BIOCHEMISTRY

Photosynthesis

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Chapter Description

- Overview

  Photosynthesis important for green plants primarily. A pathway not found in animals but relevant as energy ultimately can be traced to the sun.

- Expected Outcomes

  You should able to compare light and dark reaction, differentiate between C2, C3 and C4 pathways in plants.

- Other related Information

  Some relevant questions been provided for improving your understanding of the topic. You are expected to search for external sources for information to adequately answer the questions. All pictures and figures within this chapter categorized as creative commons for the purpose of education only.

CHAPTER OUTLINE

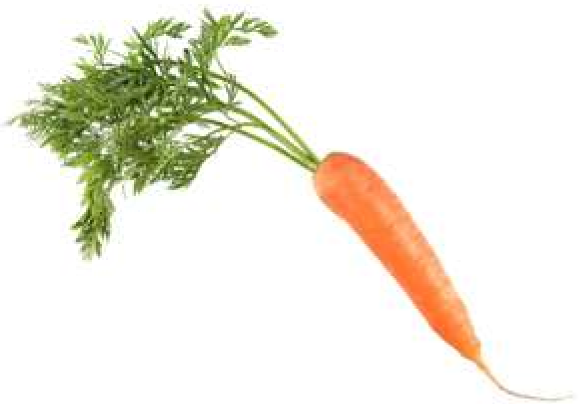
1. Chlorophyll and chloroplasts
2. Light
3. Light Reaction
4. The light-independent reactions

1. Chlorophyll and Chloroplasts

- Chlorophyll: green pigment molecules
- Chlorophylls : Absorb blue-violet and red wavelength and emitted at a longer wavelength
- ***Chlorophyll a***: absorb light energy and directly drives photochemical events.
- ***Chlorophyll b***: light-harvesting pigment which absorb light energy and passing it to *chlorophyll a*.

1. Chlorophyll and Chloroplasts

- Carotenoids
  - orange isoprenoid pigments.
  - light harvesting pigment (e.g. lutein, xanthrophyll) or protect against ROS (e.g. β-carotene)

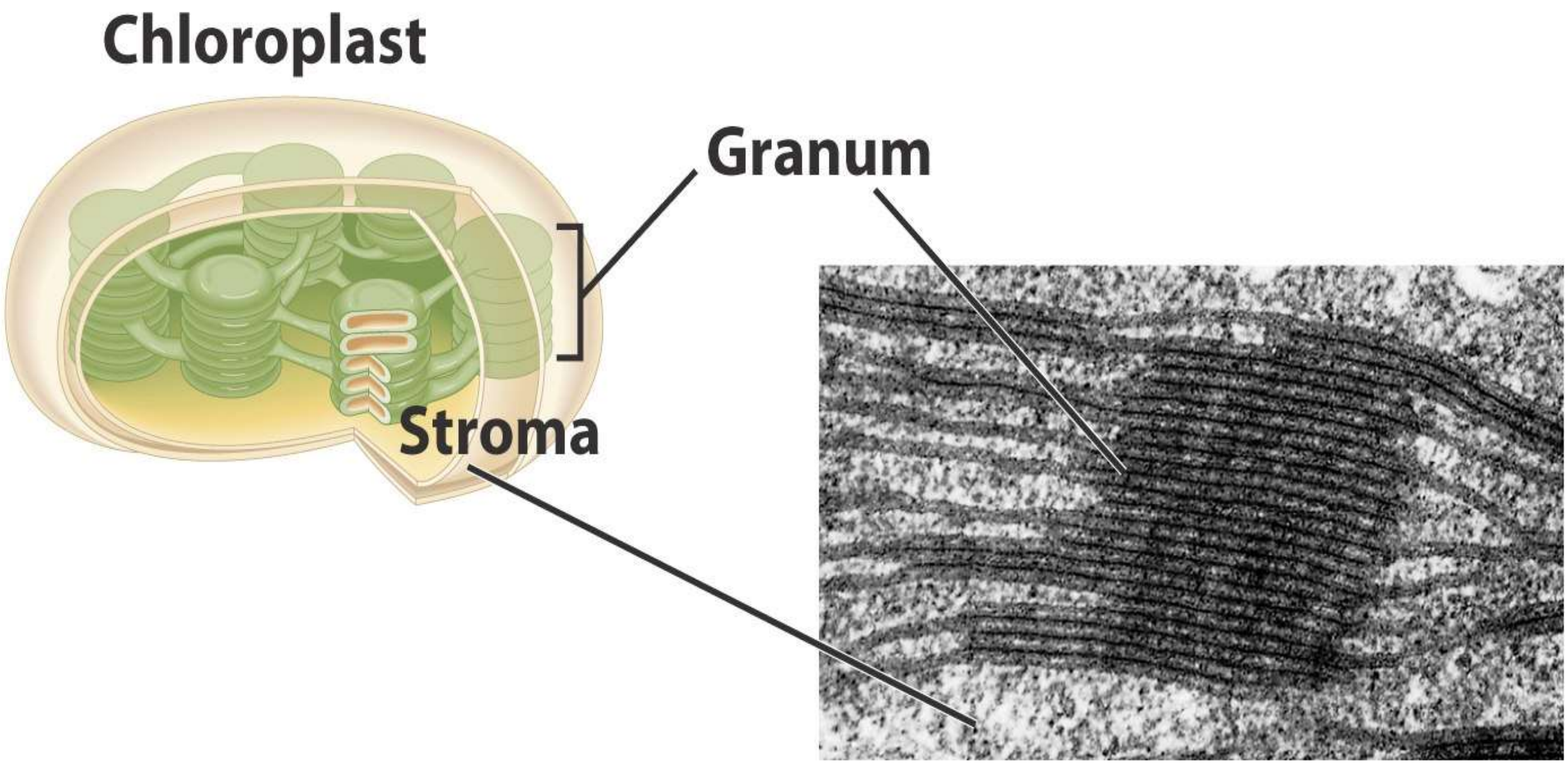


1. Chlorophyll and Chloroplasts

- Photosynthesis takes place in chloroplasts.
- Structure of chloroplasts:

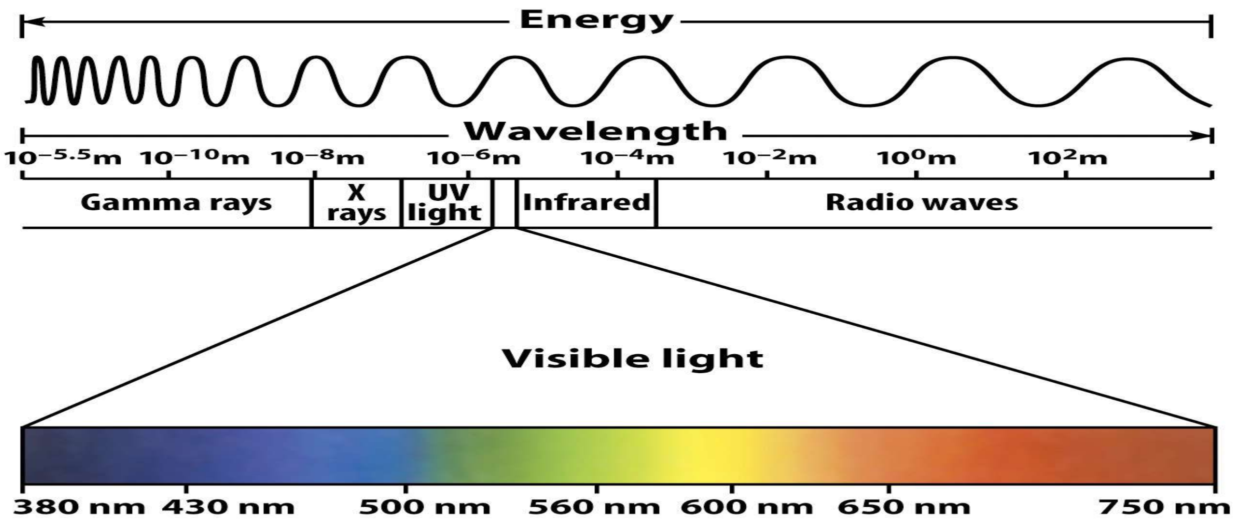
  - Thylakoids membrane = internal membranes
  - Grana = disk-like structure formed by folded thylakoids membrane
  - Granum = stacks of thylakoids membrane
  - Stroma = fluid around thylakoid membrane

1. Chlorophyll and Chloroplasts



2. Light

- Sun emits energy in the form of electromagnet radiation.
- Visible light is the energy source that drives photosynthesis.
- Visible light has wavelength from 400 nm to 700 nm.



3. The pathways

- Photosynthesis consists of 2 major phases:
  - a) light reactions
  - b) light-independent reactions
- During the light reactions, **water** is oxidized, **O_2** is released, and the **ATP** and **NADPH** are produced.
- The pigments and proteins responsible for light-dependent reactions of photosynthesis are found within the thylakoid membrane.

Light dependent reactions

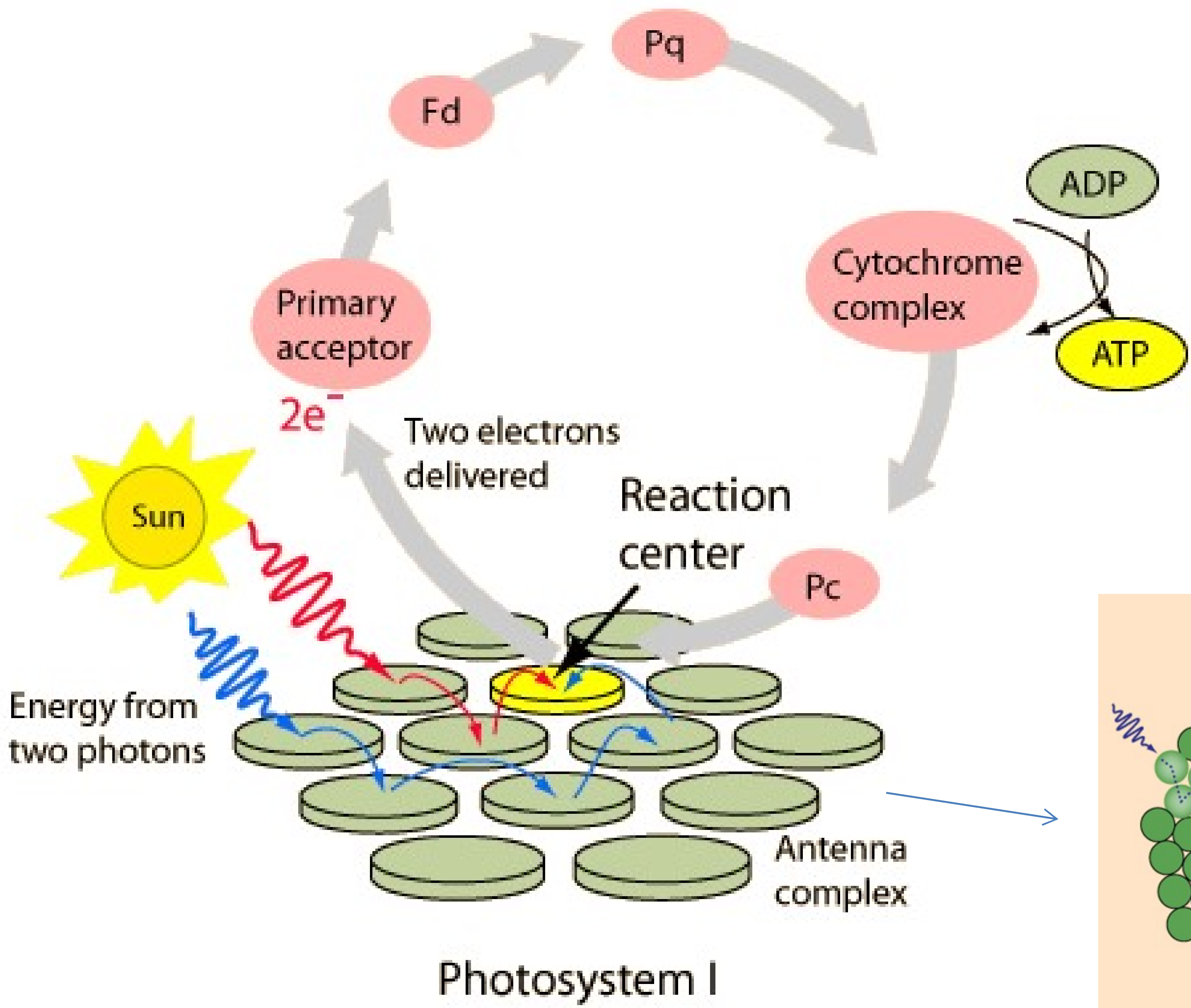
- The major working units of the light reactions photosynthesis are:

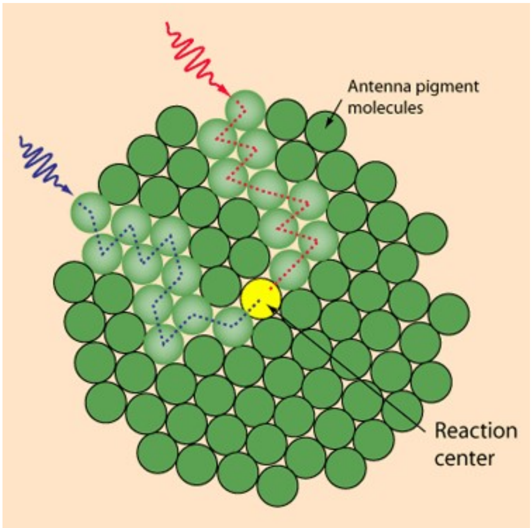
  a) photosystem I

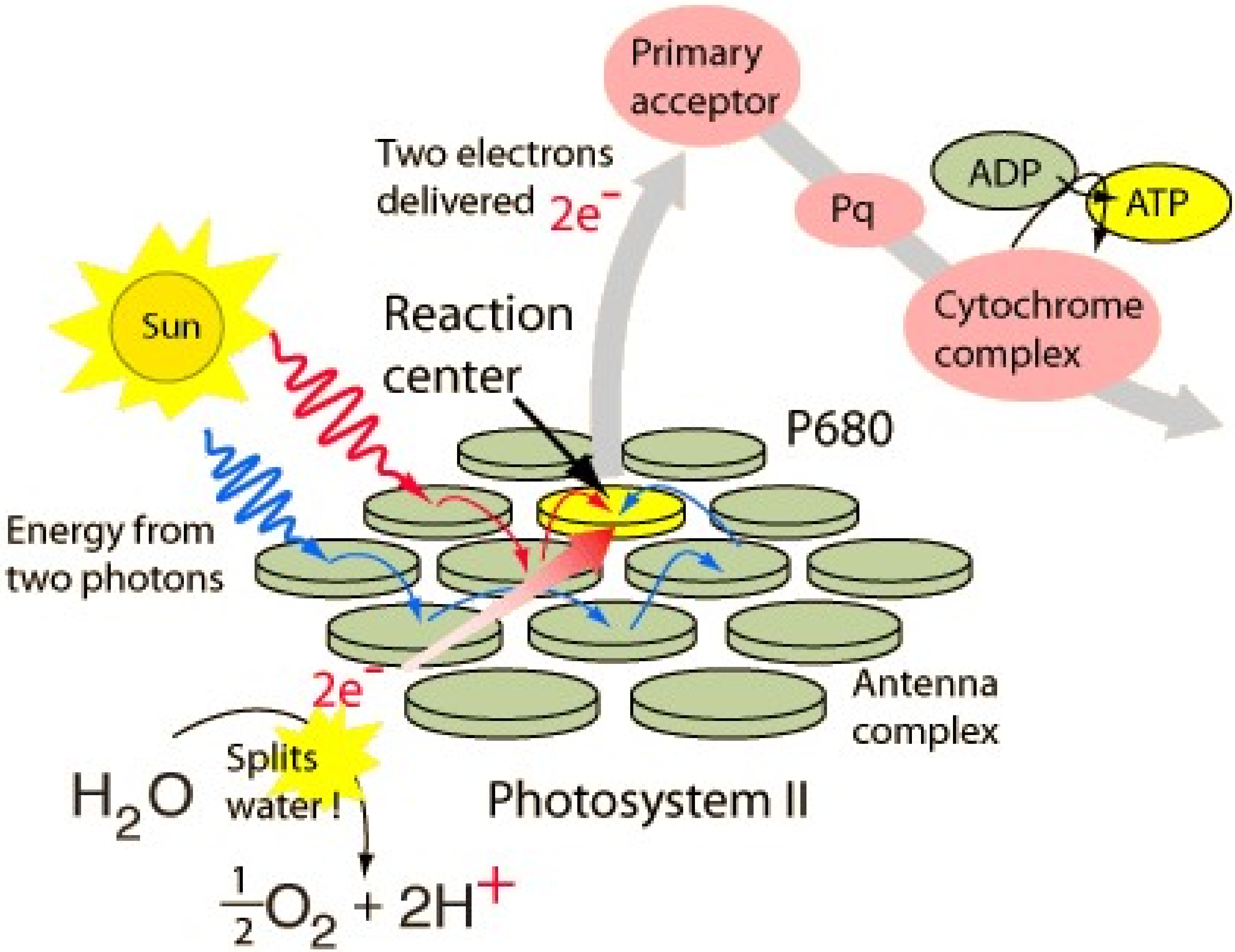
  b) photosystem II

  c) Cytochrome b_6f complex

  d) ATP synthase


Pq
Fd
ADP
Cytochrome complex
Primary acceptor
ATP
2e⁻
Two electrons delivered
Reaction center
Sun
Pc
Energy from two photons
Antenna complex
Photosystem I

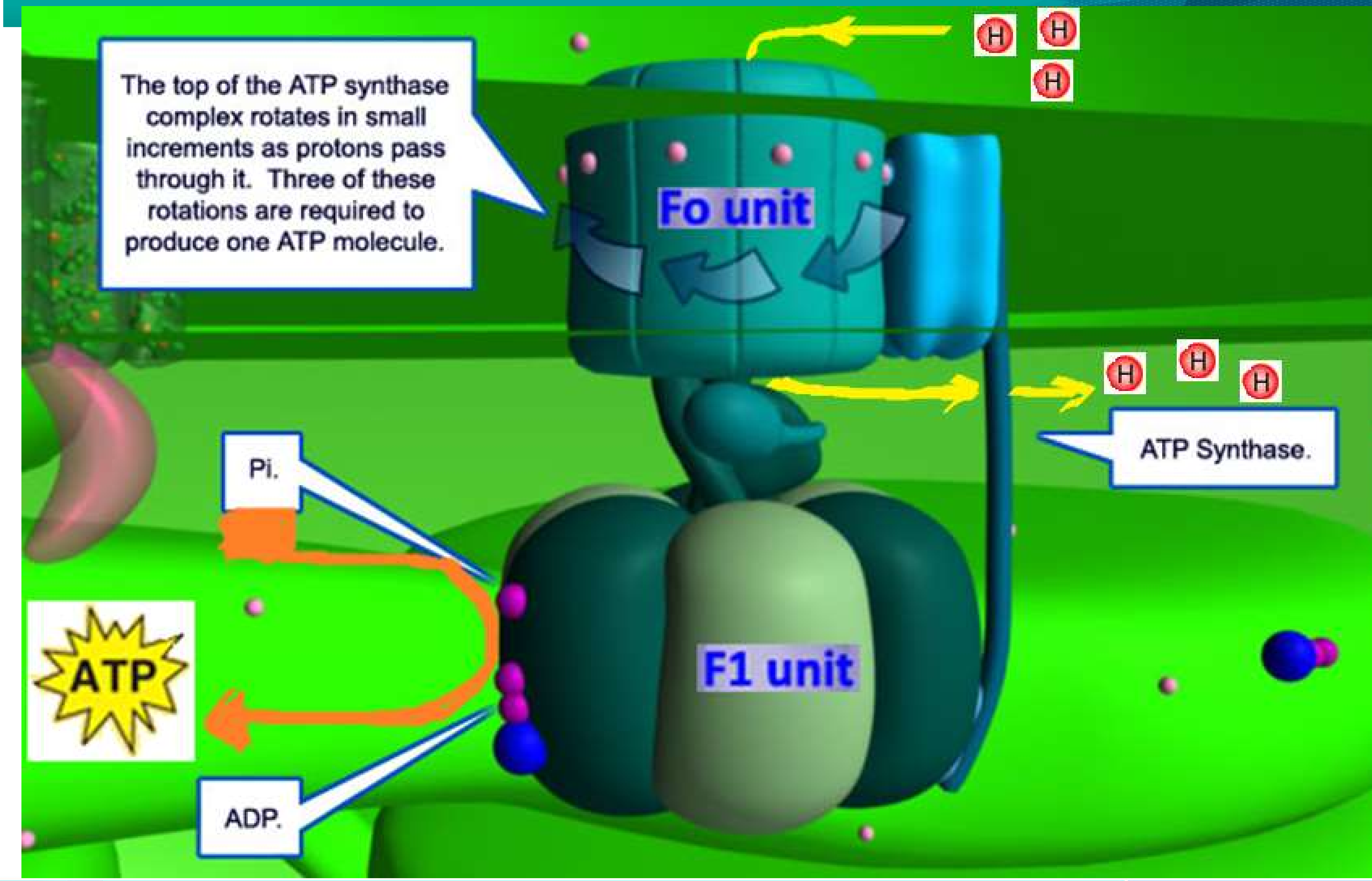

Antenna pigment molecules
Reaction center


Primary
acceptor
Two electrons
delivered $2e^-$
Pq
ADP
ATP
Cytochrome
complex
Sun
Reaction
center
P680
Energy from
two photons
$2e^-$
Antenna
complex
Splits
water !
H_2O
Photosystem II
$\frac{1}{2}O_2 + 2H^+$

- **Cytochrome b_6f complex:**
  - found throughout the thylakoid membrane.
  - play critical role in the **transfer of electrons from PSII to PSI**

- **ATP synthase:**
  - membrane-spanning protein complex.
  - found in thylakoid membrane directly contact with the stroma
  - Posses an ATP-synthesizing activity
  - The synthesis of ATP required **3 protons** into the thylakoid space

ATP synthase



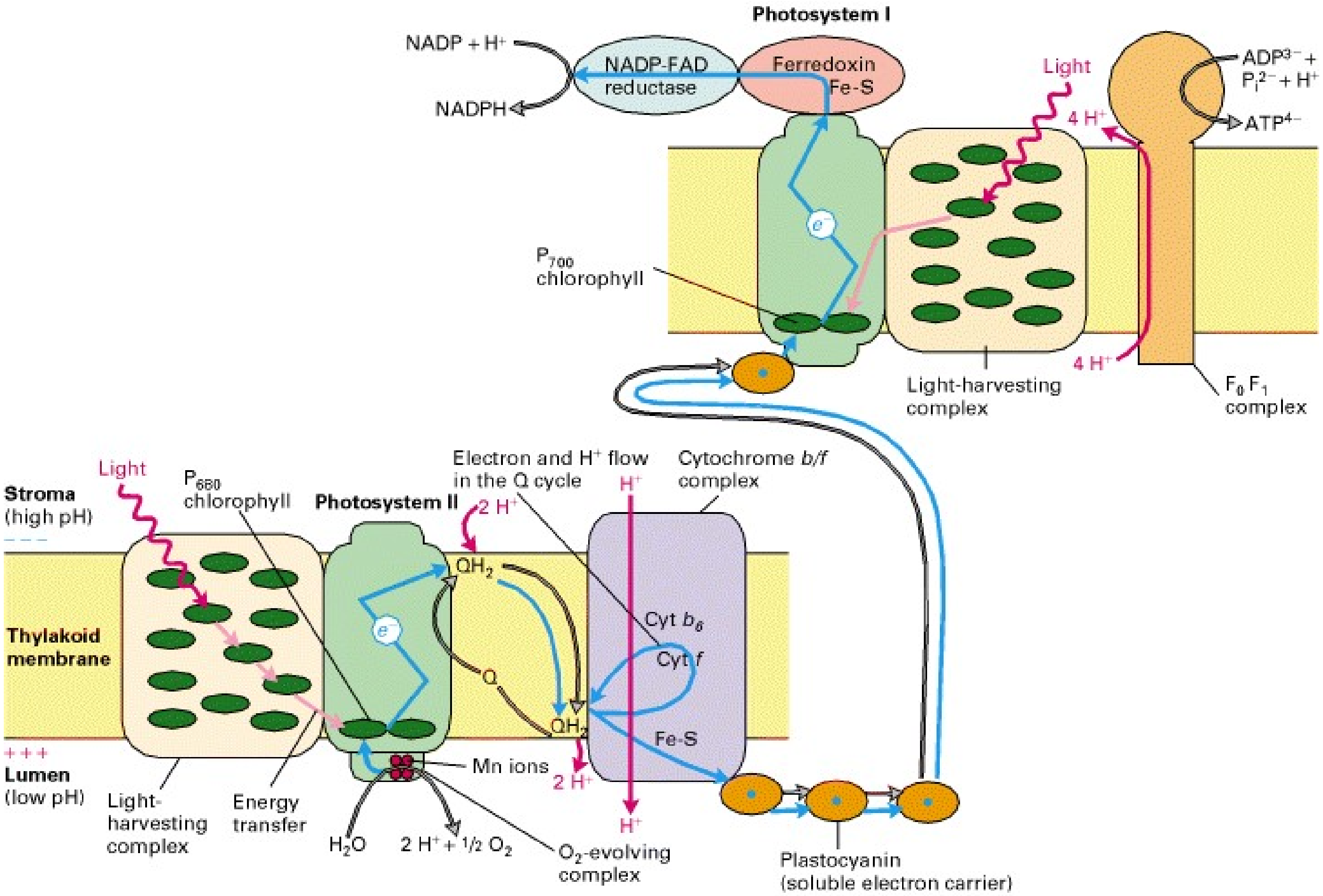
- Molecules that absorb electromagnetic energy posses structure called chromosphores.
- In chromosphores, electron moves to higher energy levels when energy is absorbed.
- In photosynthesis, light energy (photon) is absorbed and transmitted by light-harvesting complexes to reach the reaction center of chlorophyll molecules.

- When the chlorophyll molecules become excited, they can transfer an electron to a specific acceptor molecule.

- The energy is donated from one antenna molecule to another until it is trapped by a reaction center or reemitted.

- P700 passes electrons to *ferredoxin* and P680 passes electrons to *pheophytine a*

Overview on light reaction



- Light reaction: mechanism by which electron are energized and used in ATP and NADPH synthesis.

- 2 photosystems; photosystem I and photosystem II involved in light driven oxidation of water molecules to the reduction of $NADP^+$

$2\ NADP^+ + 2\ H_2O \longrightarrow 2NADPH + O_2 + H^+$

Overview of light reaction photosynthesis

1. Light- driven photosynthesis begins with the excitation of PSII by light energy.

2. One electron at a time is transferred to a chain of electron carriers that connect the 2 photosystems.

3. As electron transferred from P680 (PSII) to P700 (PSI), protons are pumped across the thylakoid membrane from stroma into the thylakoid space.

4. ATP is synthesized as protons flow back to the stroma by ATP synthase.

5. Electron transferred from P680 are replaced when H_2O is oxidized and converted to O_2.

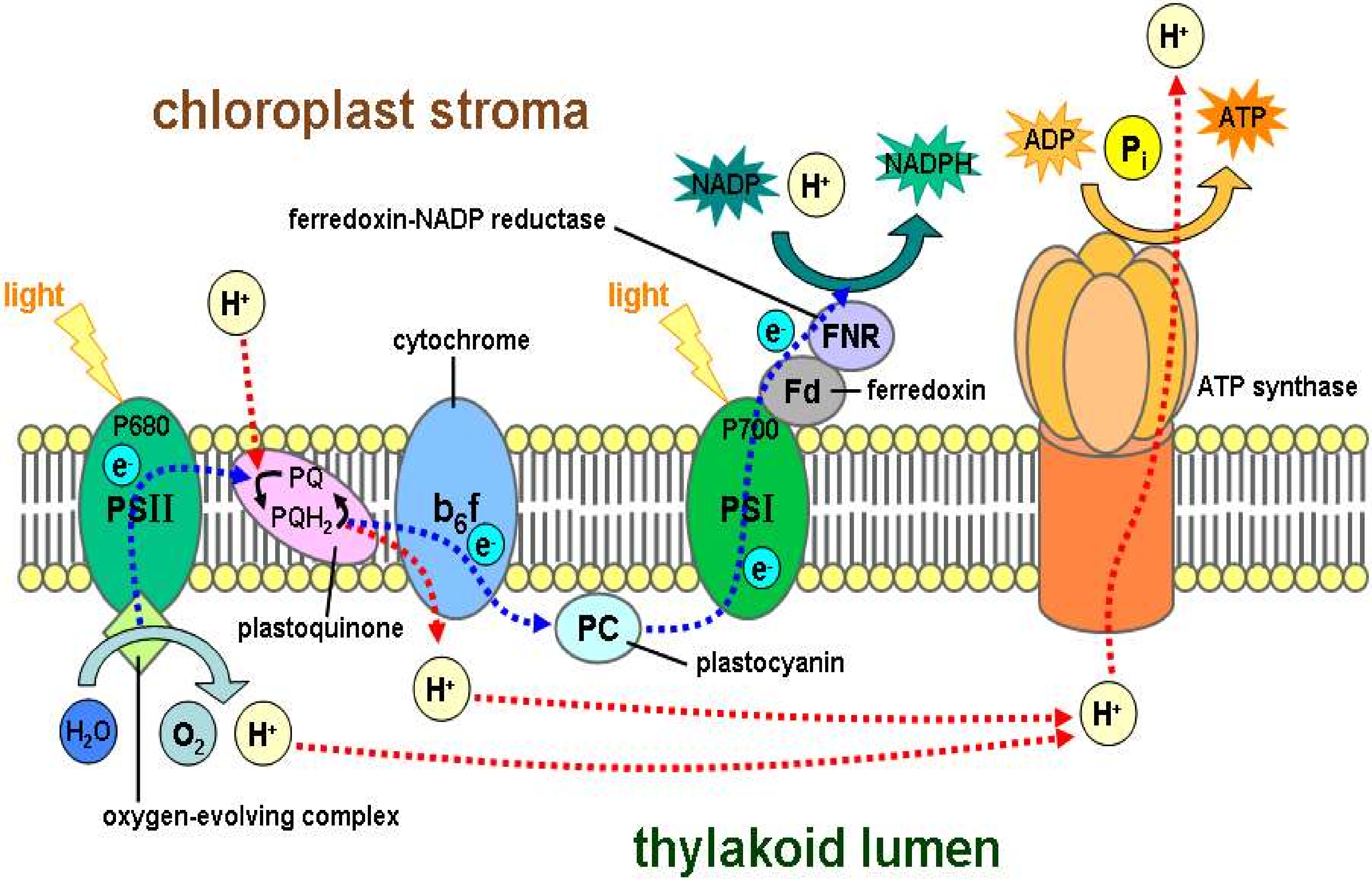
6. When P700 (PSI) absorbs an additional light energy (photon), it releases energized electron.

7. The newly energized electron passed through a series of iron-sulfur proteins and a flavoprotein to $NADP^+$ (the final electron acceptor) to produce NADPH.

8. In light reaction, **3 H ions** are removed through ATP synthase for synthesis of one molecule of ATP.

9. **Two molecules of ATP are produced** for every NADPH molecule synthesized.

10. Eukaryotic photosynthesizing cells posses 2 photosystems PSI and PSII which are connect series in a mechanism called Z-scheme.


chloroplast stroma
H+
ADP
Pi
ATP
NADP
H+
NADPH
ferredoxin-NADP reductase
light
H+
cytochrome
light
e-
FNR
Fd
ferredoxin
ATP synthase
P680
e-
PSII
PQ
PQH2
b6f
e-
P700
PSI
e-
PC
plastoquinone
plastocyanin
H+
H2O
O2
H+
H+
oxygen-evolving complex
thylakoid lumen

SUMMARY

- Overall reaction & ATP generation:
  - Electron from water end up in NADPH.

$$(PSII)\ 2H_2O \longrightarrow 4H^+ + 4e + O_2$$

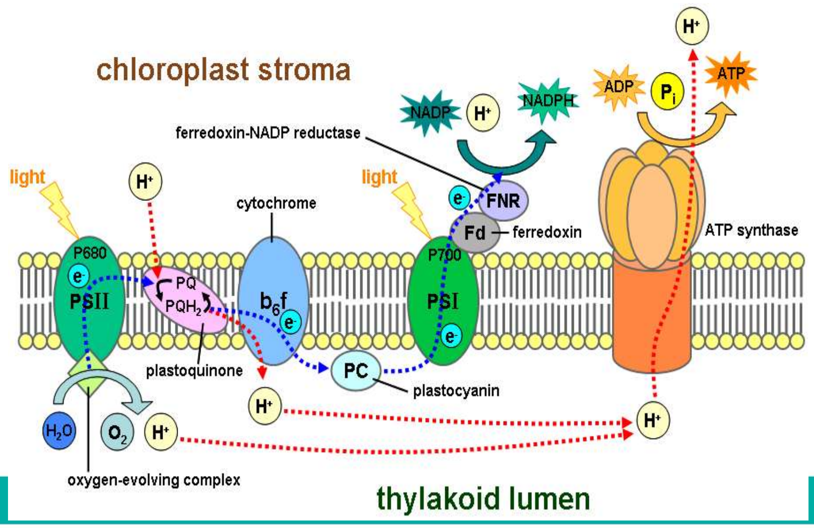
$$(PSI)\ 4e + 2H^+ + 2NADP^+ \longrightarrow 2NADPH$$

  - PSII + PSI:

$$2H_2O + 2NADP^+ \longrightarrow 2H^+ + O_2 + NADPH$$

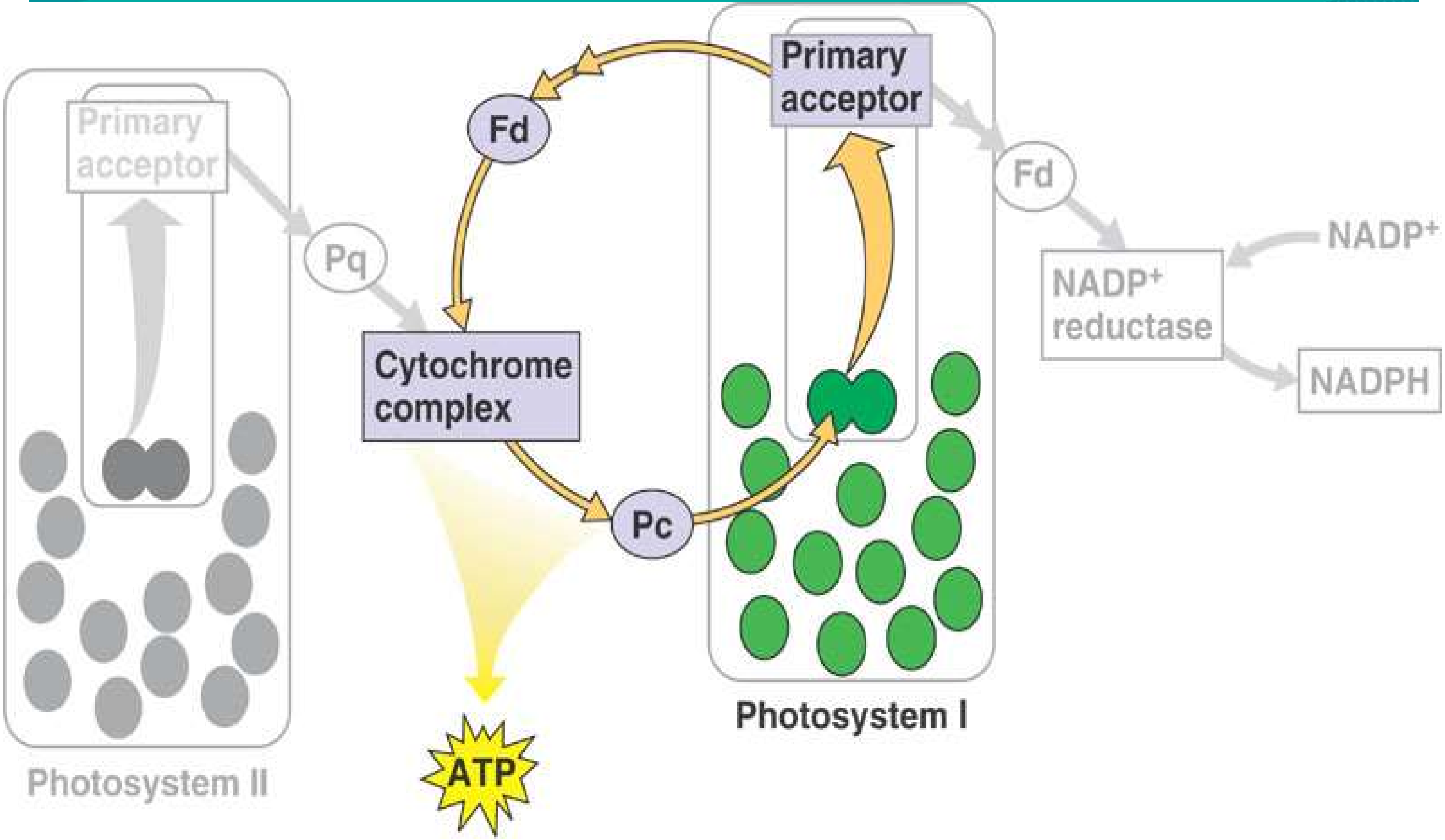
PSI&PSII – are reduction of NADP+ & generation of photon gradient across the thylakoid membrane. Lumen becoming acidic than stroma (can achieve 3.5)

- All H^+ can pass through the thylakoid membrane only through ATP synthase complex (CF_0-CF_1).
- One ATP is produced for each 3 protons passing through CF_0-CF_1 complex.



Cyclic & Non-cyclic pathways

- PSI & PSII:
  - noncyclic electron flow.
- ATP generation:
  - noncyclic photophosphrylation.
- Alternative pathway:
  - **cyclic electron flow**.
  - Utilizes components of PS1 + PC & cytochrome b6f complex.
  - **Depends on the levels of $NADP^+$** in chloroplast stroma.
  - When NADP+ level low, electron excited in the P700 center are not transferred to $NADP^+$.


Primary acceptor
Pq
Photosystem II
Fd
Cytochrome complex
Pc
ATP
Primary acceptor
Photosystem I
Fd
NADP+
NADP+ reductase
NADPH

- Alternative pathway (cont.):
  - The electrons are passed from ferredoxin (fd) to cytochrome b_6f complex, then return to PC to P700 ground state.
  - b_6f complex & $NADP^+$ as competitors for the electrons from fd.
  - Then, **b_6f complex will pump proton** across the thylakoid membrane during cyclic process to ensuring the generation of ATP.
  - One ATP is generated for every 2 electrons that complete the cycle (cyclic photophosphorylation).
  - **No O_2** is released & **no $NADP^+$** is reduced.

Light Independent Reaction / Dark reaction

- occur in stroma of chloroplast.
- Function:
  - Fix CO_2 into carbohydrate, utilizing ATP energy & NADPH (light reaction)
- Occurs without light & accelerated in presence of light.
- The process is called Calvin cycle where ATP and NADPH are employed.
- The reaction of Calvin cycle divided into 3 phases:

  1) carbon fixation

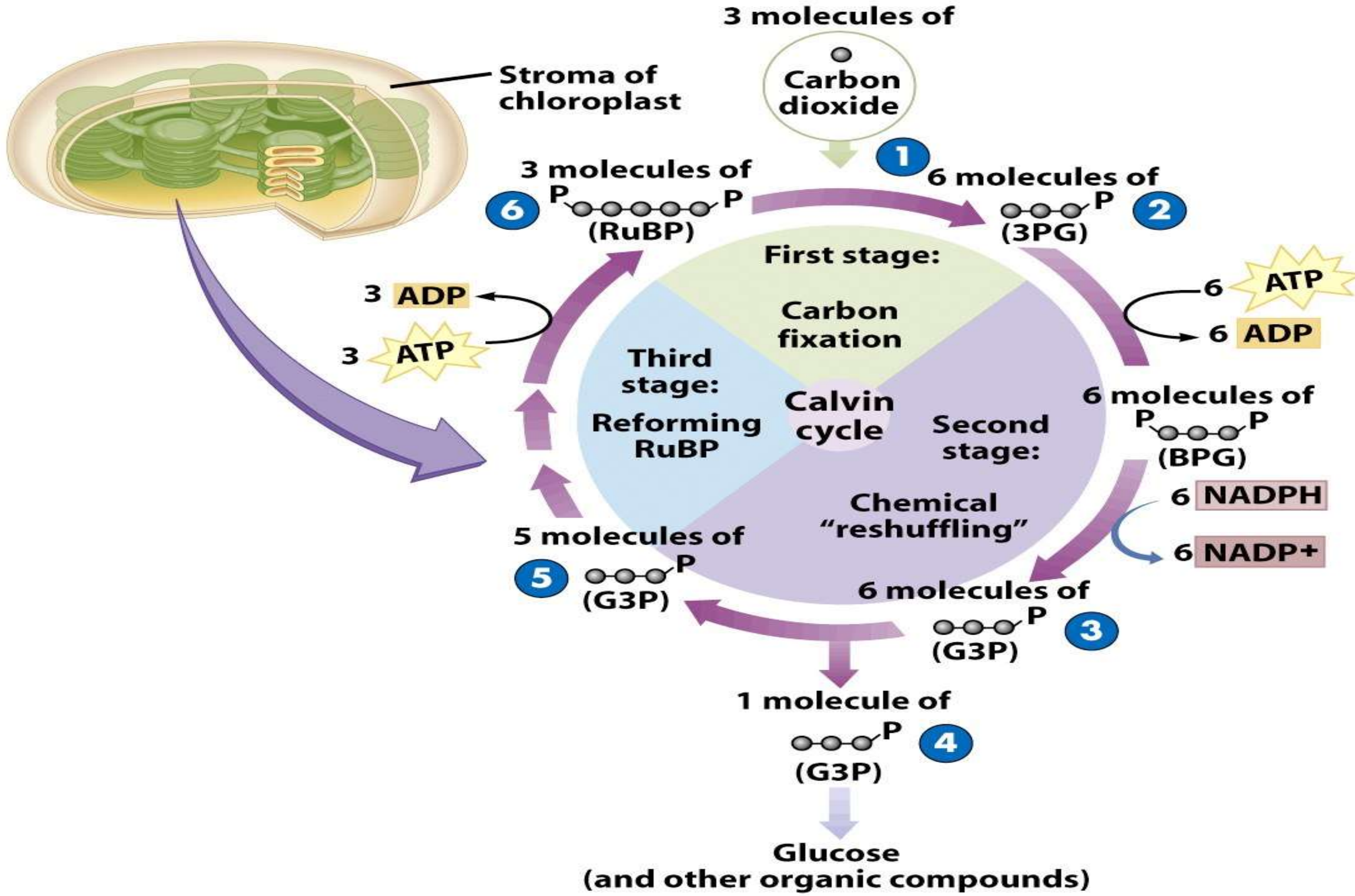
  2) reduction

  3) regeneration of the acceptor

- The net equation for the Calvin cycle:

$3\ CO_2 + 6NADPH + 2ATP \rightarrow G\text{-}3\text{-}P + 6NADP + 9ADP + 8Pi$

- For every 3 molecules of CO_2, there is gain of one molecule of glyceraldehyde-3-phosphate.


Stroma of chloroplast
3 molecules of
Carbon dioxide
1
6 molecules of
P
(3PG)
2
6 ATP
6 ADP
6 molecules of
P P
(BPG)
6 NADPH
6 NADP+
6 molecules of
P
(G3P)
3
1 molecule of
P
(G3P)
4
Glucose
(and other organic compounds)
5 molecules of
P
(G3P)
5
3 ATP
3 ADP
3 molecules of
P P
(RuBP)
6
First stage:
Carbon fixation
Second stage:
Chemical "reshuffling"
Third stage:
Reforming RuBP
Calvin cycle

Carbon fixation

- Consist of a single reaction.
- Ribulose-1,5-bisphosphate carboxylase (RuBisCO) catalyzes carboxylation of ribulose-1,5-bisphosphate to form 2 molecules of 3-Phosphoglycerate (3PG)

- Ribulose-1,5-bisphosphate carboxylase:
  - Complex molecules composed of 8 large subunit (L) & 8 small subunit (S), as a pacemaker enzyme.
  - Its activity regulated by CO_2, O_2, Mg^{2+} & pH.

Ribulose-1,5-bisphosphate (5C)

Ribulose-1,5-bisphosphate carboxylase ↓ **CO_2 (3 molecules)**

3-Phosphoglycerate (3PG)

(2 molecules)

Reduction

- The next phase of the cycle consists of two reactions.
- 6 molecules of 3-Phosphoglycerate (3PG) are phosphorylated, 6 ATP molecules used to form 1,3-bisphosphoglycerate (BPG).
- The molecules are then reduced by NADP-glucerate-1,3-phosphate dehydrogenase to form 6 molecules of glyceraldehyde-3-phosphate (similar to the reaction in **gluconeogenesis**)

Ribulose-1,5-bisphosphate

(2 molecules x 3)

↓

3-Phosphoglycerate (3PG)

(6 molecules)

ATP → ADP

phosphorylated

↓

1,3-bisphosphoglycerate (BPG)

(6 molecules)

NADPH → $NADP^+$ +Pi

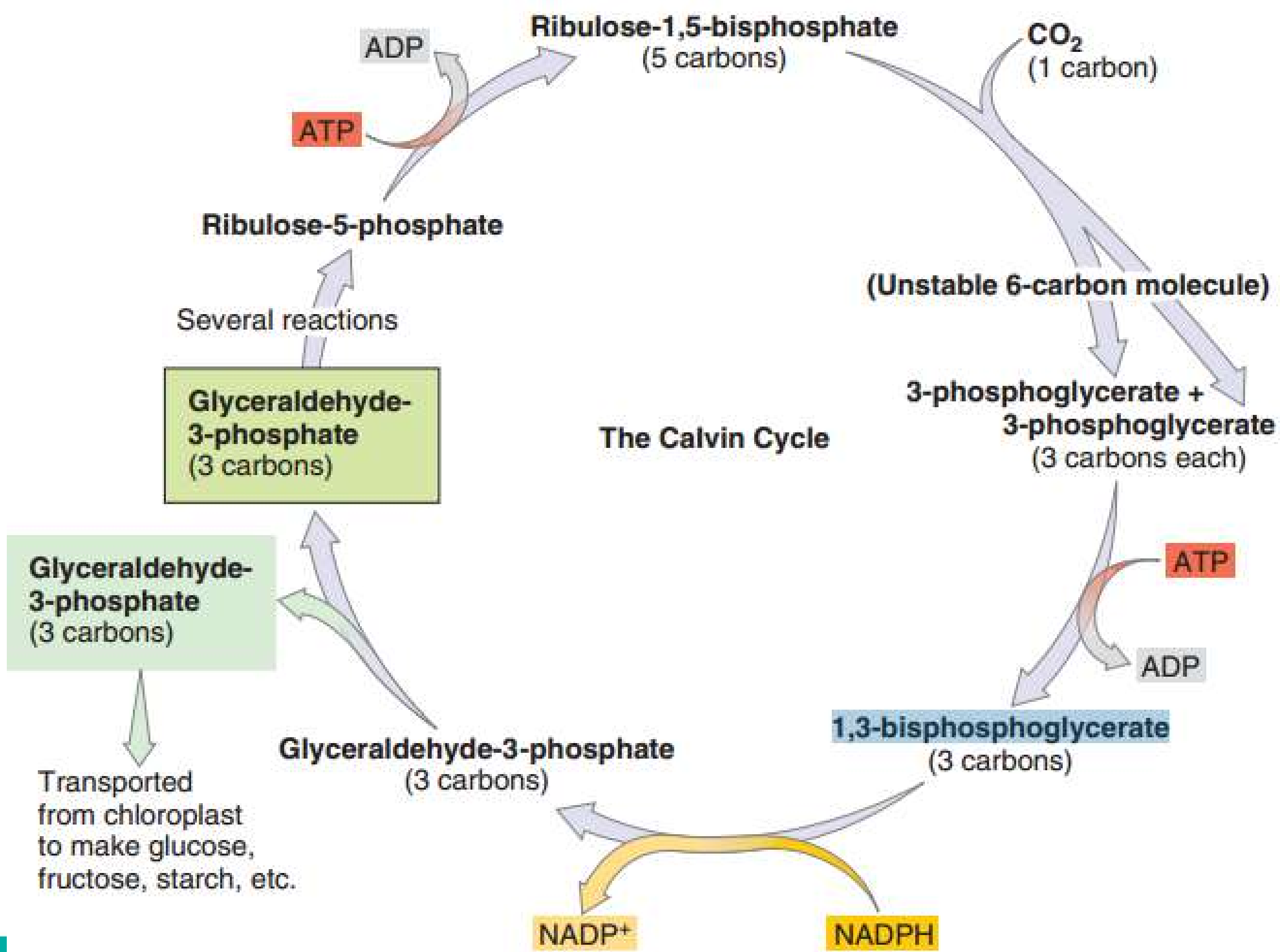
Reduced by NADPH-glyceraldehyde-3-phosphate

↓

Glyceraldehyde-3-phosphate

(6 molecules)

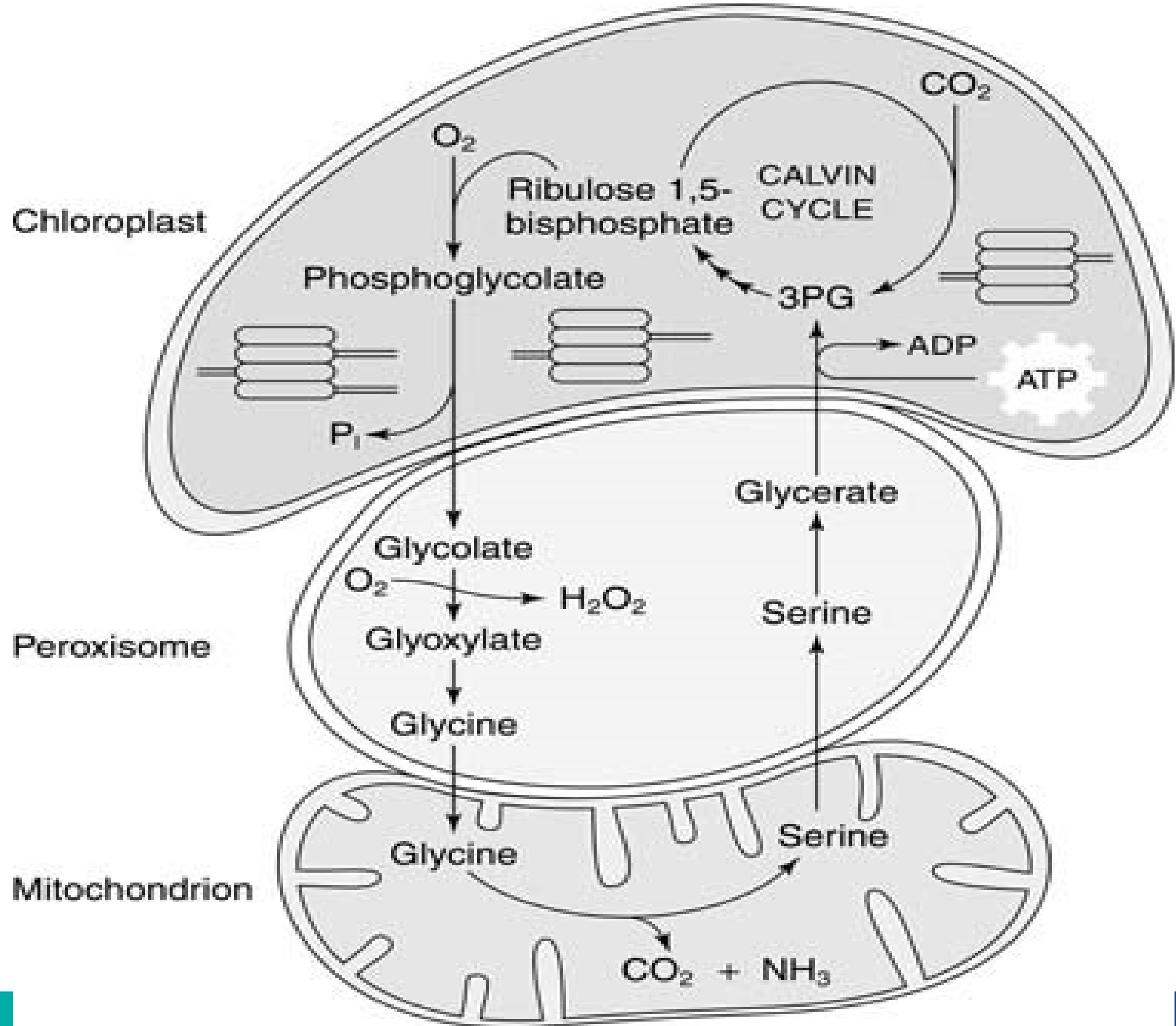
Overview: Calvin Cycle



Photorespiration & C_4 Cycle

- Ribulose bisphosphate carboxylase:
  - Peculiar enzyme (behave as **oxygenase** instead of **carboxylase**)
- Under condition with high O_2 & low CO_2 concentration likely due to temporary rise high in environment temperature.
- When oxygenase become significant, it initiates a reaction pathway ~ photorespiration.

Photorespiration

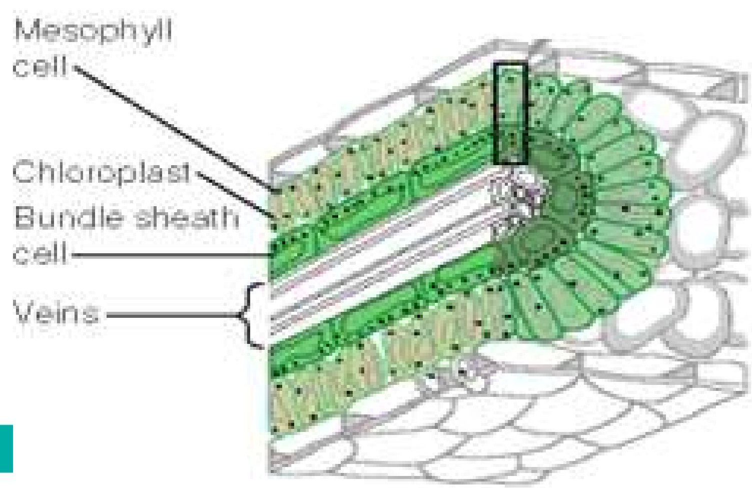


Photorespiration

- Losing process
- Ribulose-1,5-bisphosphate is lost from the Calvin Cycle.
- Fixation of CO_2 is reversed; O_2 is consumed, CO_2 is released.
- Only a part of carbon is returned to the chloroplast.
- ATP is needlessly wasted.
- **Essentially works against photosynthesis process**.
- Becomes important only under conditions where CO_2 levels are very low.
- Decreases the efficiency of most plants.

C_4 plants

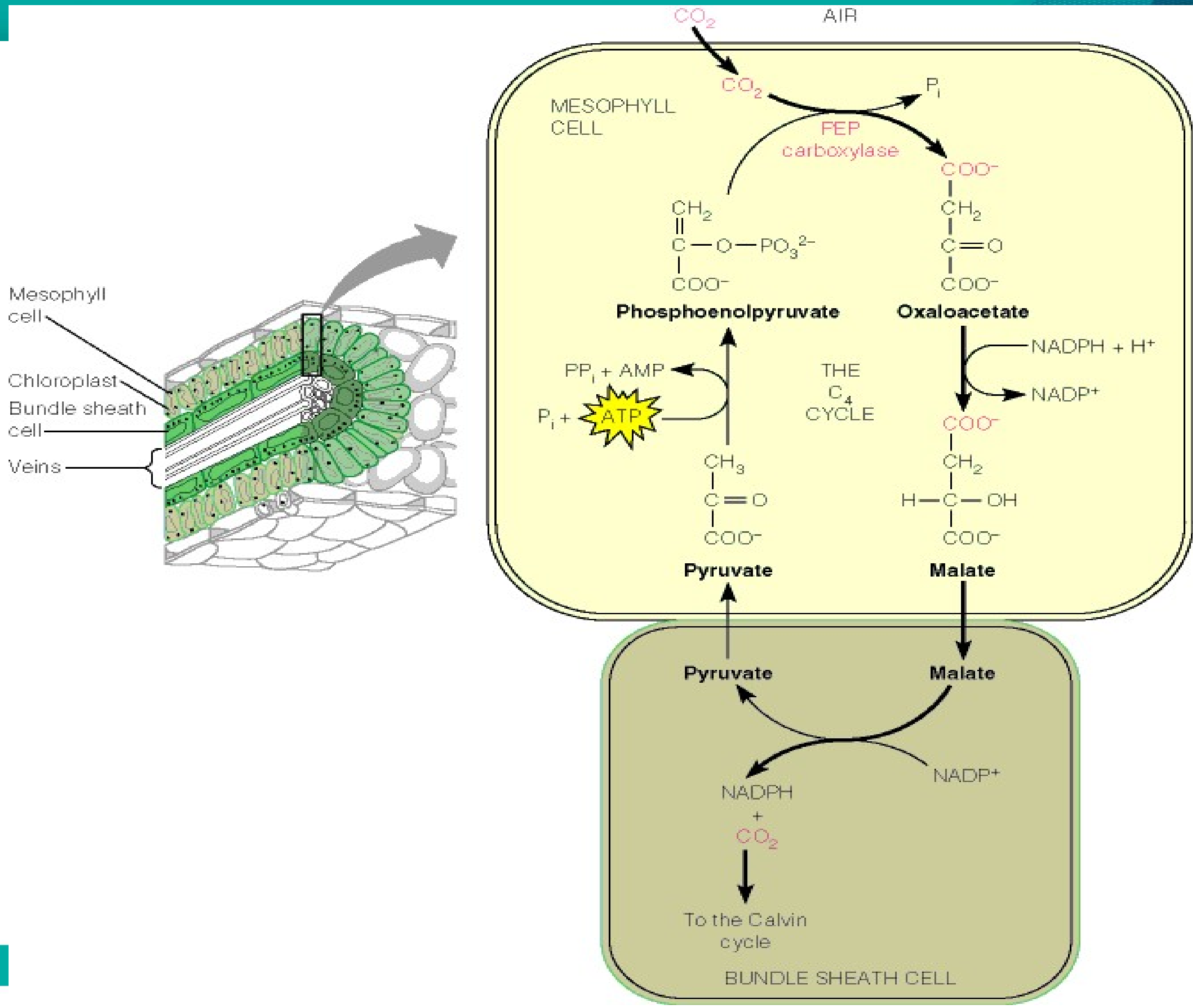
- Concentrate their Calvin cycle (C_3) photosynthesis in specialized bundle sheath cells (below mesophyll cells).
- Mesophyll cells – directly exposed to external CO_2, contain enzyme for the C_4 cycle.



C_4 cycle

- Operates in most C_4 plants found in high temperature or drought environment.
- Mechanism for trapping CO_2 into 4C compound OAA & passing it on the bundle sheath cells for use in their C_3 cycle.
- Key of efficiency of C_4 plants:
  - **PEP carboxylase**
- High $[O_2]$, low $[CO_2]$, mesophyll cells continue to pump CO_2 to the photosynthesizing bundle sheath cells.
- If photorespiration does occur, the CO_2 that is released in the process can be largely salvaged in the surrounding mesophyll cells & return to the Calvin Cycle.

Reaction of the C4 cycle



- CO_2 is transported from mesophyll cells to the bundle sheath cells by coupling to the PEP forming OAA.

- OAA is then reduced to malate, which is passed to the bundle sheath cells & carboxylated.

- Pyruvate – return back to the mesophyll cells & phosphorylated to generate PEP.

- C_4 cycle - costs the plant energy in the form of ATP.
- ATP hydrolyzed to AMP & inorganic phosphate in regenerating of PEP.
- The expense is equivalent to 2 extra ATPs for every CO_2 molecules fixed.

References:

Title/URL	Author	Publisher	Year
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Biochemistry.2010	Garret, R.H., Grisham, C.	Thompson Brooks	2007
Biochemistry	Hames,D	USA: Taylor and Fran	-
Color Atlas of Biochemistry	Koolman, J., Roehm, K.H	Thieme Stuttgart	2005
Biochemistry demystified	Walker, S.	New York, USA; McGr	2008
Biochemistry, 7th Edition	Stryer	W.H Freeman and Co	2010
Biochemistry, 4th Edition	Donald Voet and Judith (	Wiley and Co	2011
Google with keyword of biochemistr	Various Online Biochemi	various	
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