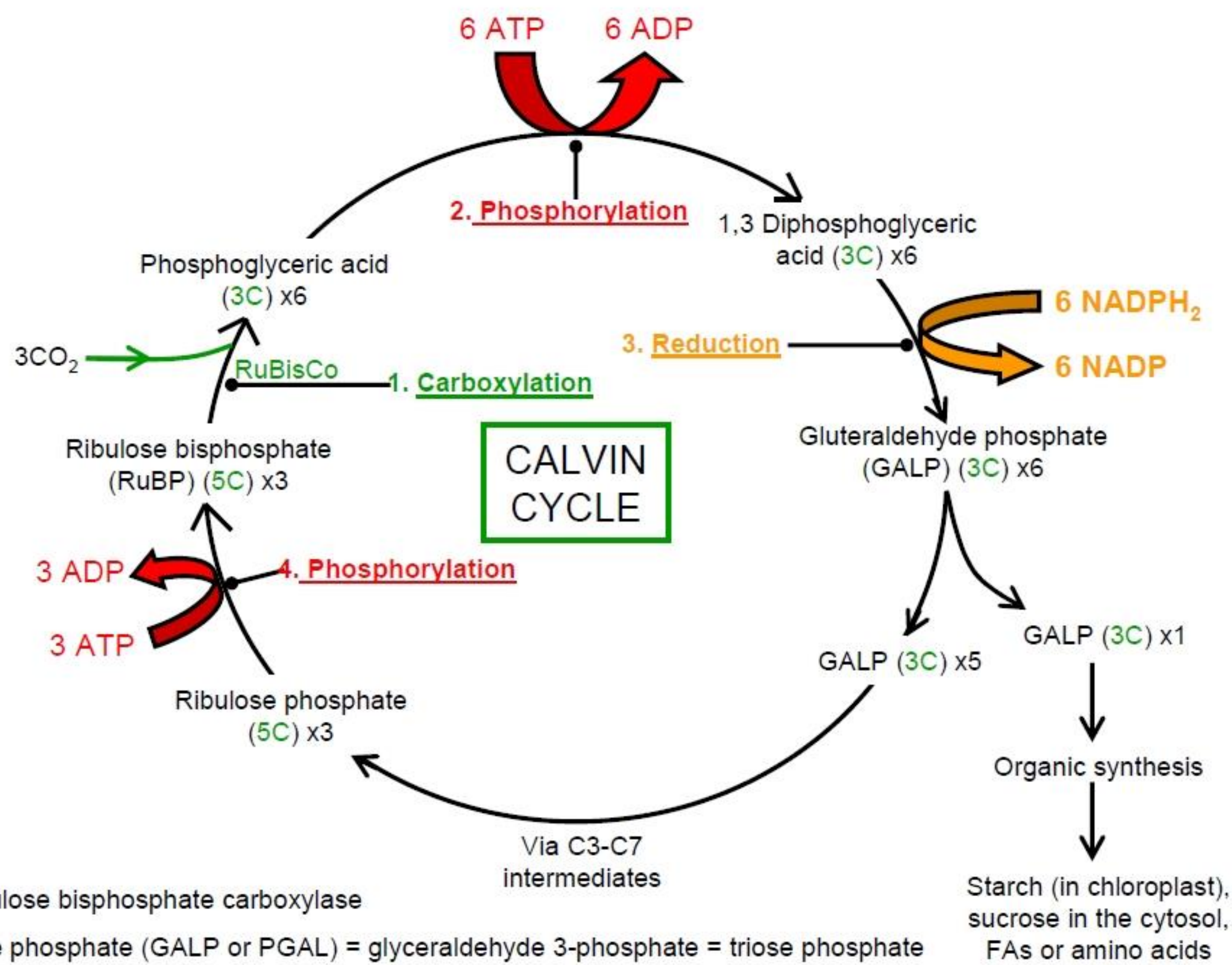
- Calvin cycle
  - chloroplast <u>stroma</u>
- Need products of light reactions to drive synthesis reactions
  - ATP



  - NADPH



Light-Independent Reactions



RuBisCo = ribulose bisphosphate carboxylase

Gluteraldehyde phosphate (GALP or PGAL) = glyceraldehyde 3-phosphate = triose phosphate

Glycerate 3-phosphate (GP) = phosphoglyceric acid

RuBP is the CO_2 acceptor molecule and is a 5C pentose sugar

❖ To G3P and Beyond!

- Glyceraldehyde-3-P
  - end product of Calvin cycle
  - energy rich <u>3 carbon sugar</u>
  - "<u>C_3 photosynthesis</u>"
- G3P is an important intermediate
- G3P $\rightarrow\rightarrow$ glucose $\rightarrow\rightarrow$ carbohydrates

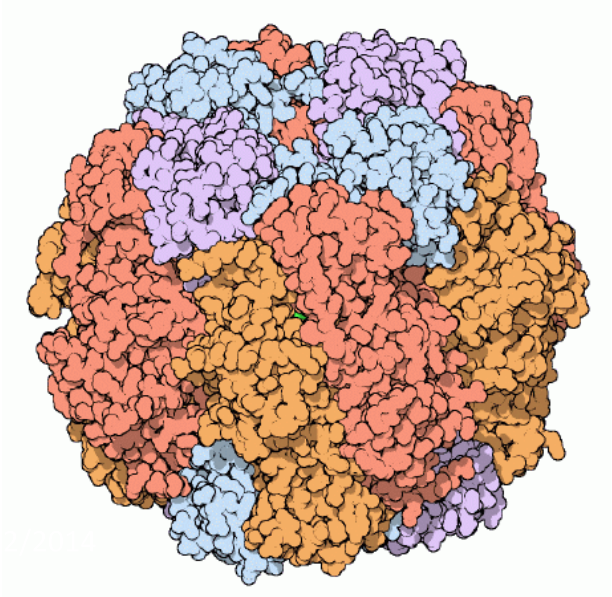
  $\rightarrow\rightarrow$ lipids $\rightarrow\rightarrow$ phospholipids, fats, waxes

  $\rightarrow\rightarrow$ amino acids $\rightarrow\rightarrow$ proteins

  $\rightarrow\rightarrow$ nucleic acids $\rightarrow\rightarrow$ DNA, RNA

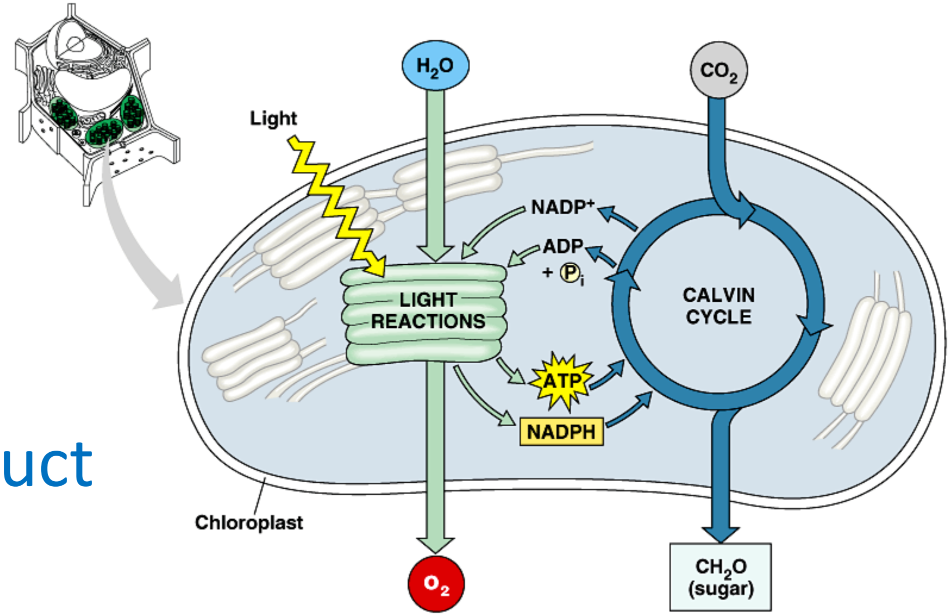
❖ RuBisCo

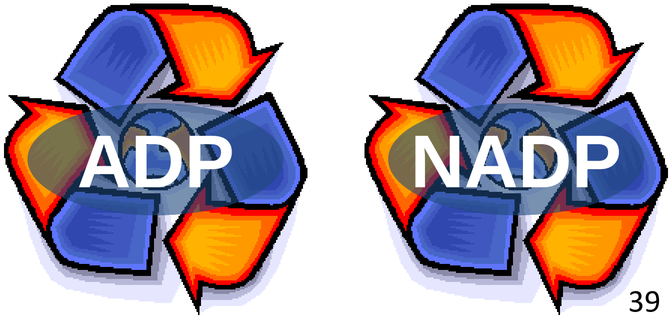
- Enzyme which fixes carbon from air
  - ribulose bisphosphate carboxylase
  - the most important enzyme in the world!
    - it makes life out of air!
  - definitely the most abundant enzyme



❖ Photosynthesis summary

- Light reactions
  - produces ATP
  - produces NADPH
  - consumes H_2O
  - produced O_2 as byproduct
- Calvin cycle
  - consumes CO_2
  - produces G3P (sugar)
  - regenerates ADP
  - regenerates NADP

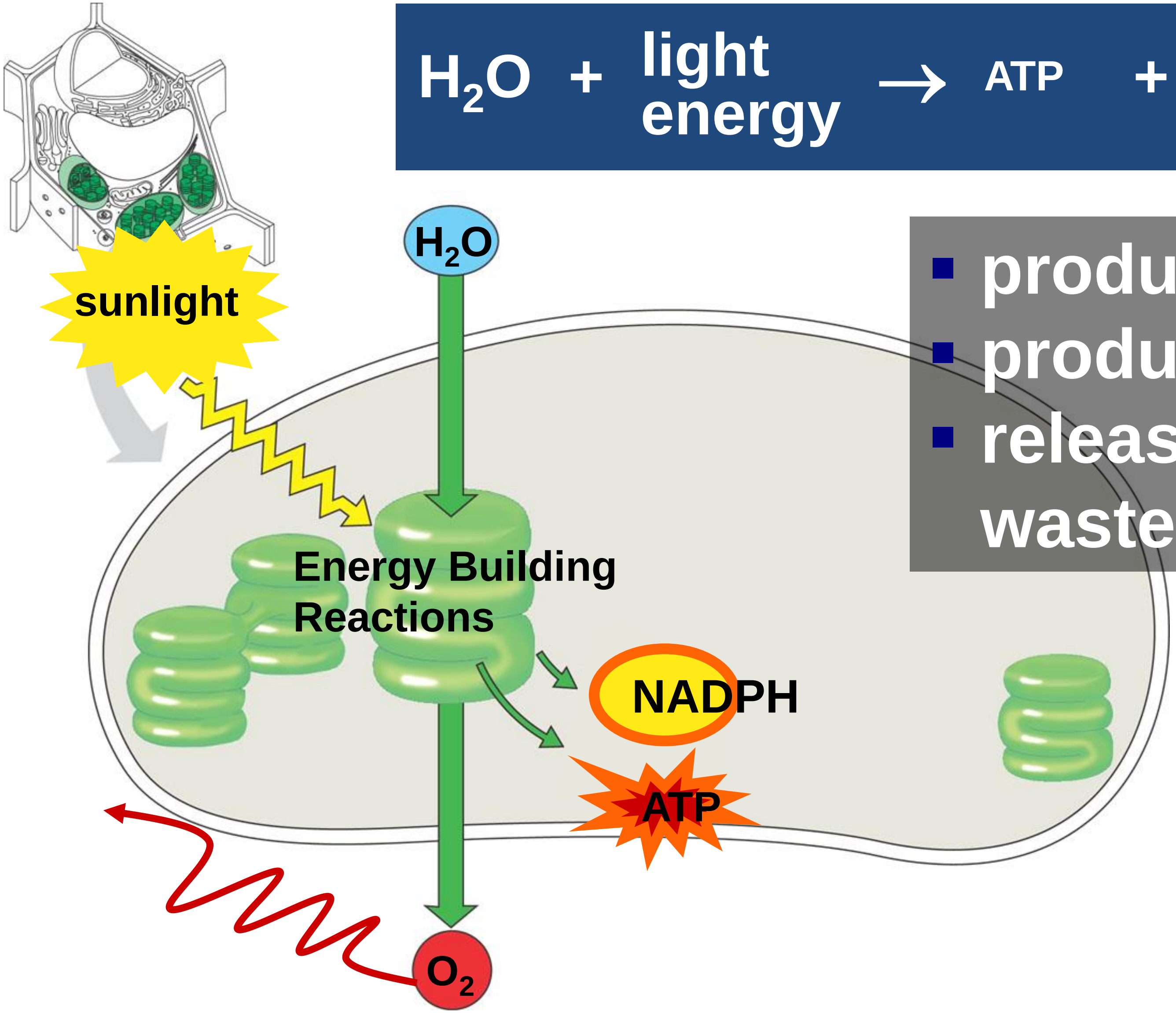




❖ Light Reactions

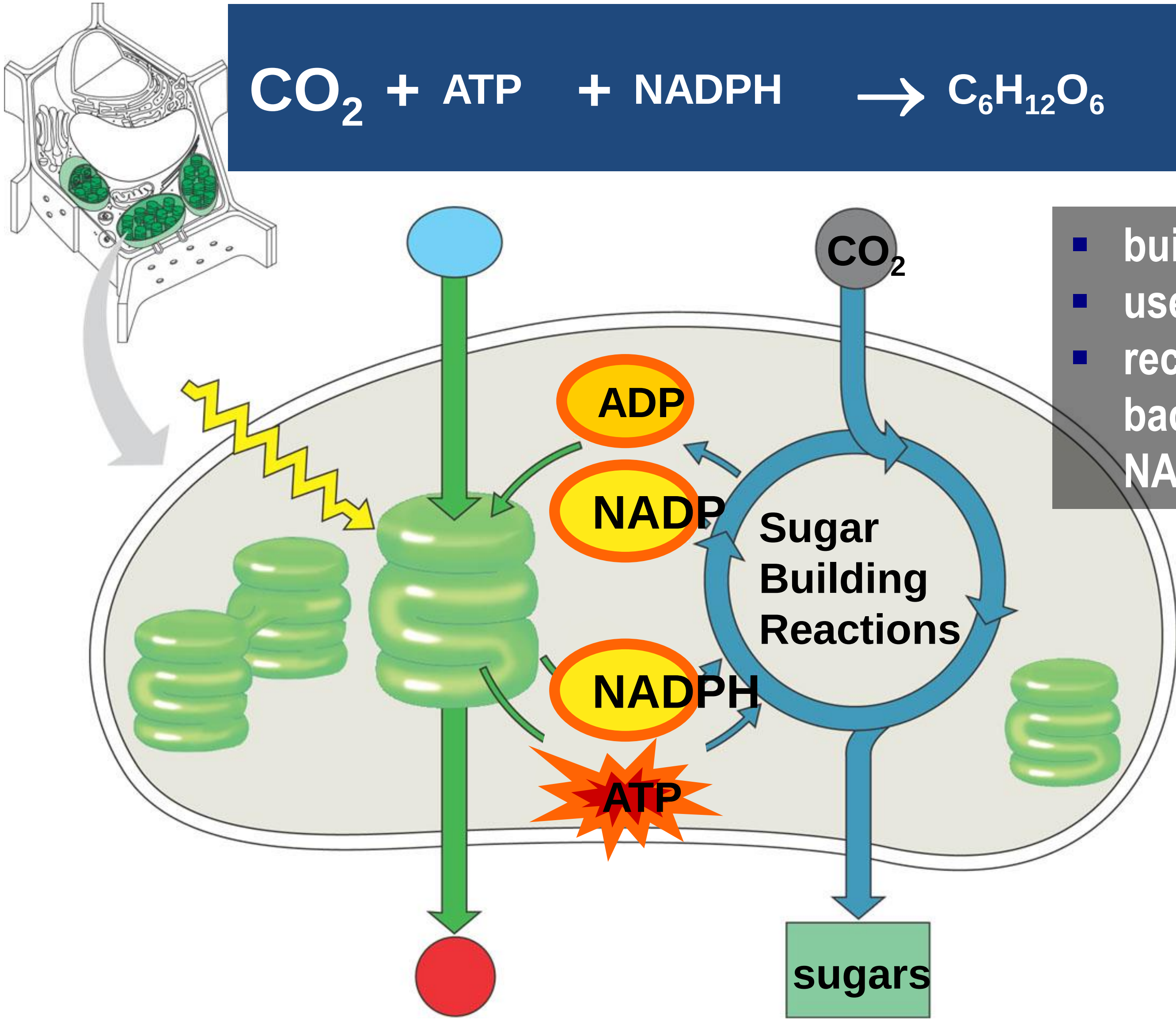
H_2O + light energy → ATP + NADPH + O_2

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



❖ Calvin Cycle

$$CO_2 + ATP + NADPH \rightarrow C_6H_{12}O_6 + ADP + NADP$$

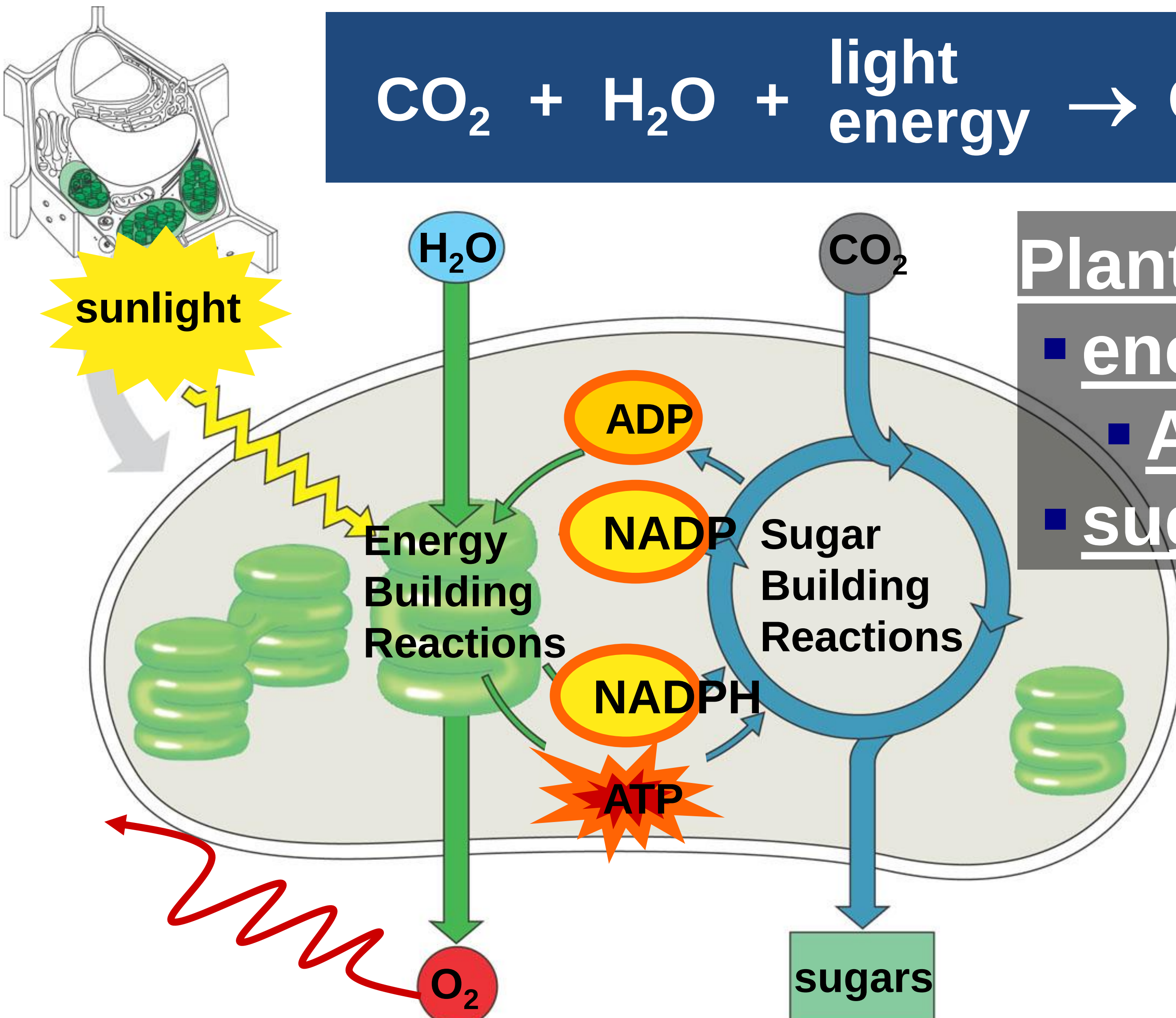


- builds sugars
- uses ATP & NADPH
- recycles ADP & NADP back to make more ATP & NADPH

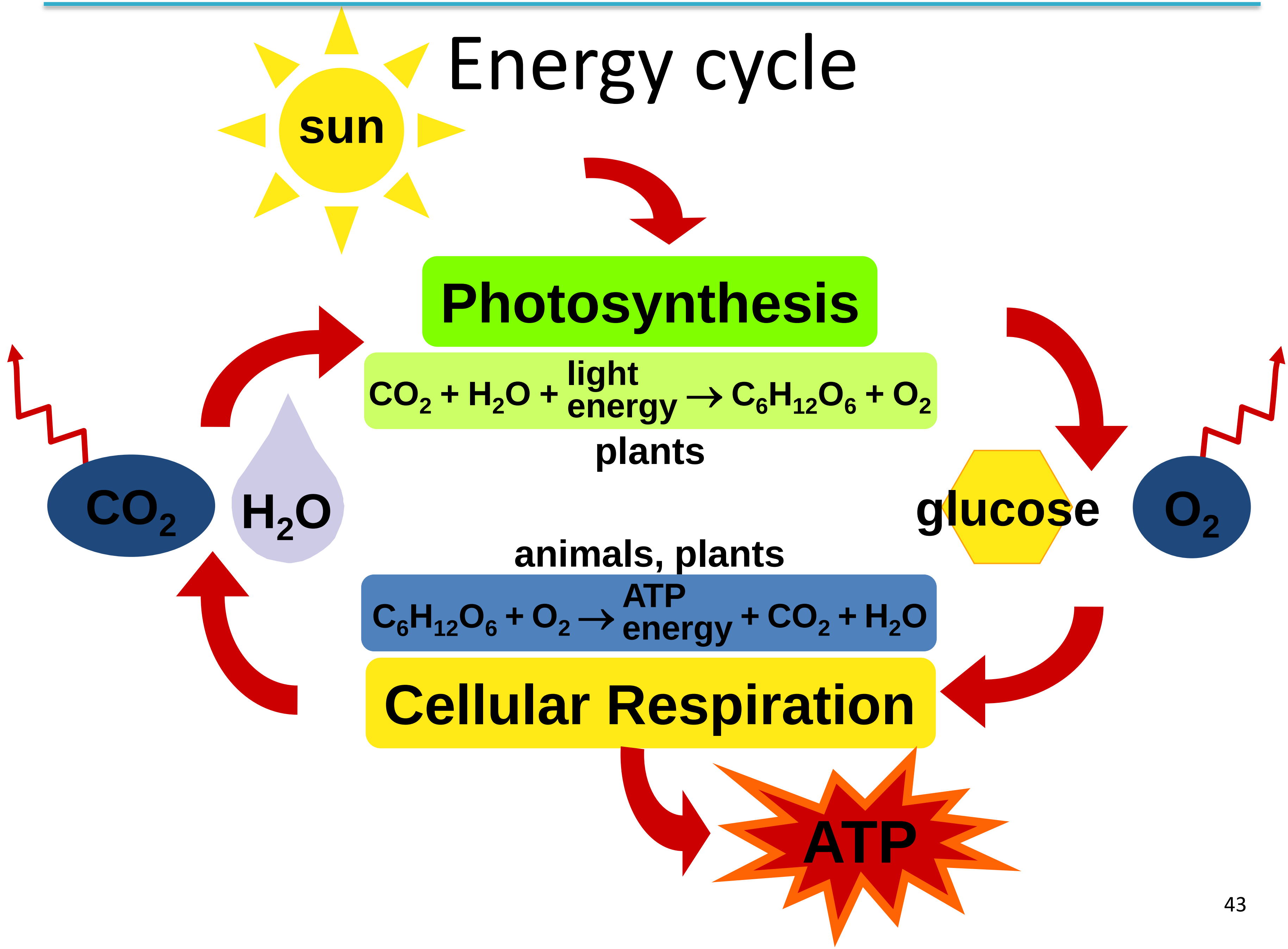
❖ Putting it all together

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

Plants make both:
- energy
  - ATP & NADPH
- sugars



Energy cycle

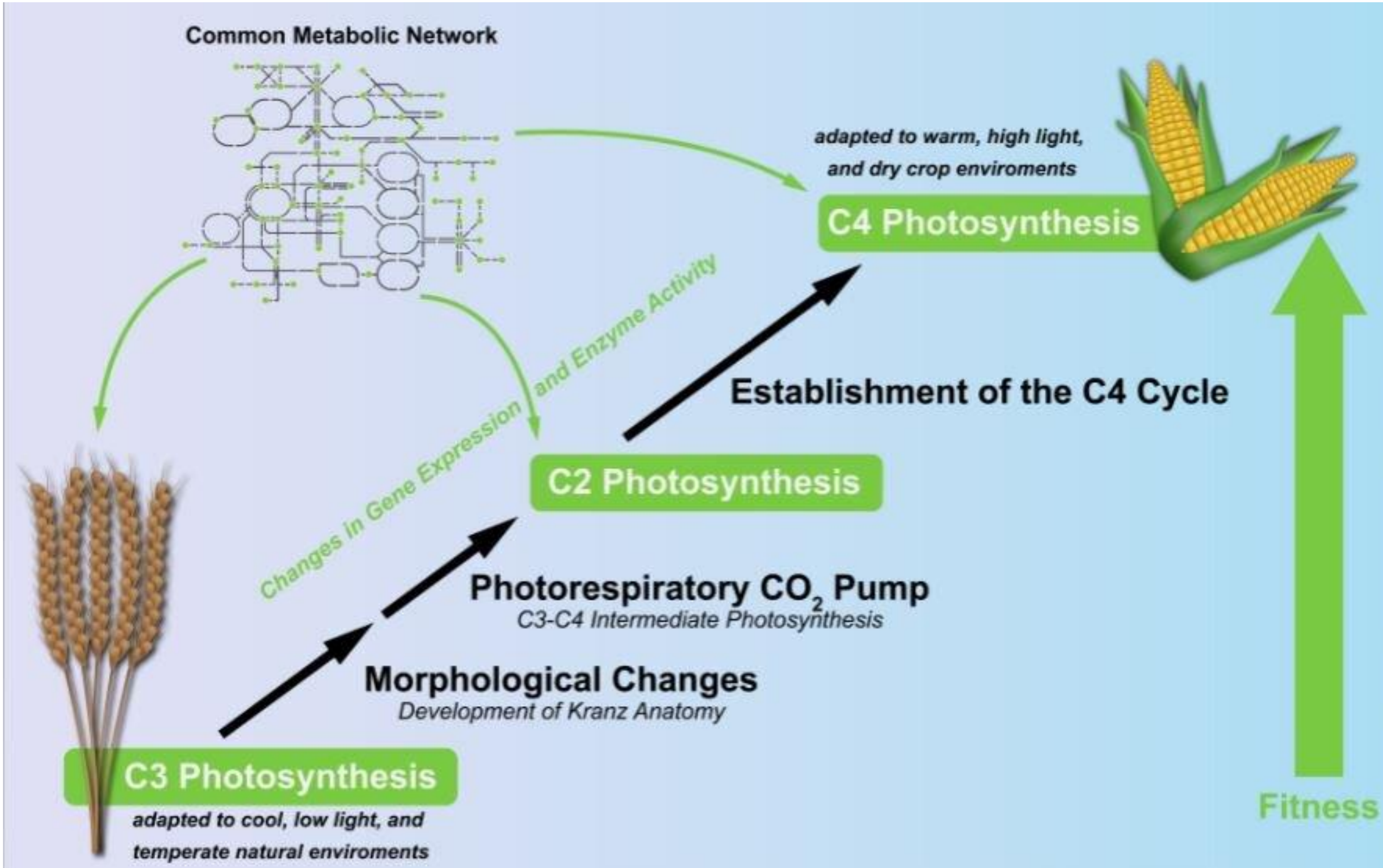


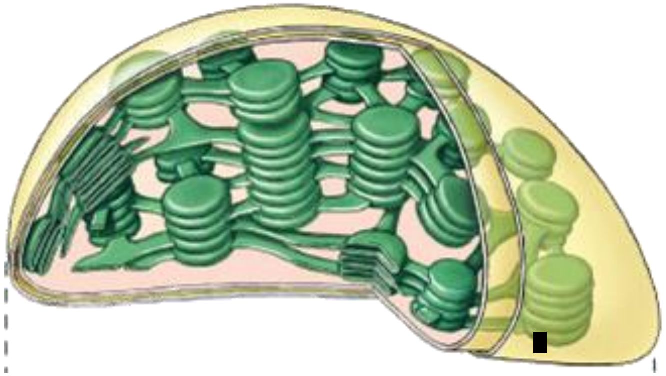
❖ Supporting a biosphere

- 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

If plants can do it…
You can learn it*!*

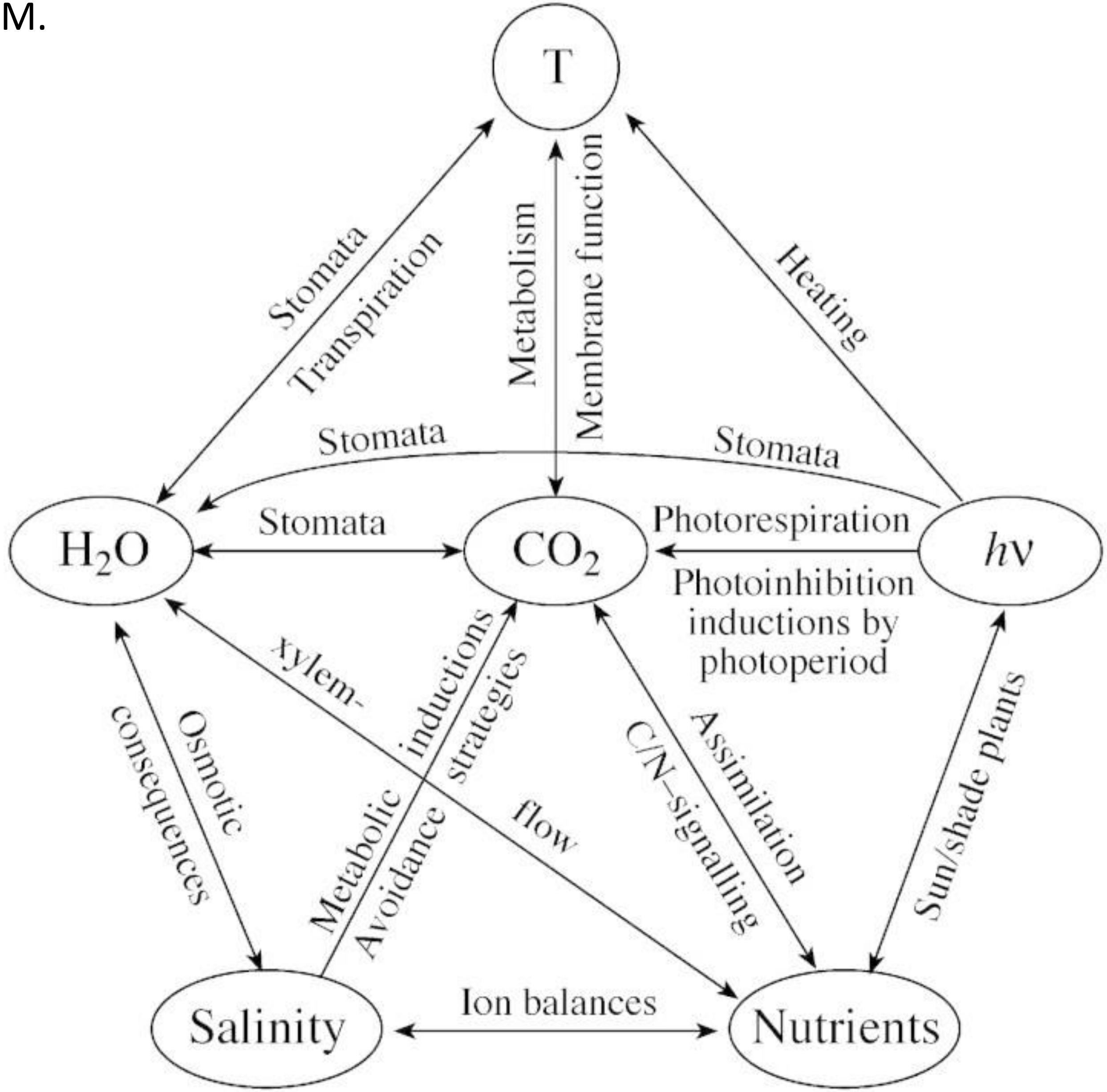
Ask Questions*!!*


Common Metabolic Network
adapted to warm, high light, and dry crop enviroments
C4 Photosynthesis
Changes in Gene Expression and Enzyme Activity
Establishment of the C4 Cycle
C2 Photosynthesis
Photorespiratory CO_2 Pump
C3-C4 Intermediate Photosynthesis
Morphological Changes
Development of Kranz Anatomy
C3 Photosynthesis
adapted to cool, low light, and temperate natural enviroments
Fitness



Photosynthesis:
Variations on the Theme

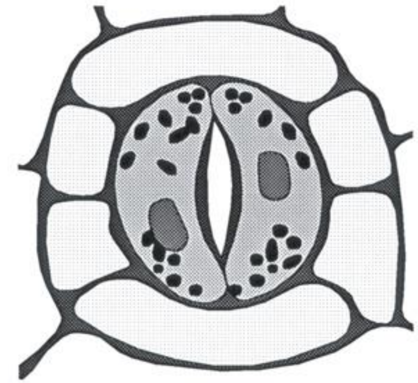
Network of the most important environmental parameters and connections of their effects in CAM.

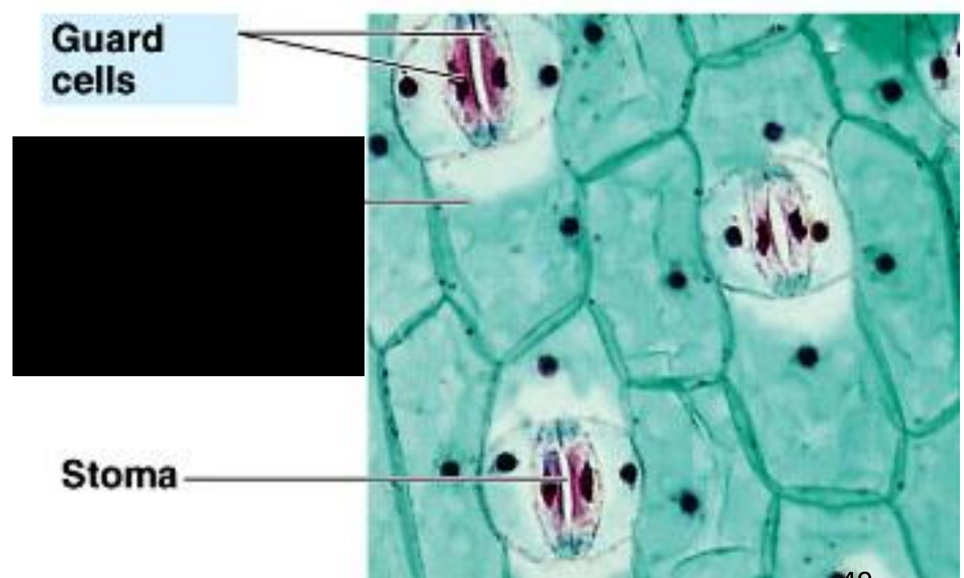


❖ Controlling water loss from leaves

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

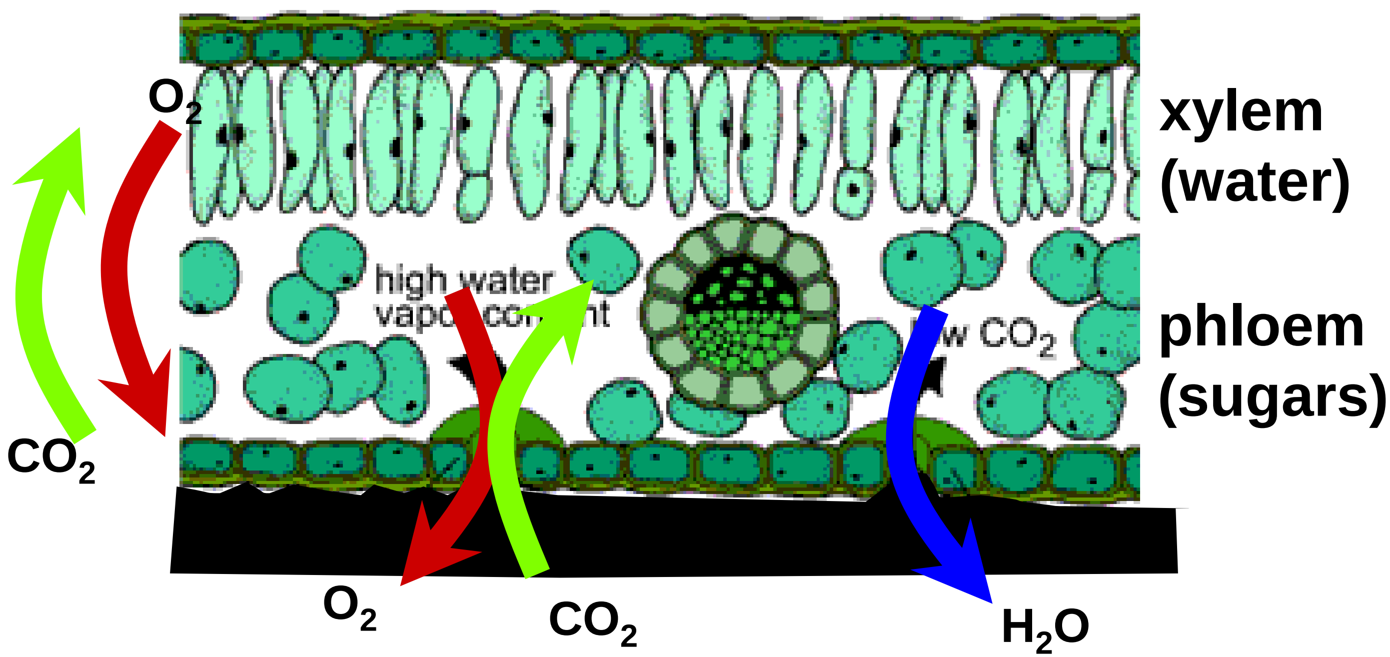
  creates PROBLEMS!





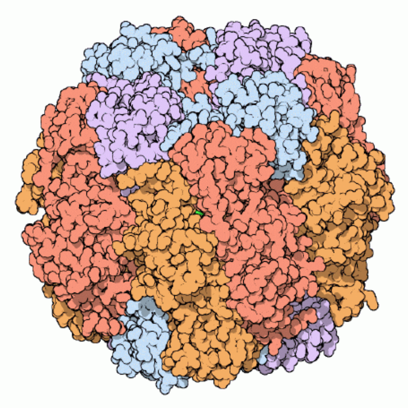
❖ When stomates close…

- **Closed stomata 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

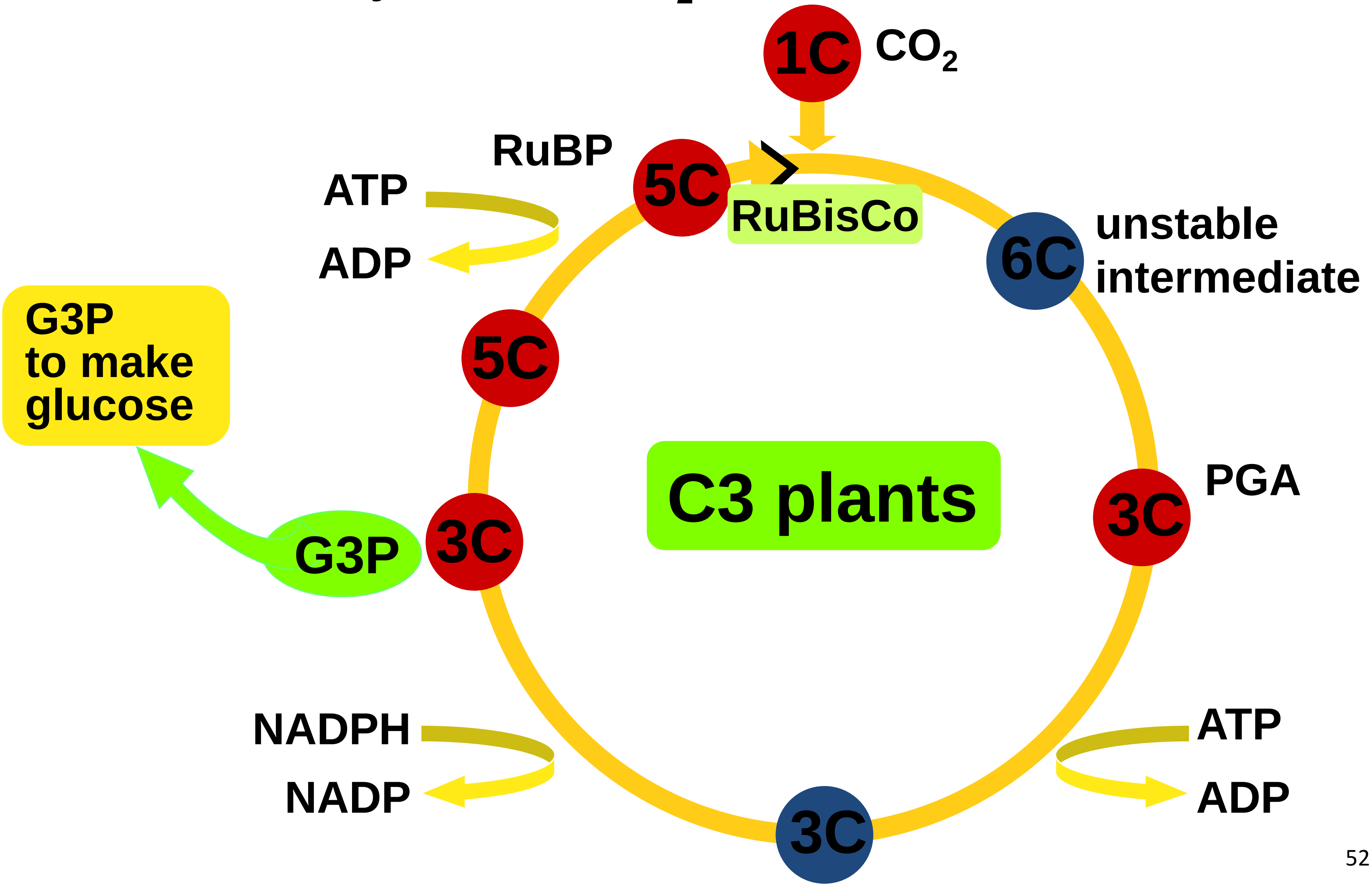
- **RuBisCo in Calvin cycle**
  - <u>carbon fixation enzyme</u>
    - normally bonds <u>C</u> to RuBP
    - CO_2 is the optimal substrate
    - <u>reduction</u> of RuBP
    - <u>building</u> sugars
  - <u>when O_2 concentration is high</u>
    - RuBisCo bonds <u>O</u> to RuBP
    - O_2 is a competitive substrate
    - <u>oxidation</u> of RuBP
    - <u>breakdown</u> sugars



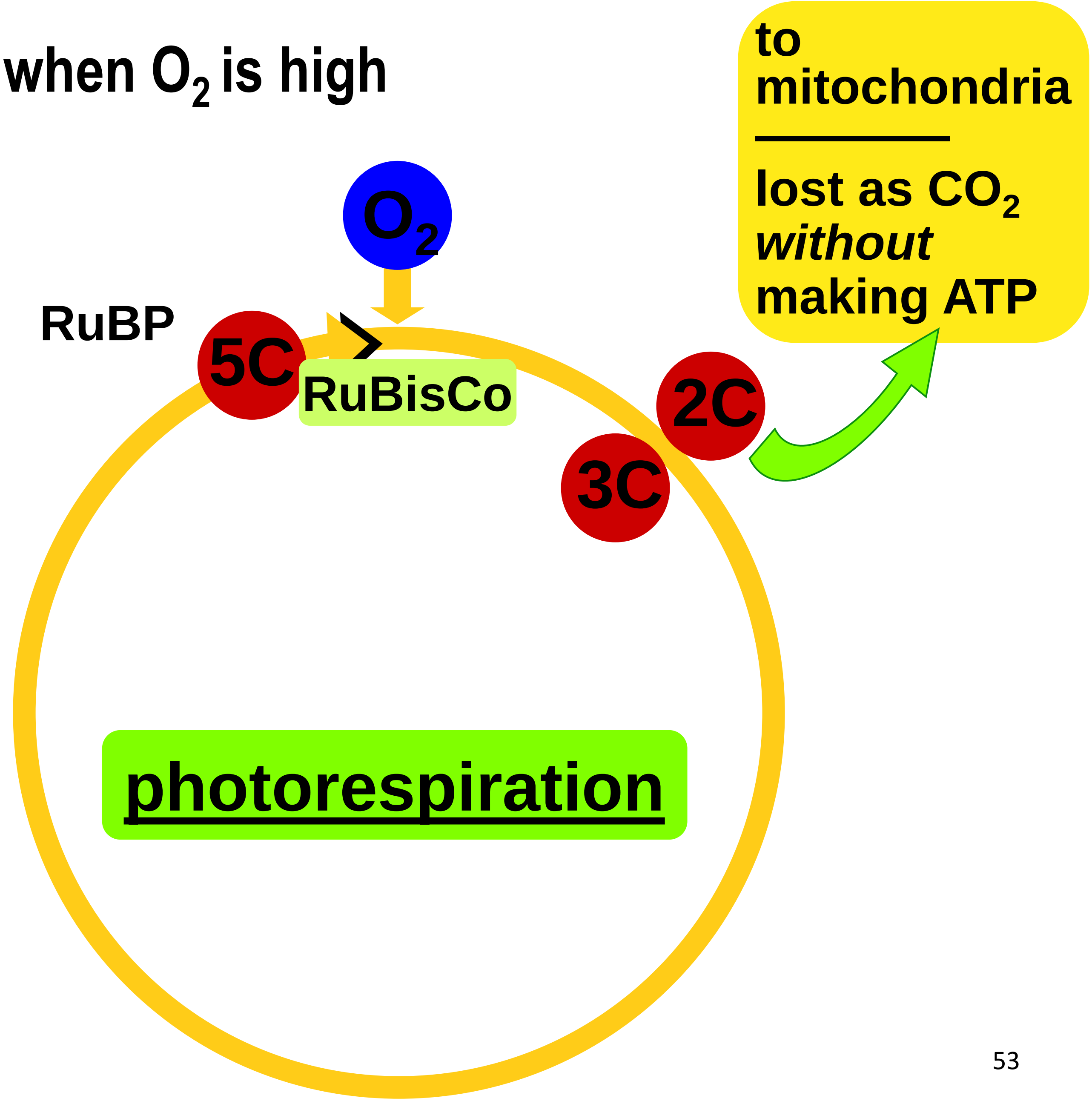
photo<u>synthesis</u>

photo<u>respiration</u>

❖ 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
  - <u>C_4 plants</u>

1. <u>PHYSICALLY separate carbon fixation from Calvin cycle</u>
   - different cells to fix carbon vs. where Calvin cycle occurs
   - store carbon in 4C compounds
2. Different enzyme to capture CO_2 (fix carbon)
   - <u>PEP carboxylase</u>
3. Different leaf structure

- <u>CAM plants</u>

1. <u>Separate carbon fixation from Calvin cycle by TIME OF DAY</u>
2. Fix carbon during night
   - store carbon in 4C compounds
3. Perform Calvin cycle during day

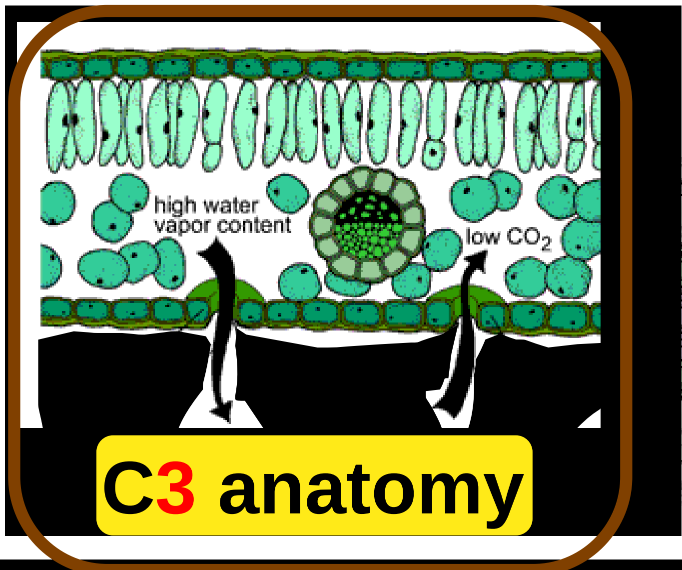
❖ C_4 plants

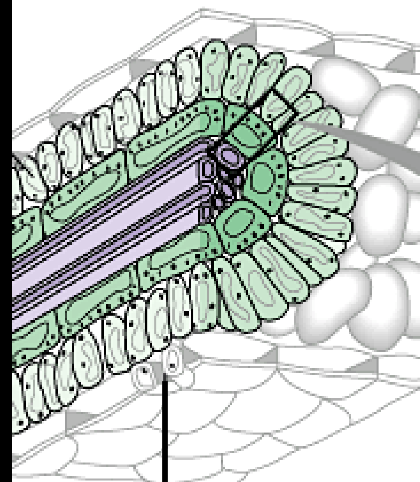
- A better way to capture CO_2
  - 1st step before Calvin cycle, fix carbon with enzyme <u>PEP carboxylase</u>
    - store as 4C compound
  - <u>adaptation to hot, dry climates</u>
    - have to close stomates a lot
    - different leaf anatomy
  - sugar cane, corn, other grasses…

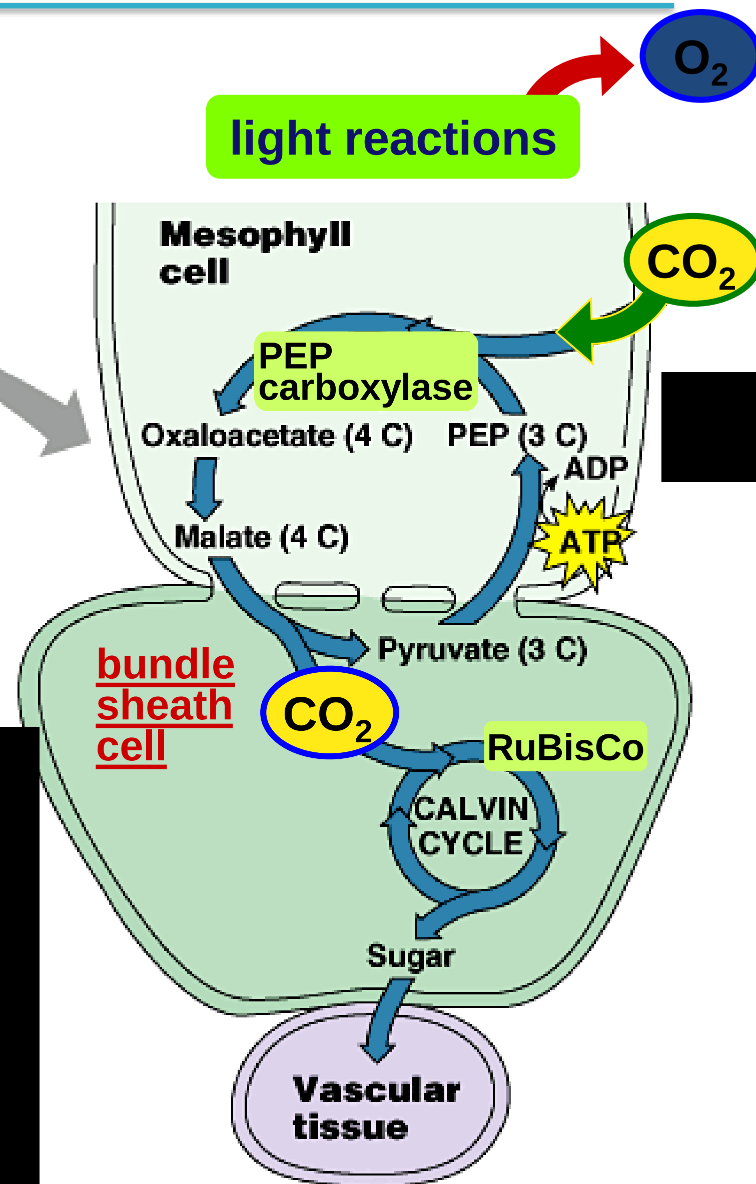
corn

sugar cane

PEP (3C) + $CO_2 \rightarrow$ oxaloacetate (4C)





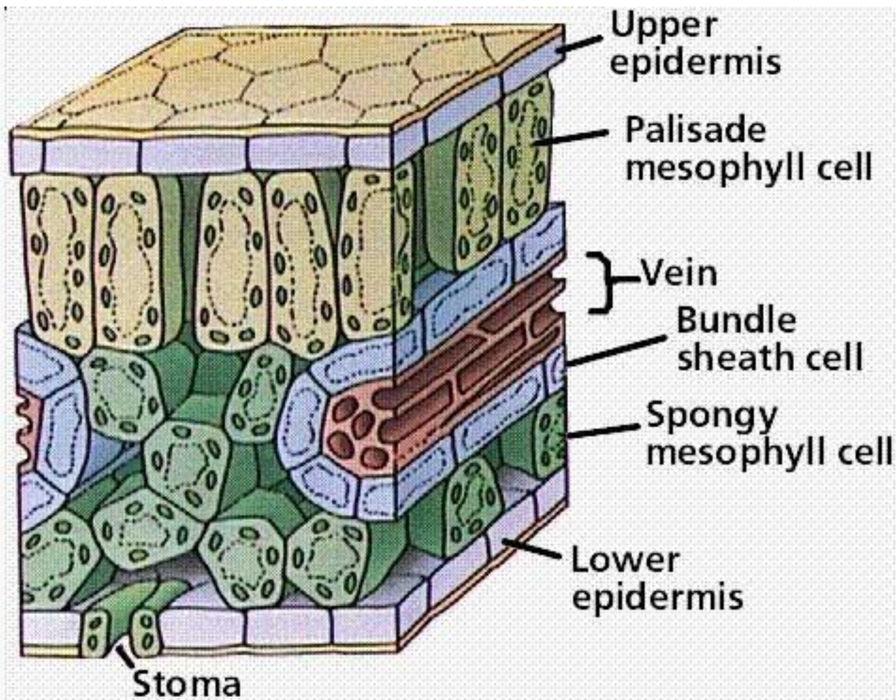


C4 anatomy

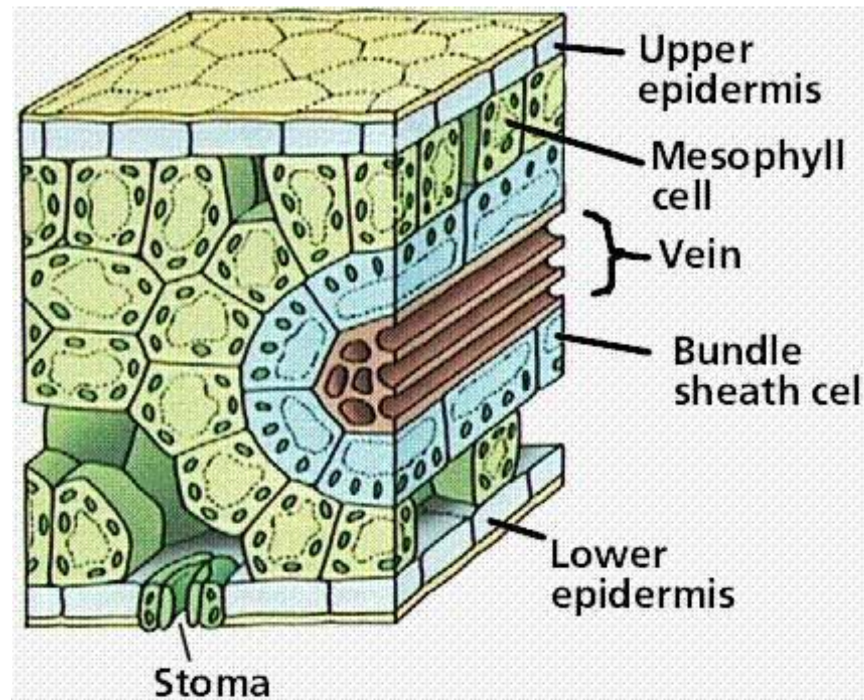
- **PEP carboxylase enzyme**
  - higher attraction for CO_2 than O_2
    - better than RuBisCo
  - fixes CO_2 in 4C compounds
  - regenerates CO_2 in inner cells for RuBisCo
    - keeping O_2 away from RuBisCo

❖ Comparative anatomy

C_3

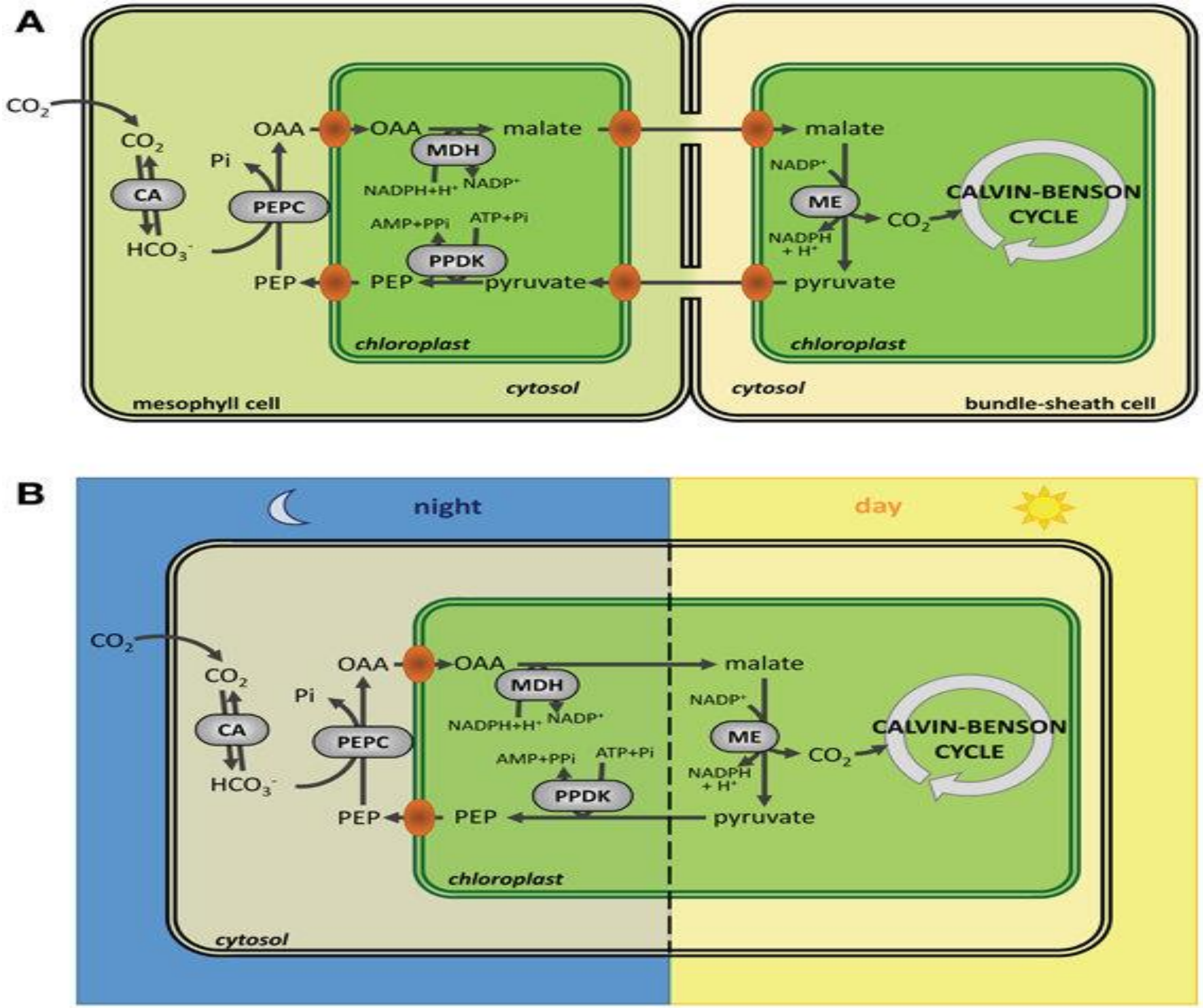


C_4



PHYSICALLY separate C fixation from Calvin cycle

A. C4 B. CAM



A
CO_2
CO_2
CA
HCO_3^-
Pi
OAA
PEPC
PEP
OAA
MDH
NADPH+H⁺
NADP⁺
malate
AMP+PPi
ATP+Pi
PPDK
PEP
pyruvate
chloroplast
cytosol
mesophyll cell
malate
NADP⁺
ME
NADPH + H⁺
CO_2
CALVIN-BENSON CYCLE
pyruvate
chloroplast
cytosol
bundle-sheath cell
B
night
day
CO_2
CO_2
CA
HCO_3^-
Pi
OAA
PEPC
PEP
OAA
MDH
NADPH+H⁺
NADP⁺
AMP+PPi
ATP+Pi
PPDK
PEP
malate
NADP⁺
ME
NADPH + H⁺
CO_2
CALVIN-BENSON CYCLE
pyruvate
chloroplast
cytosol

❖ 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

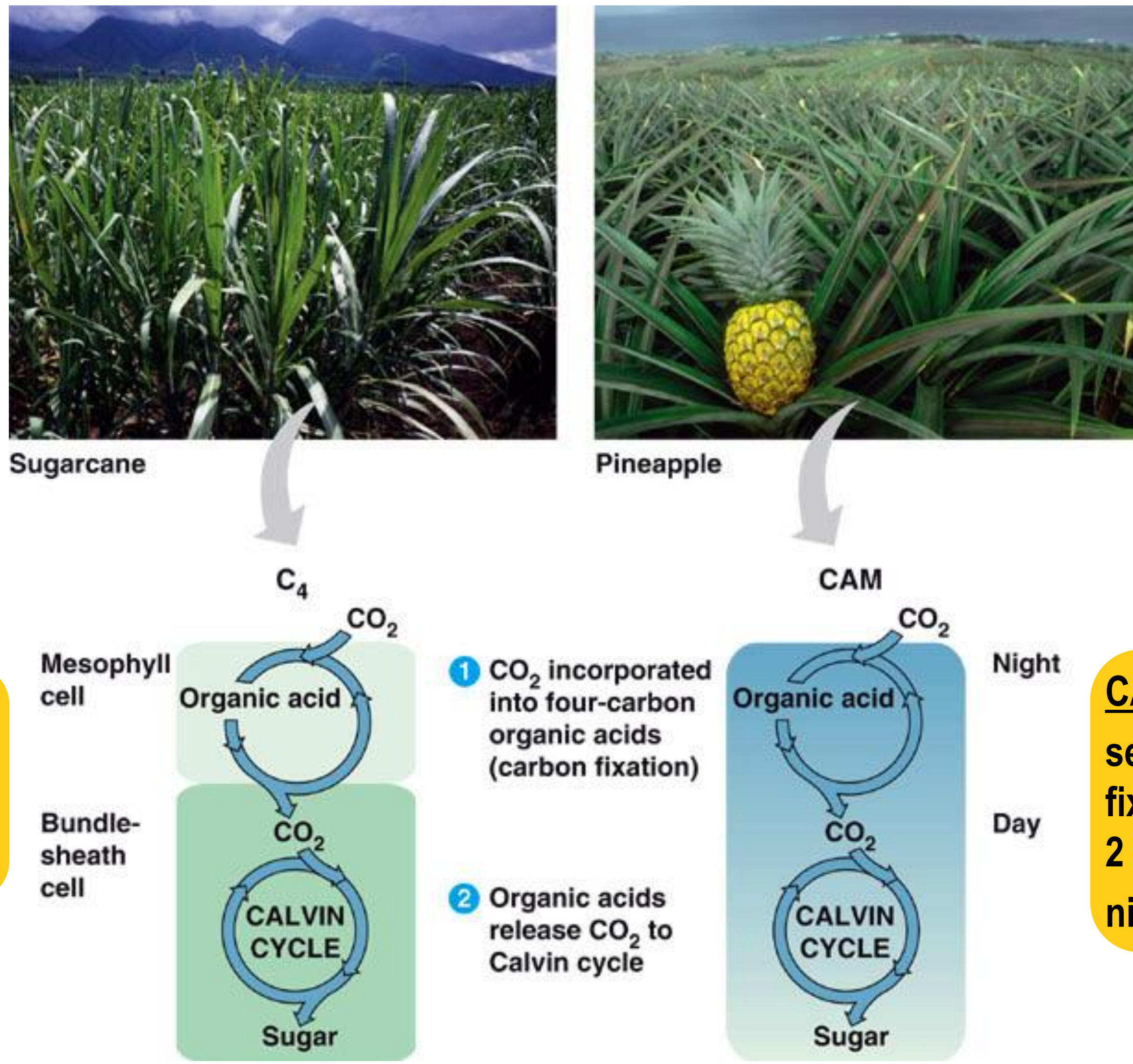
CAM plants

cacti

succulents

❖ C4 vs CAM Summary

solves CO_2 / O_2 gas exchange vs. H_2O loss challenge



<u>C4 plants</u>

separate 2 steps of C fixation <u>anatomically</u> in 2 different cells

<u>CAM plants</u>

separate 2 steps of C fixation <u>temporally</u> = 2 different times night vs. day

❖ Why the C_3 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??