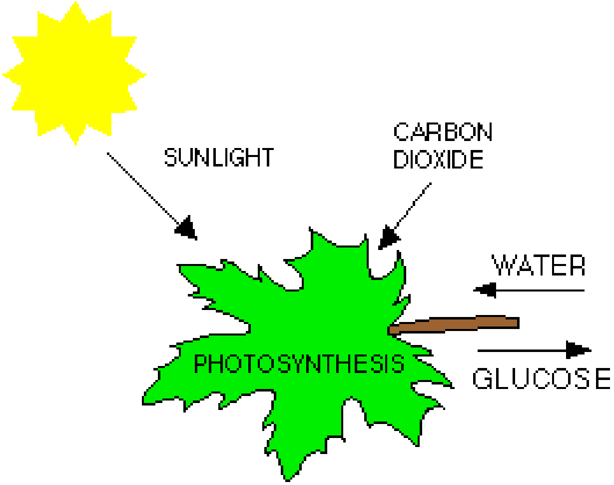
PHOTOSYNTHESIS

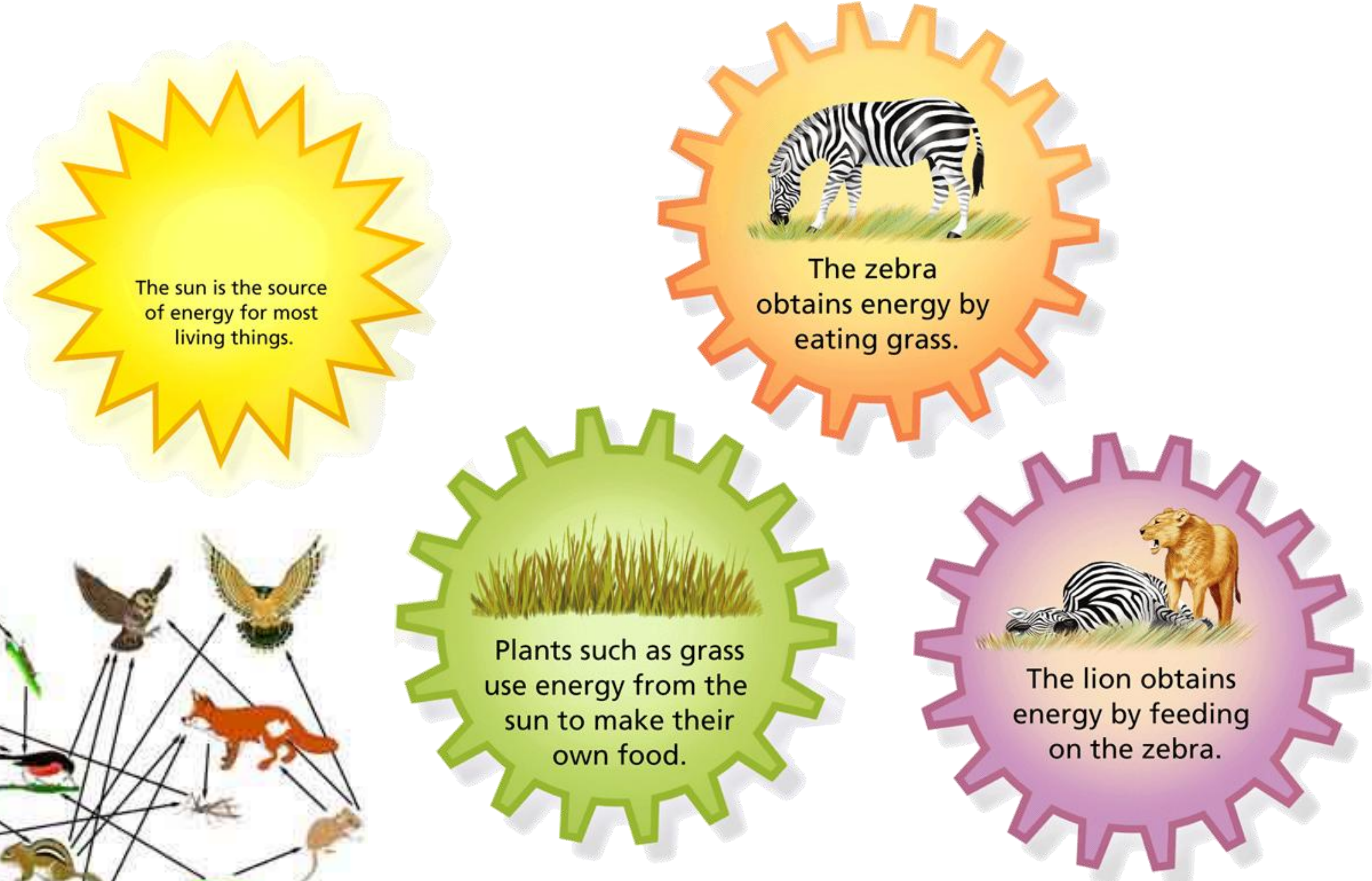
- Autotrophic Process: Plants and plant-like organisms make their energy (glucose) from sunlight.
- Stored as carbohydrate in their bodies.
- $6CO_2 + 6H_2O + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$

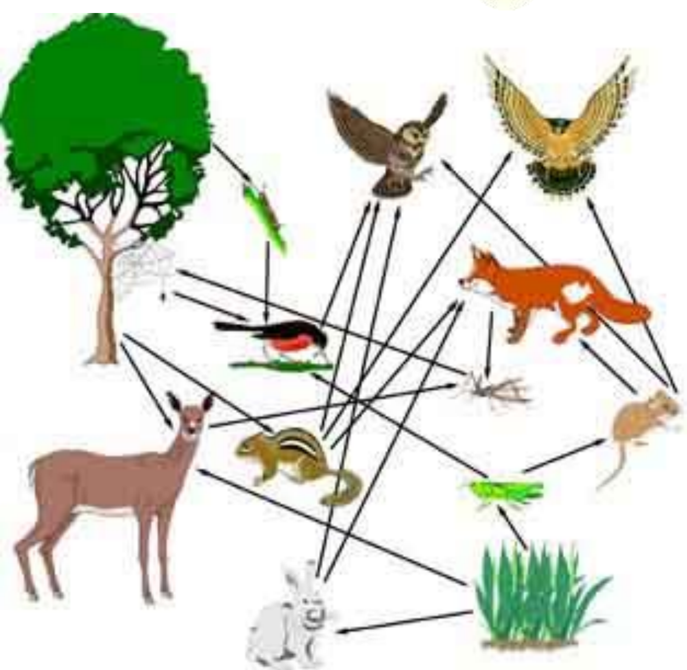


Why is Photosynthesis important?

- Makes organic molecules (glucose) out of inorganic materials (carbon dioxide and water).
- It begins all food chains/webs. Thus all life is supported by this process.
- It also makes oxygen gas!!

Photosynthesis-starts to ecological food webs!





Introduction

- Life on Earth is solar powered.
- The chloroplasts of plants use **photosynthesis** to capture light energy from the sun and convert it to chemical energy stored in sugars and other organic molecules.
- $6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$
- Basically this reaction is the **OPPOSITE** of cellular respiration

- Autotrophs can be classified by the source of energy that drives their metabolism.
  - *Photo*autotrophs use light as the energy source.
  - Photosynthesis occurs in plants, algae, some other protists, and some prokaryotes.
  - *Chemo*autotrophs harvest energy from oxidizing inorganic substances, including sulfur and ammonia.
  - Chemoautotrophy is unique to bacteria.

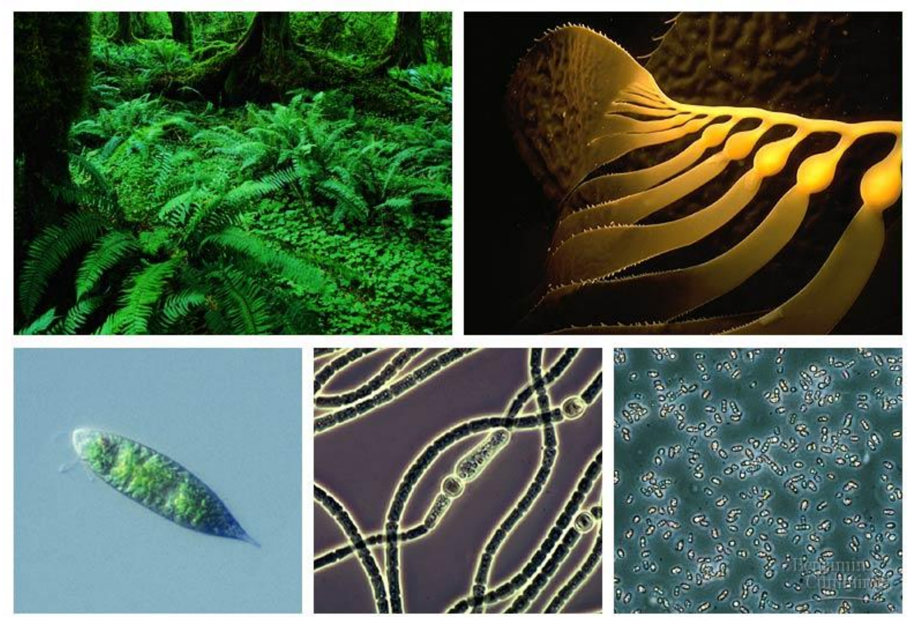


Fig. 9.1

- **Heterotrophs** live on organic compounds produced by other organisms.
  - These organisms are the *consumers* of the biosphere.
  - The most obvious type of heterotrophs feed on plants and other animals.
  - Other heterotrophs decompose and feed on dead organisms and on organic litter, like feces and fallen leaves.
  - Almost all heterotrophs are completely dependent on photoautotrophs for food and for oxygen, a byproduct of photosynthesis.

Plants

Leaves are green because they contain

the pigment:

chlorophyll

Leaves have a large surface area to absorb as much light as possible

Chloroplasts are the sites of photosynthesis in plants

- Any **green** part of a plant has **chloroplasts**.
- However, the leaves are the major site of photosynthesis for most plants.
  - There are about half a million chloroplasts per square millimeter of leaf surface.
- The color of a leaf comes from **chlorophyll**, the **green** pigment in the chloroplasts.
  - Chlorophyll absorbs light energy during photosynthesis.

- Chloroplasts are found mainly in **mesophyll** cells forming the tissues in the interior of the leaf.
- O_2 exits and CO_2 enters the leaf through microscopic pores, **stomata,** in the leaf.
- Veins deliver water through the xylem from the roots and transport sugar from mesophyll cells to other plant areas (phloem).

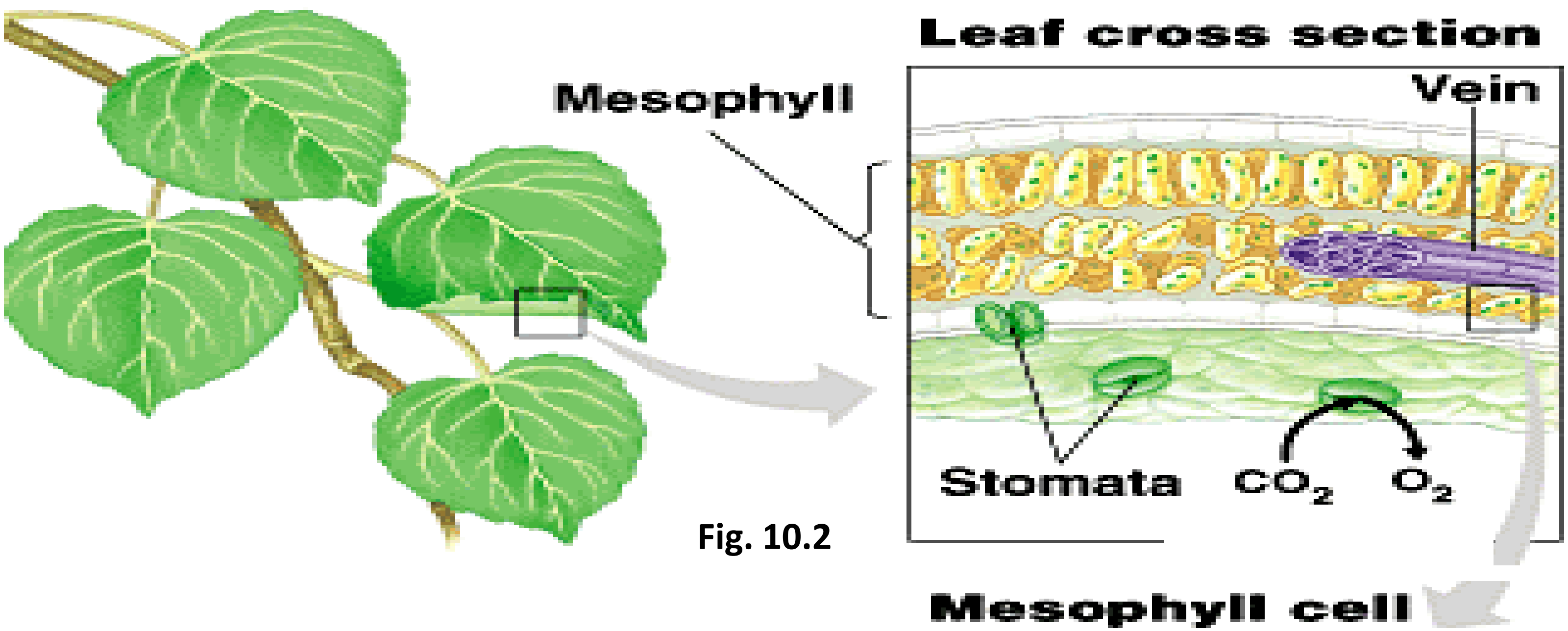
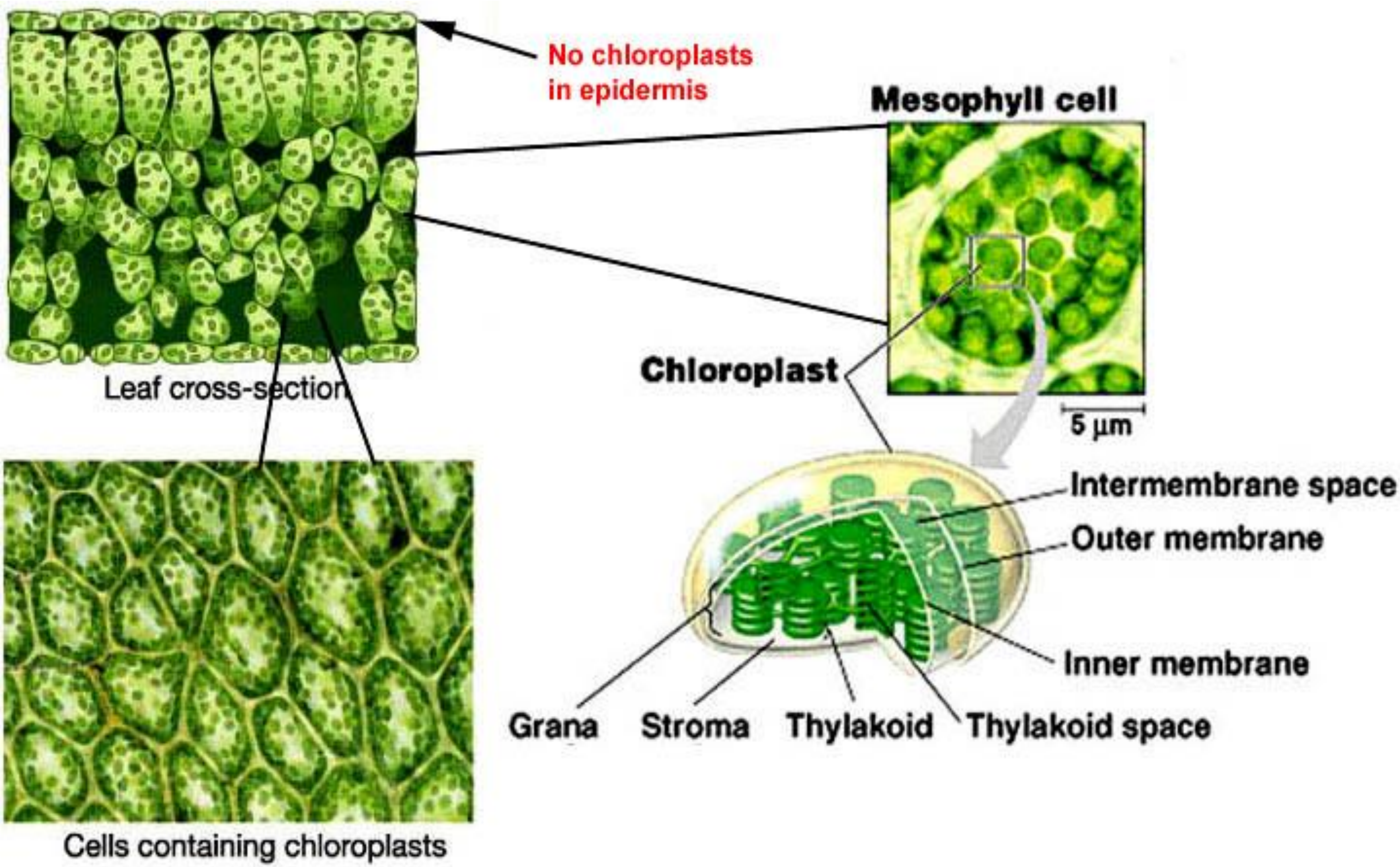


Fig. 10.2

Plant Cells


No chloroplasts
in epidermis
Mesophyll cell
Leaf cross-section
Chloroplast
5 µm
Intermembrane space
Outer membrane
Inner membrane
Grana
Stroma
Thylakoid
Thylakoid space
Cells containing chloroplasts

- A typical mesophyll cell has 30-40 chloroplasts, each about 2-4 microns by 4-7 microns long .
- Each chloroplast has two membranes around a central aqueous space, the stroma.
- In the stroma are membranous sacs, the thylakoids.
- These have an internal aqueous space, the thylakoid lumen or thylakoid space.
- Thylakoids may be stacked into columns called grana.

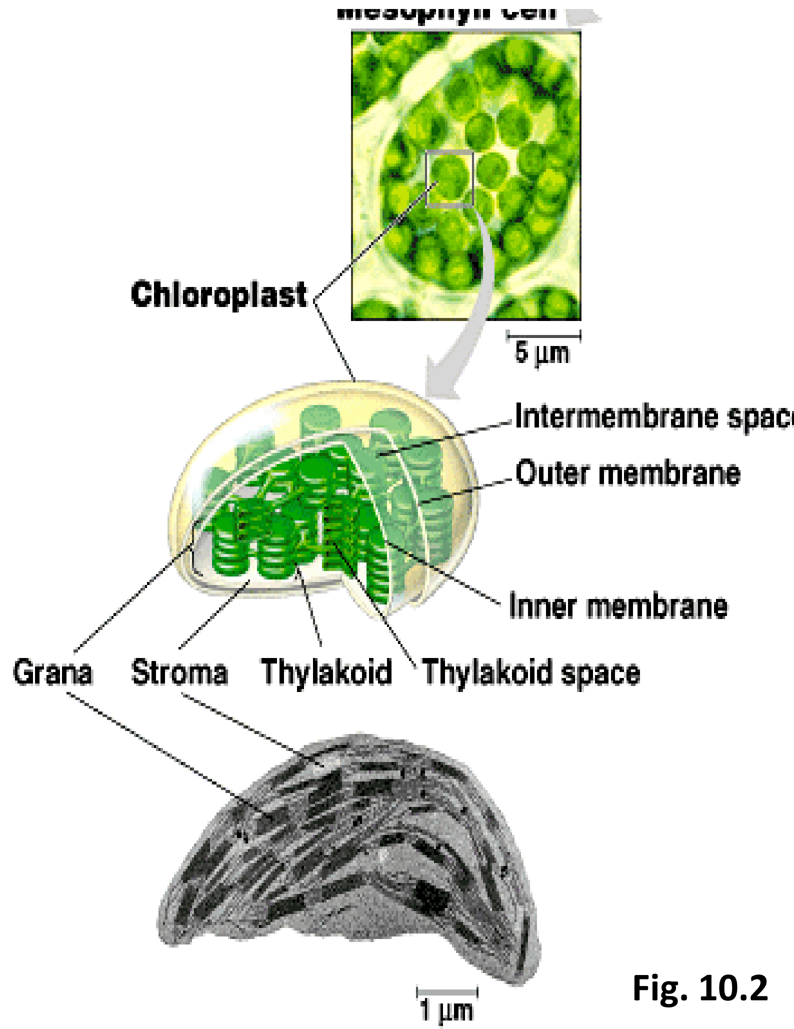
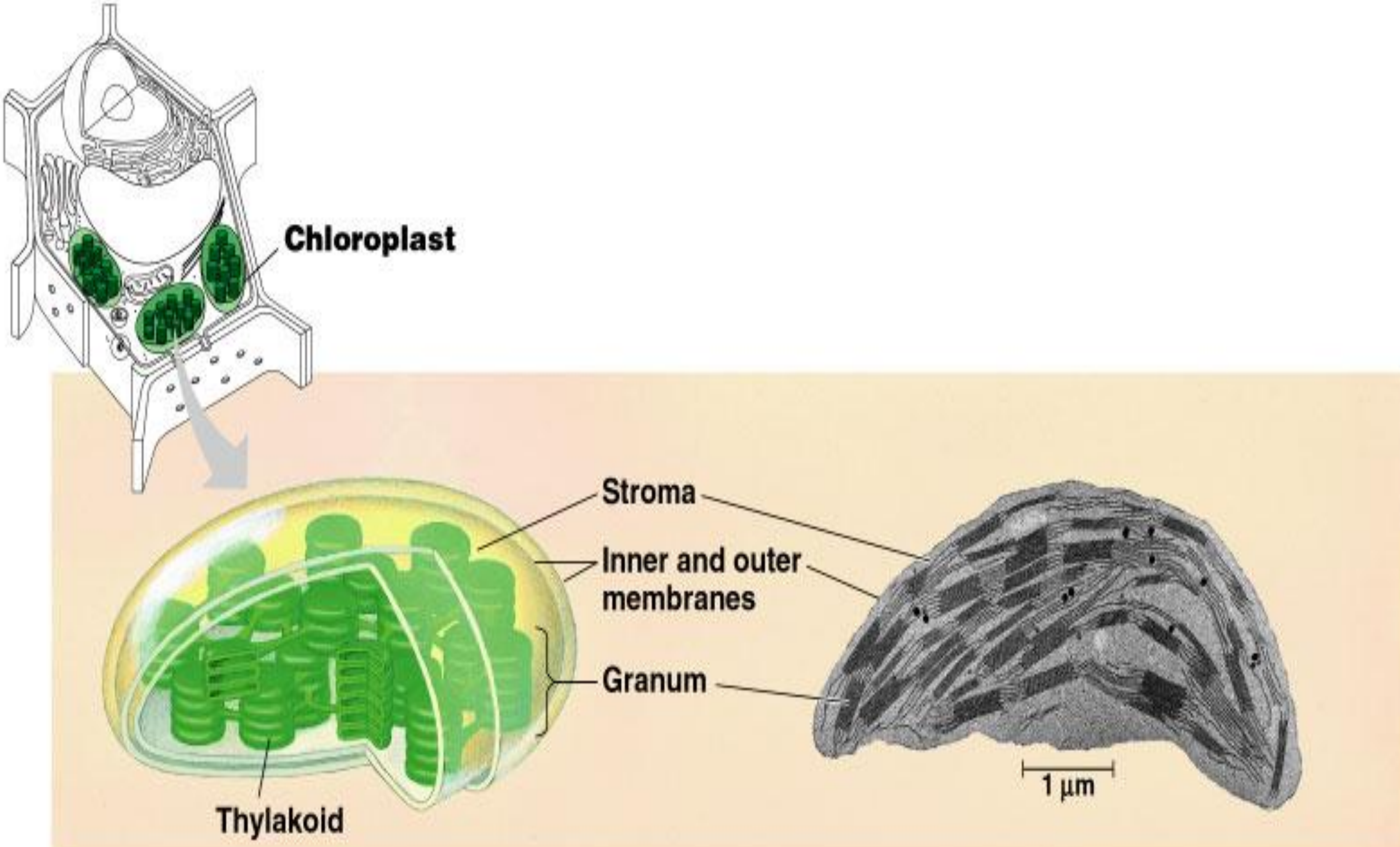


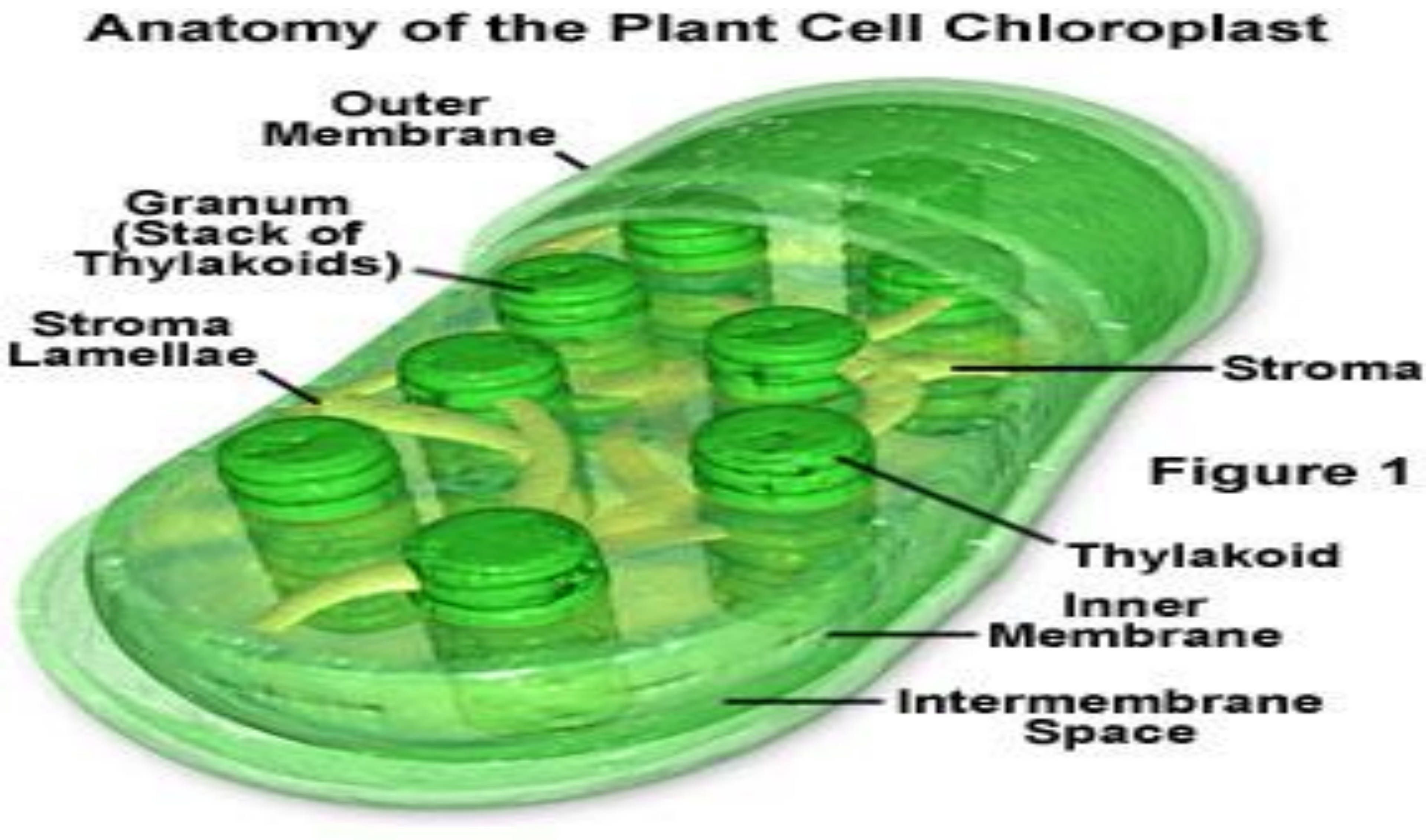
Fig. 10.2

Chloroplasts make the sugars!



Structure of chloroplast

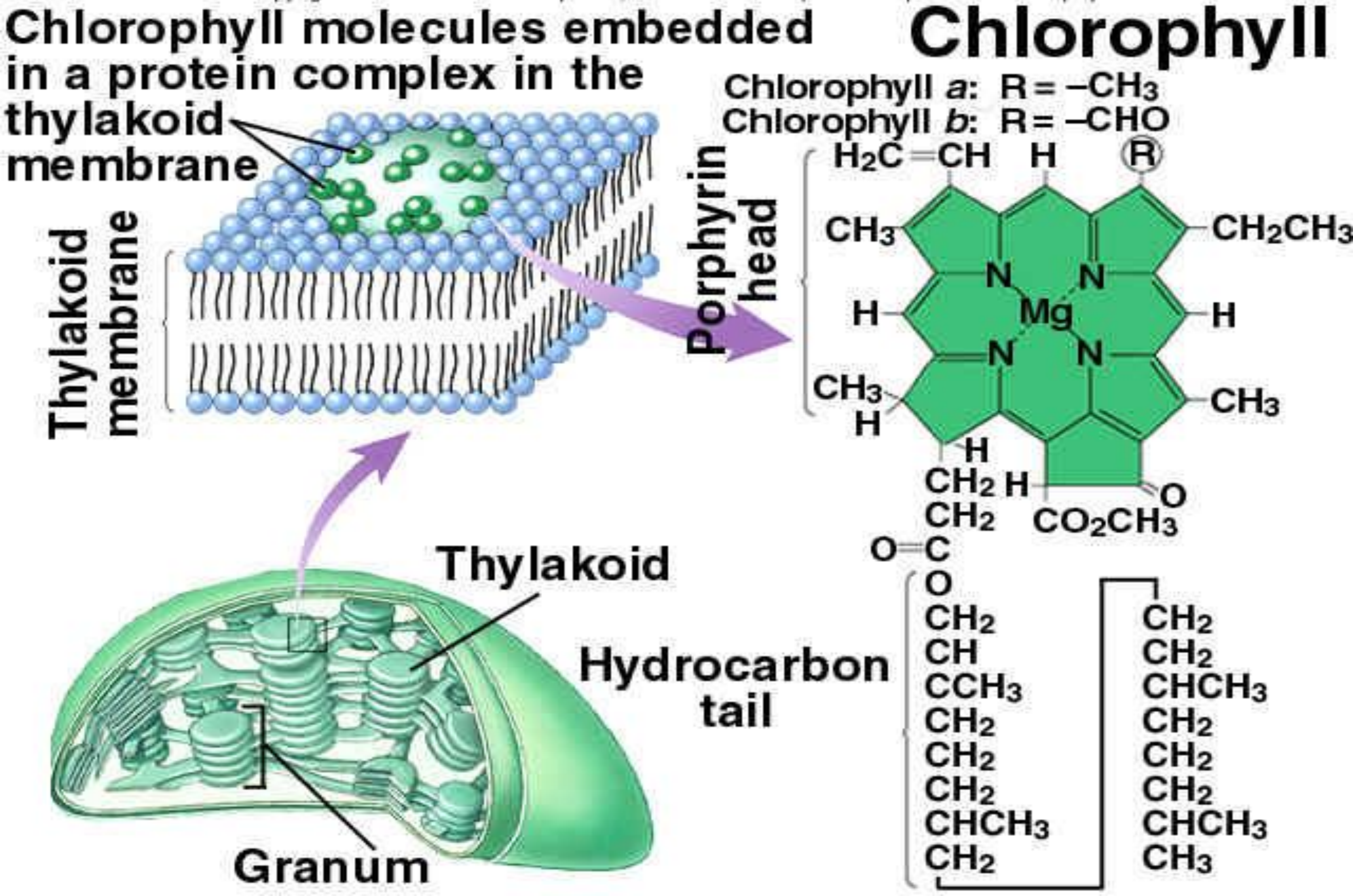
Chloroplast: organelle responsible for photosynthesis



PHOTOSYNTHESIS

- Absorbing Light Energy to make chemical energy: glucose!
  - Pigments: Absorb different colors of white light
    - Main pigment: Chlorophyll a
    - Accessory pigments: Chlorophyll b, Carotenoids & Phycobilins
    - Caretenoids are of two types: Carotenes and xanthophyll
    - These accessory pigments absorb and provide light energy to chlorophyll molecules
    - These pigments absorb all wavelengths (light) BUT green!

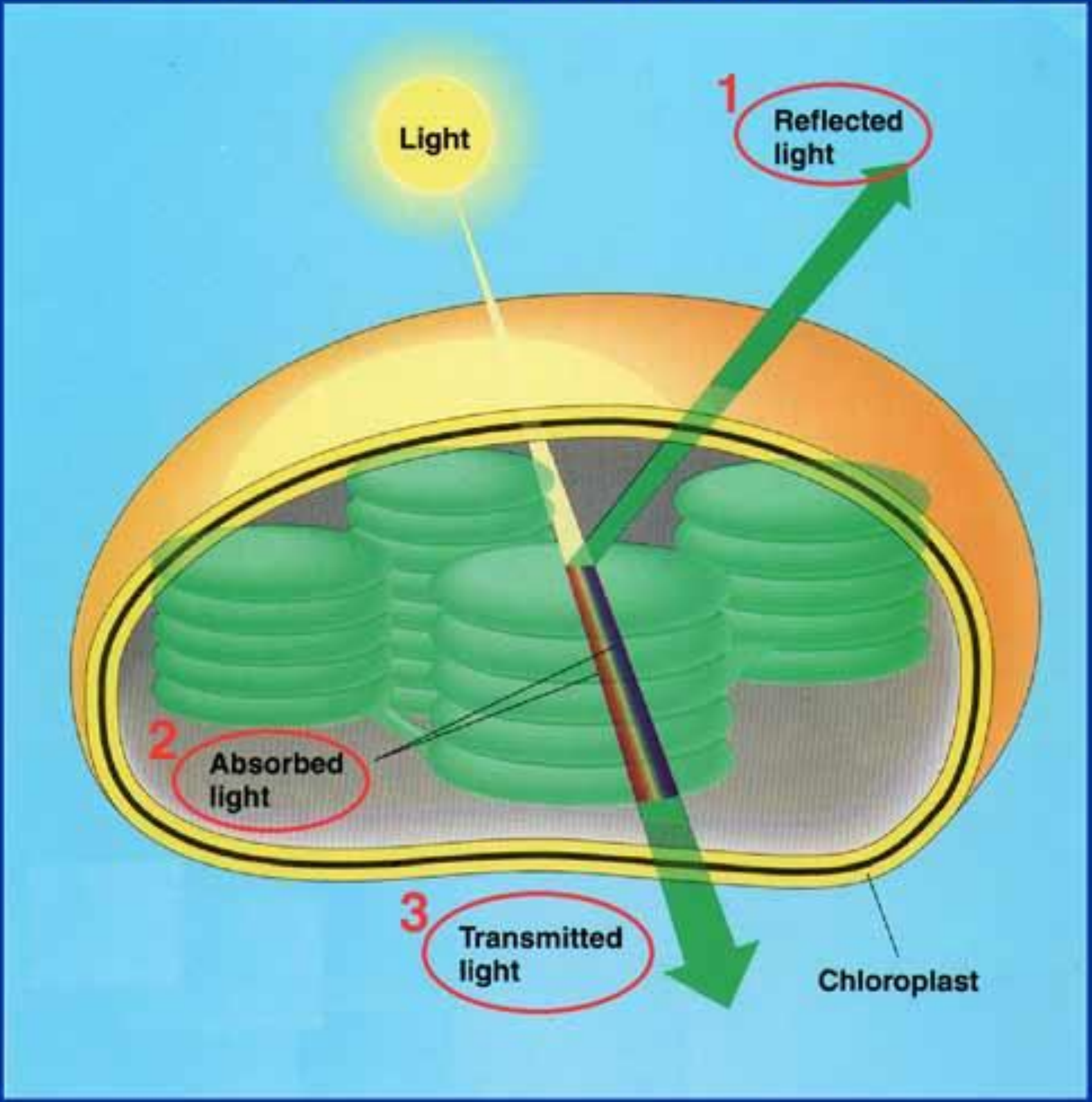
Chlorophyll: A Light Absorbing Pigment The Solar Panel Chemical!



- When light meets matter, it may be reflected, transmitted, or absorbed.
  - Different pigments absorb photons of different wavelengths.
  - A leaf looks **green** because chlorophyll, the dominant pigment, absorbs **red** and **blue** light, while transmitting and reflecting **green** light.

Fig. 10.6

INTERACTION OF LIGHT WITH MATTER IN CHLOROPLAST; LIGHT DIVIDED INTO THREE PARTS

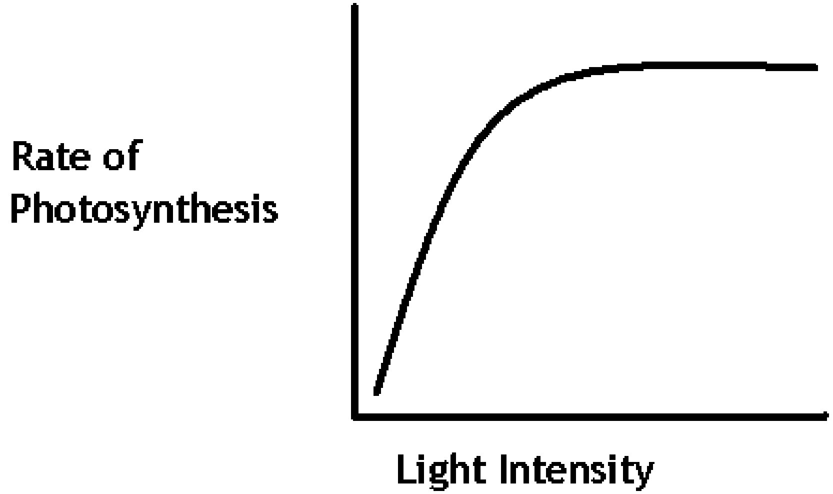


Steps of Photosynthesis

1. Light reaction (depends on light)
   - Traps sunlight
   - Produces electrons and ATP required to power the dark reaction
   - Oxygen released
2. Dark reaction, Calvin Cycle (does not **directly** depend on light)
   - Uses ATP and electrons from light reaction and Carbondioxide to make glucose

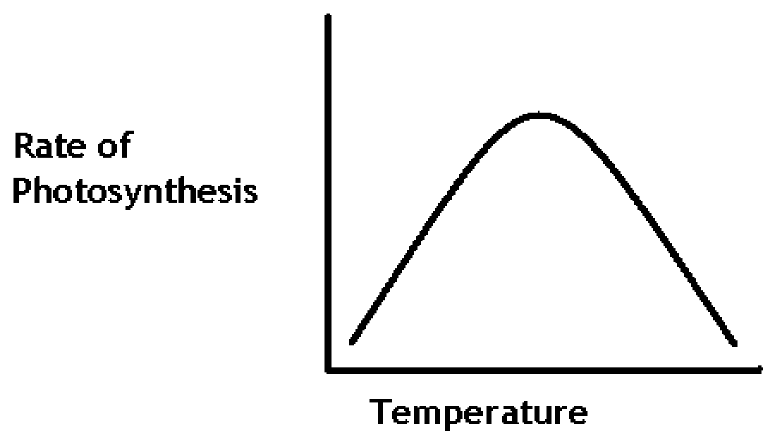
PHOTOSYNTHESIS

- What affects photosynthesis?
  - Light intensity: as light increases, rate of photosynthesis increases



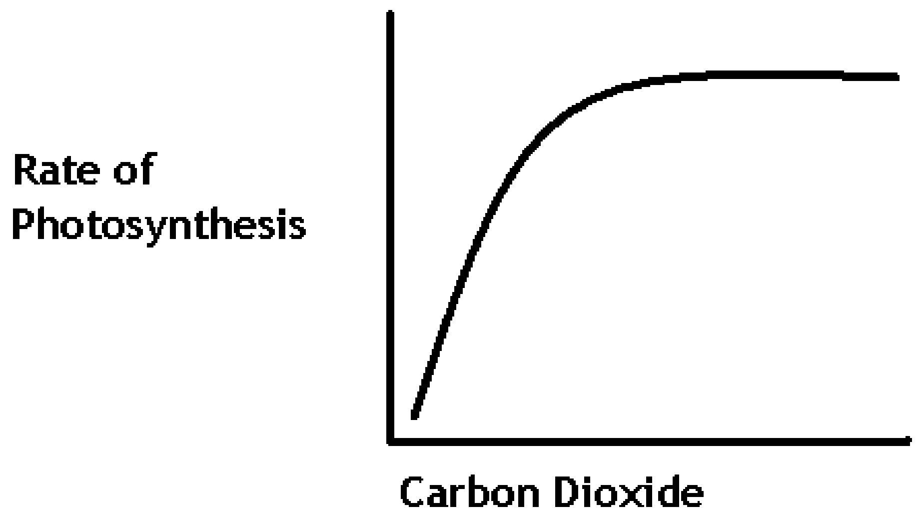
PHOTOSYNTHESIS

- What affects photosynthesis?
  - Temperature:
    - Temperature Low = Rate of photosynthesis low
    - Temperature Increases = Rate of photosynthesis increases
    - If tem



PHOTOSYNTHESIS

- What affects photosynthesis?
  - Carbon Dioxide: As CO_2 increases, rate of photosynthesis increases



PHOTOSYNTHESIS

- Light-dependent reaction (LIGHT Reaction)
  - Requires light
  - Occurs in chloroplast (in thylakoids)
  - Chlorophyll (thylakoid) traps energy from light
  - Light excites electron (e-)
    - Moves e- out of chlorophyll to an electron transport chain
    - Electron transport chain: series of proteins in thylakoid membrane
      - Bucket brigade

PHOTOSYNTHESIS

- Light-dependent reaction (LIGHT Reaction)
  - Energy is lost along electron transport chain
  - Lost energy used to recharge ATP from ADP

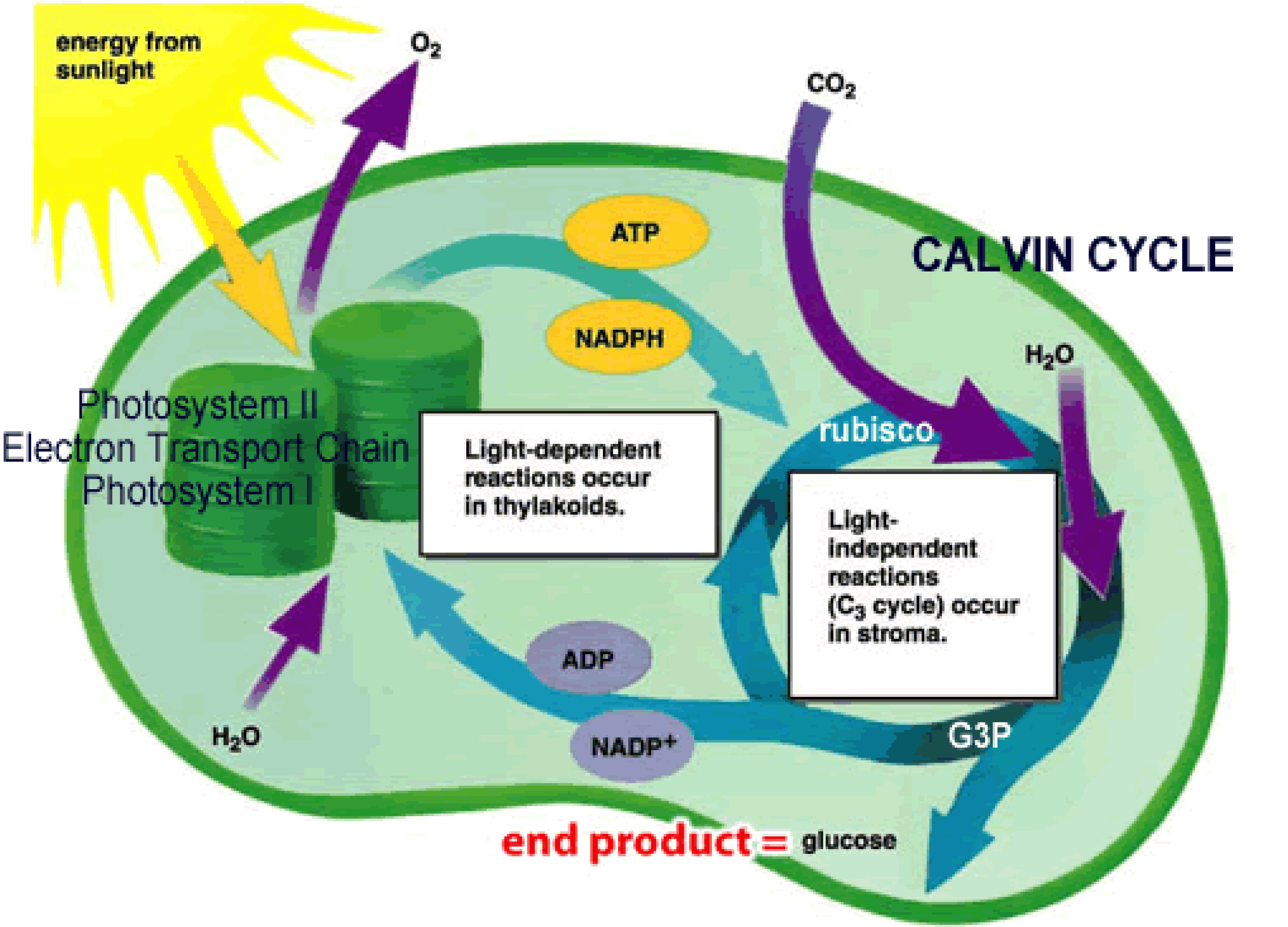
  - NADPH produced from e- transport chain
    - Stores energy until transfer to stroma
    - Plays important role in light-independent reaction

  - Total byproducts: ATP, NADPH, O_2

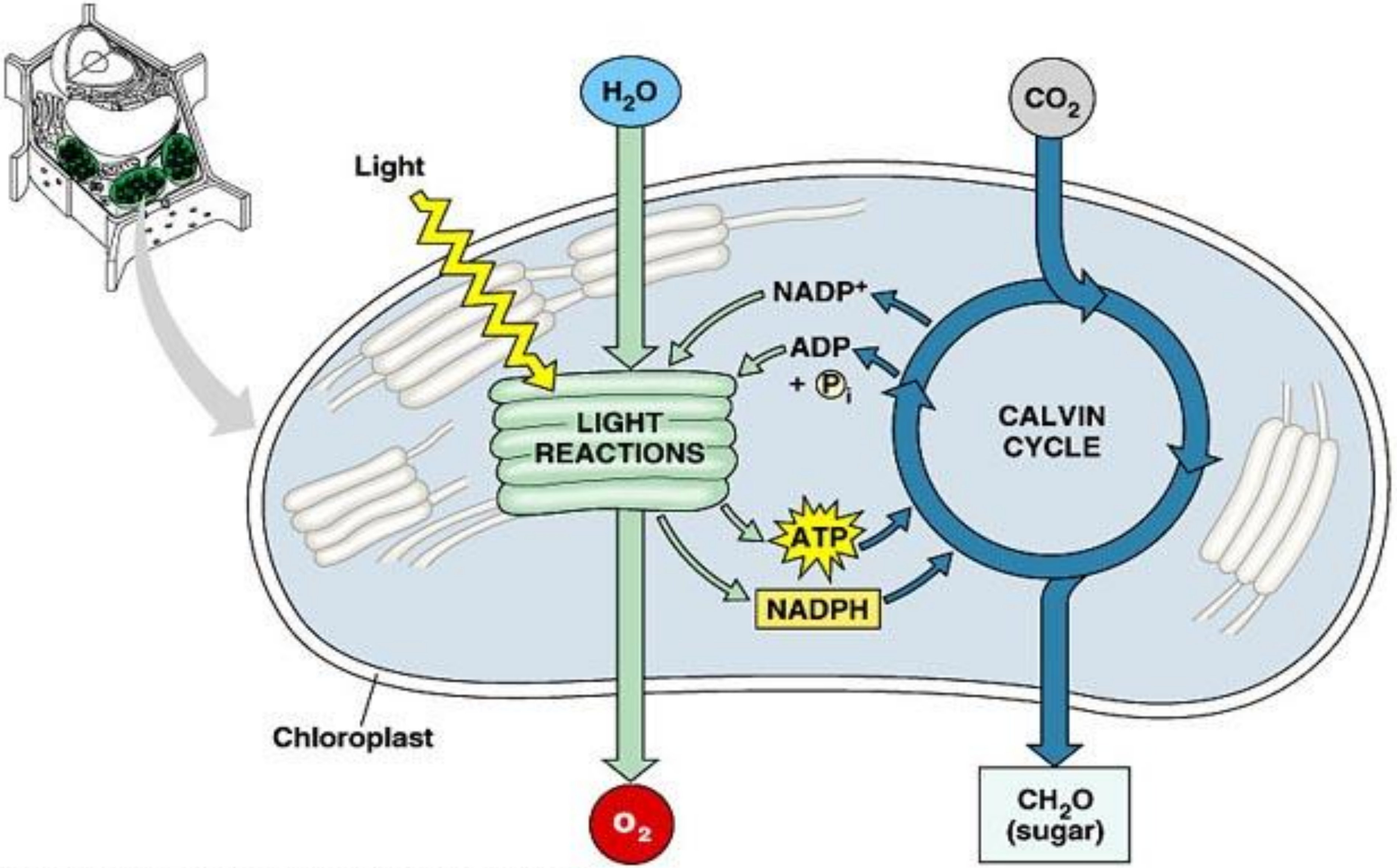
PHOTOSYNTHESIS

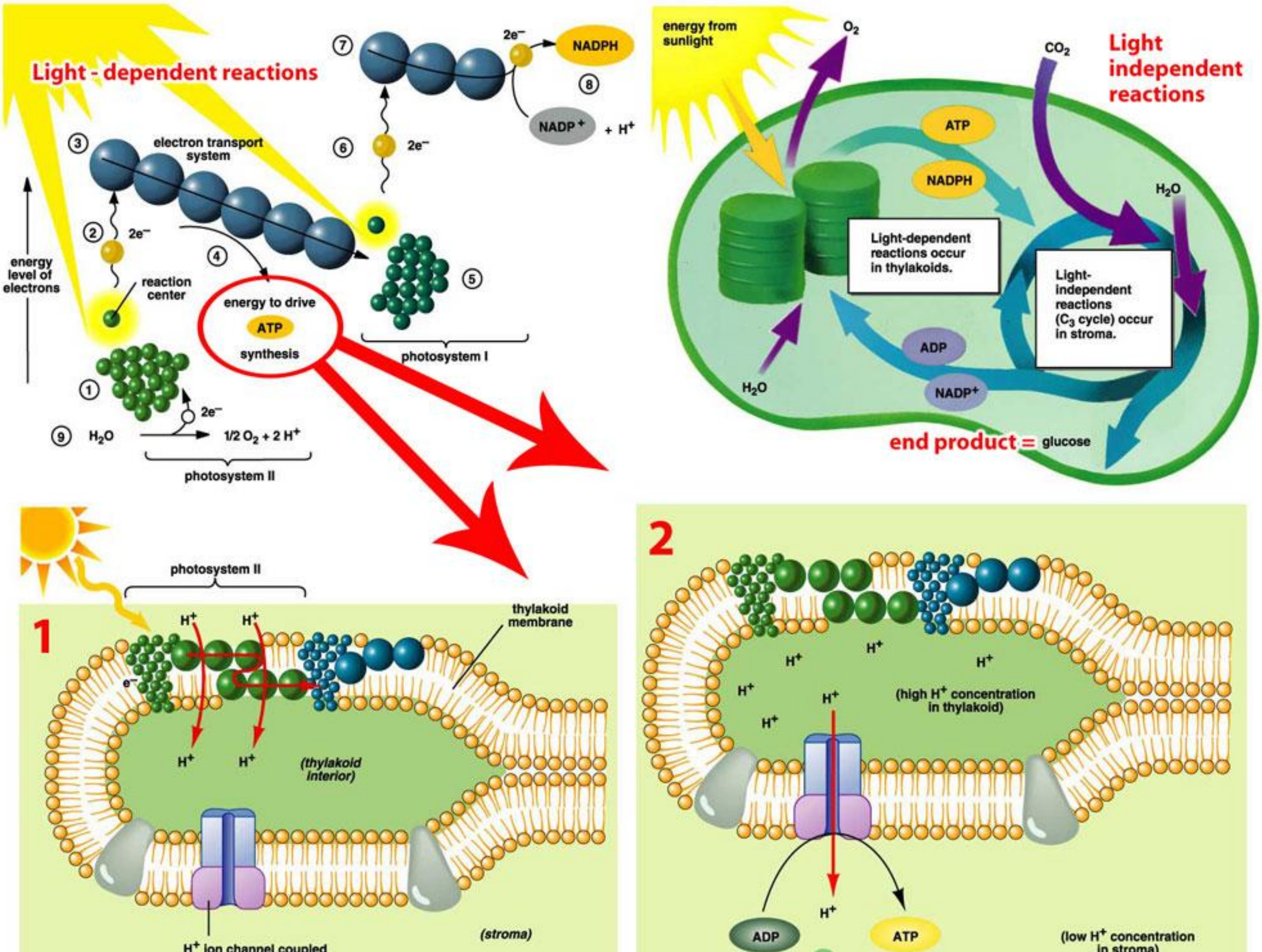
- Light-independent reaction (Dark Reaction)
  - Does not require light
  - Calvin Cycle
    - Occurs in stroma of chloroplast
    - Requires CO_2
    - Uses ATP and NADPH as fuel to run
    - Makes glucose from CO_2 and Hydrogen

- In the light reaction light energy absorbed by chlorophyll in the thylakoids drives the transfer of electrons and hydrogen from water to **NADP$^+$** (nicotinamide adenine dinucleotide phosphate), forming NADPH.
  - NADPH, an electron acceptor, provides energized electrons, reducing power, to the Calvin cycle.
- The light reaction also generates ATP by **photophosphorylation** for the Calvin cycle.


energy from sunlight
O_2
CO_2
CALVIN CYCLE
ATP
NADPH
H_2O
Photosystem II
Electron Transport Chain
Photosystem I
Light-dependent reactions occur in thylakoids.
rubisco
Light-independent reactions (C_3 cycle) occur in stroma.
ADP
$NADP^+$
H_2O
G3P
end product = glucose

Oxygen and Sugar!





Light - dependent reactions
energy level of electrons
electron transport system
2e⁻
reaction center
energy to drive
ATP
synthesis
photosystem I
photosystem II
NADPH
NADP⁺
+ H⁺
H₂O
1/2 O₂ + 2 H⁺
energy from sunlight
O₂
CO₂
Light independent reactions
ATP
NADPH
H₂O
Light-dependent reactions occur in thylakoids.
Light-independent reactions (C₃ cycle) occur in stroma.
ADP
NADP⁺
end product = glucose
1
photosystem II
thylakoid membrane
H⁺
e⁻
(thylakoid interior)
(stroma)
2
(high H⁺ concentration in thylakoid)
ADP
ATP

- The light reactions use the solar power of photons absorbed by both photosystem I and photosystem II to provide chemical energy in the form of ATP and reducing power in the form of the electrons carried by NADPH.

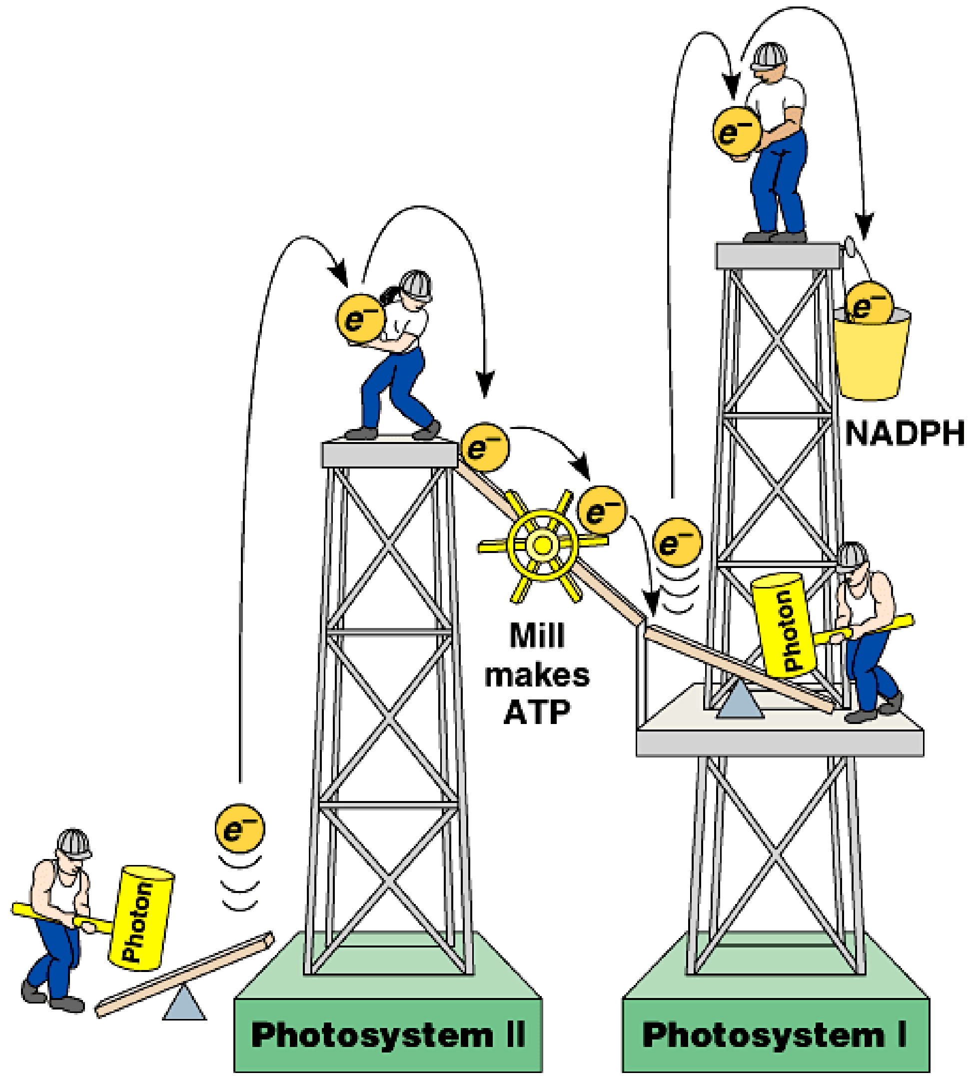


Fig. 10.13

- In the thylakoid membrane, chlorophyll is organized along with proteins and smaller organic molecules into **photosystems**.
- A photosystem acts like a light-gathering "antenna complex" consisting of a few hundred chlorophyll *a,* chlorophyll *b,* and carotenoid molecules.

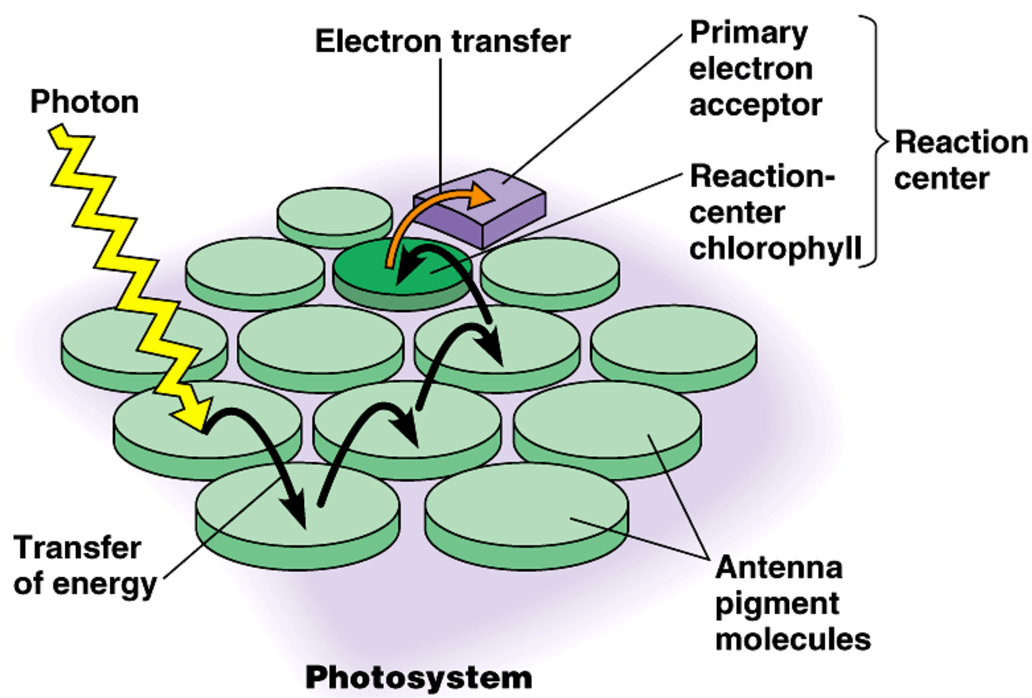
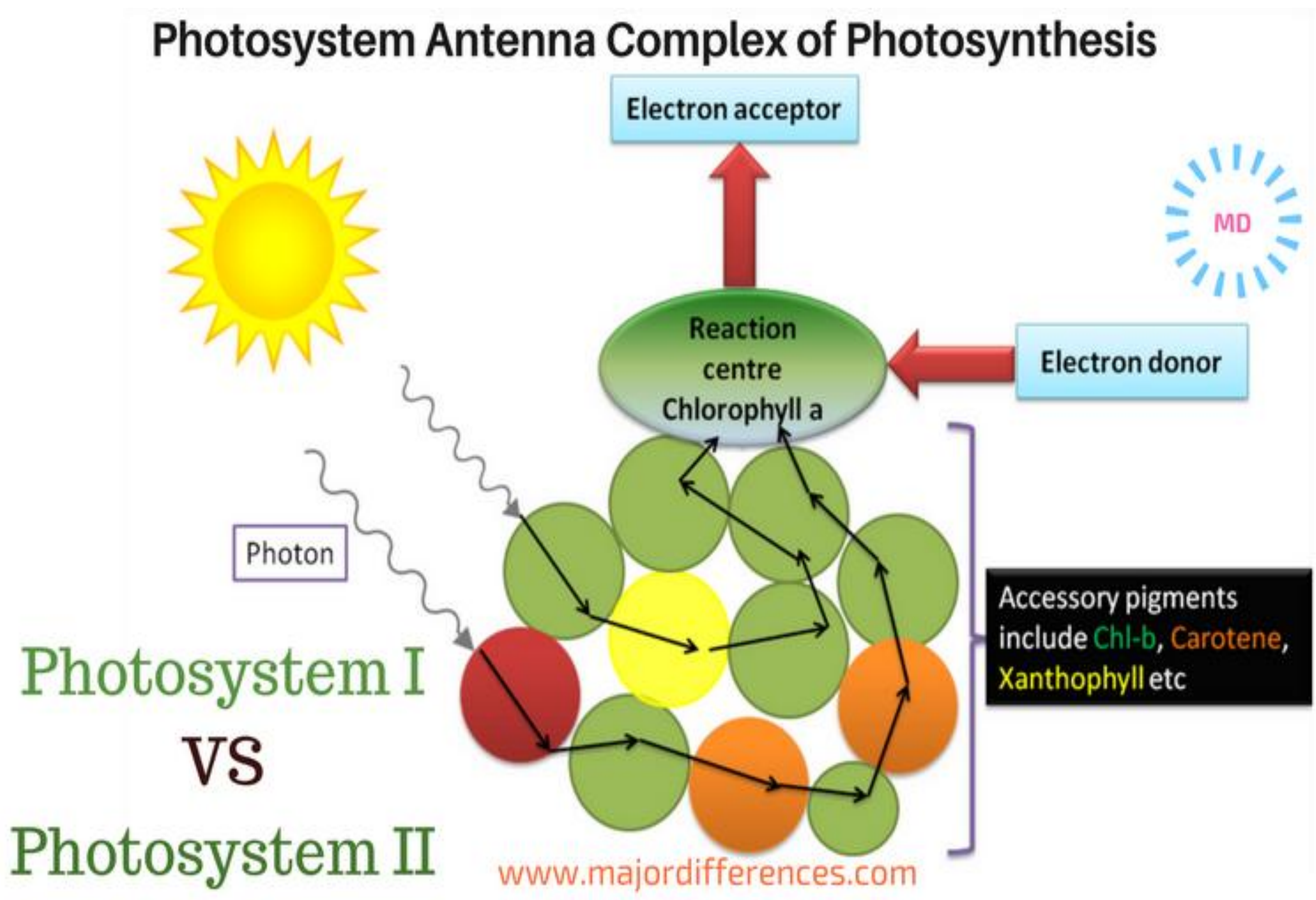
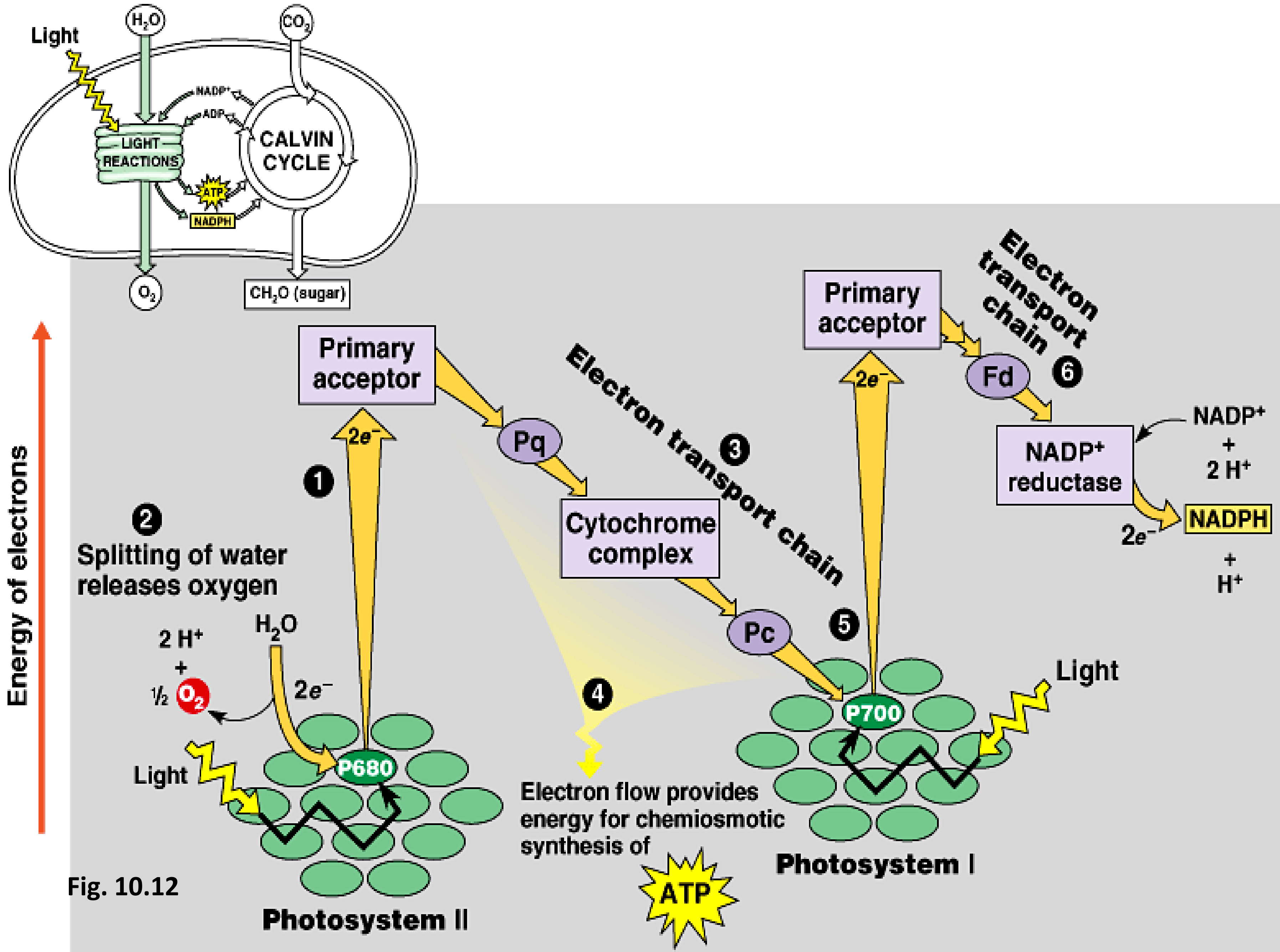


Fig. 10.11


Photosystem Antenna Complex of Photosynthesis
Electron acceptor
MD
Reaction
centre
Chlorophyll a
Electron donor
Photon
Accessory pigments
include Chl-b, Carotene,
Xanthophyll etc
Photosystem I
VS
Photosystem II
www.majordifferences.com

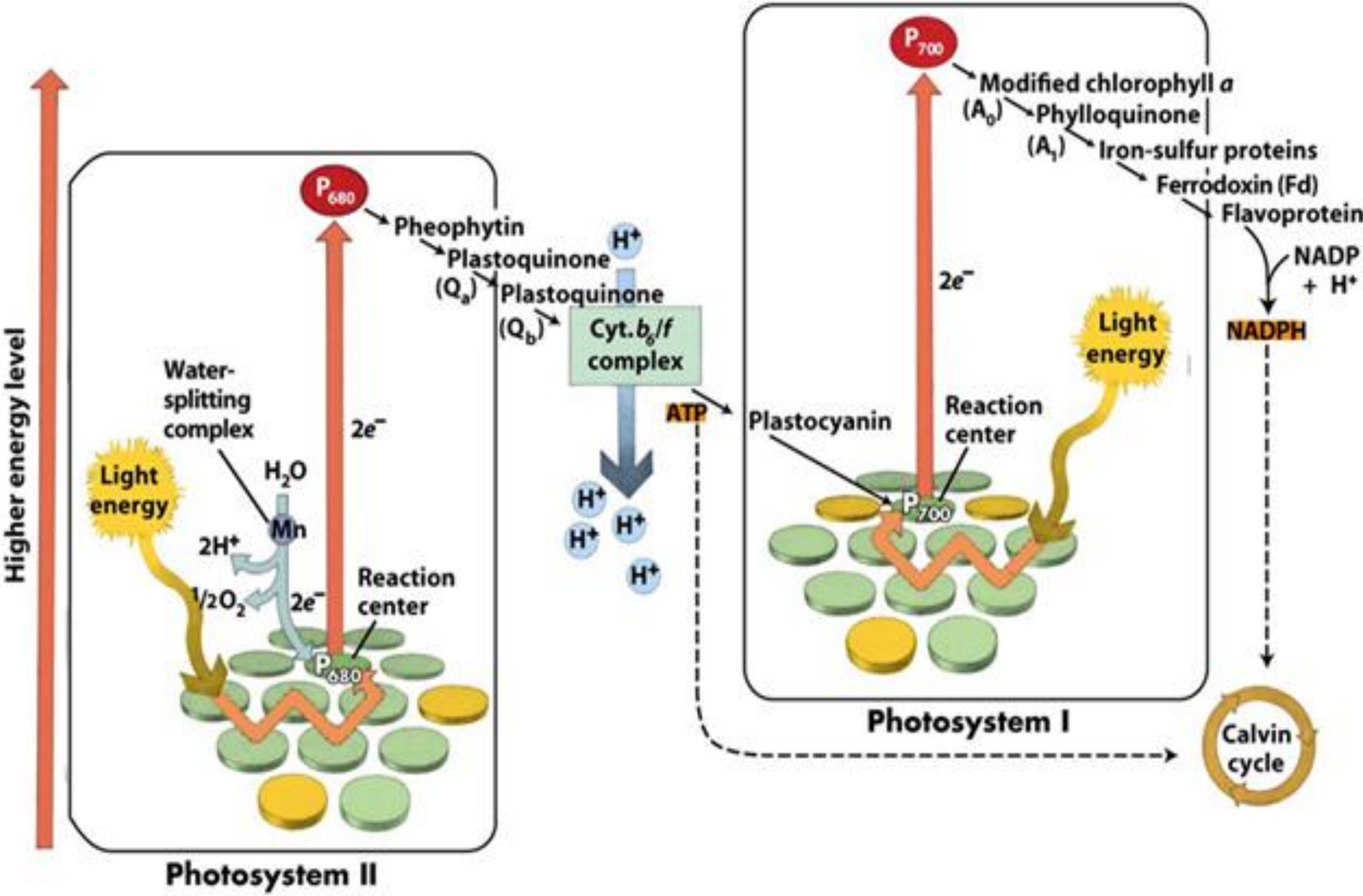
- There are two types of photosystems. Each requires a specific wavelength of light.
- **Photosystem I**
- **Photosystem II**
- These two photosystems work together to use light energy to generate ATP and NADPH to be used in the Calvin Cycle.

➢ Photosytem II comes before photosystem I

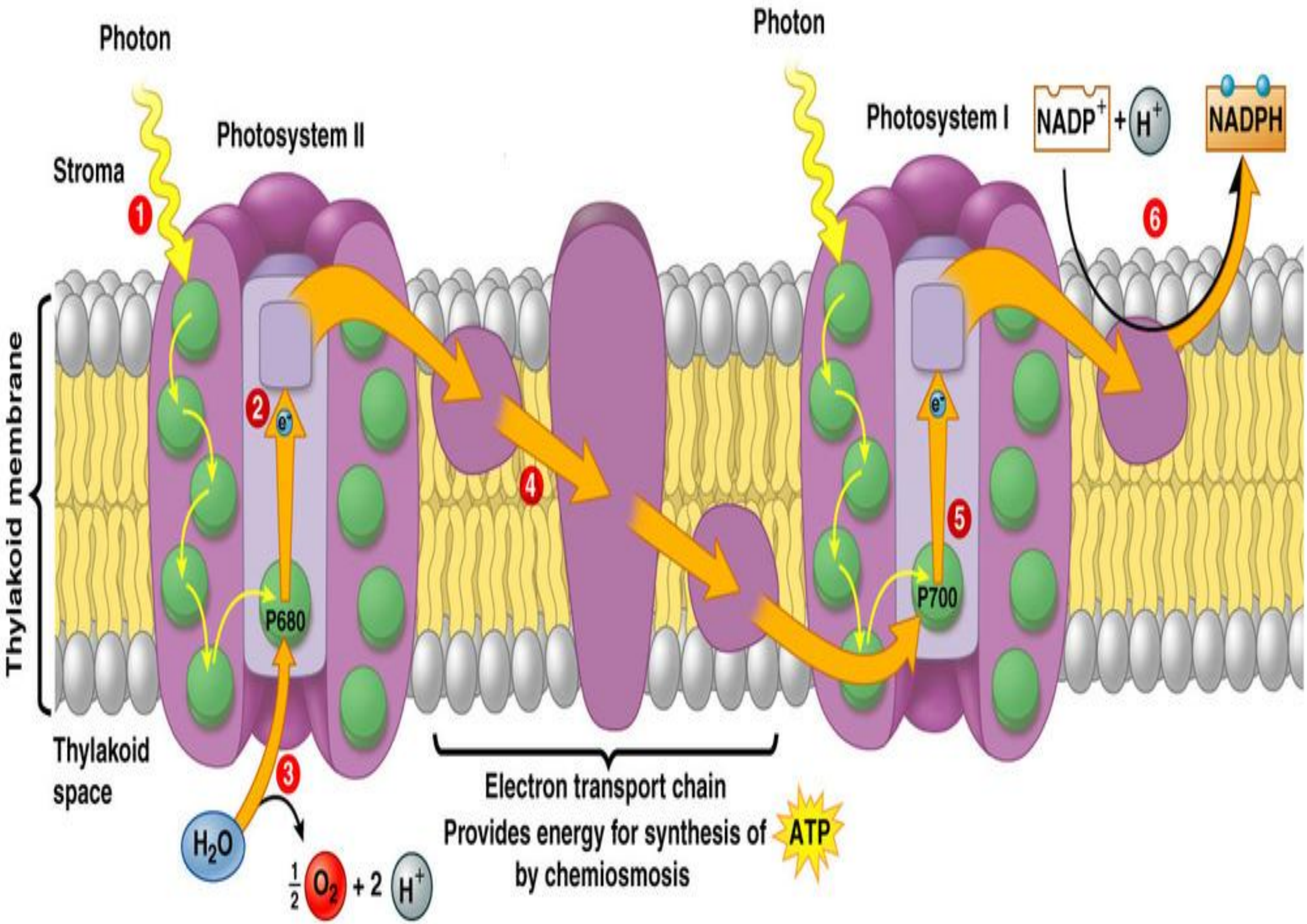


Light
H2O
CO2
NADP+
ADP
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
O2
CH2O (sugar)
Energy of electrons
Primary acceptor
2e−
1
2
Splitting of water releases oxygen
2 H+ + ½ O2
H2O
2e−
Light
P680
Photosystem II
Pq
Cytochrome complex
Pc
Electron transport chain
3
4
Electron flow provides energy for chemiosmotic synthesis of
ATP
Primary acceptor
2e−
5
P700
Light
Photosystem I
Electron transport chain
Fd
6
NADP+ reductase
NADP+ + 2 H+
2e−
NADPH
+ H+

Fig. 10.12



Higher energy level
P680
Pheophytin
Plastoquinone (Qa)
Plastoquinone (Qb)
Cyt. b6/f complex
H+
Water-splitting complex
H2O
Mn
2H+
1/2O2
2e−
Light energy
Reaction center
P680
Photosystem II
ATP
Plastocyanin
P700
Modified chlorophyll a (A0)
Phylloquinone (A1)
Iron-sulfur proteins
Ferrodoxin (Fd)
Flavoprotein
NADP+ + H+
NADPH
Light energy
Reaction center
P700
Photosystem I
Calvin cycle


Photon
Photon
Photosystem II
Photosystem I
NADP$^+$ + H$^+$
NADPH
Stroma
1
6
Thylakoid membrane
2
e^-
4
e^-
5
P680
P700
Thylakoid space
3
Electron transport chain
Provides energy for synthesis of ATP by chemiosmosis
H_2O
$\frac{1}{2}$ O_2 + 2 H^+

- During the light reactions, there are two possible routes for electron flow: cyclic and noncyclic.
- **Noncyclic electron flow**, the predominant route, produces both ATP and NADPH.

  1. When photosystem II (1^{st} part) absorbs light, an excited electron is captured by the primary electron acceptor, leaving an electron "vacancy"

  2. Water gets split into two hydrogen ions, two electrons and an oxygen atom
     - The two electrons will fill two "vacancies"
     - The oxygen atom combines with another to form O_2.

3. Photoexcited electrons pass along an electron transport chain before ending up at the photosystem I reaction center.

4. As these electrons pass along the transport chain, their energy is harnessed to produce ATP.

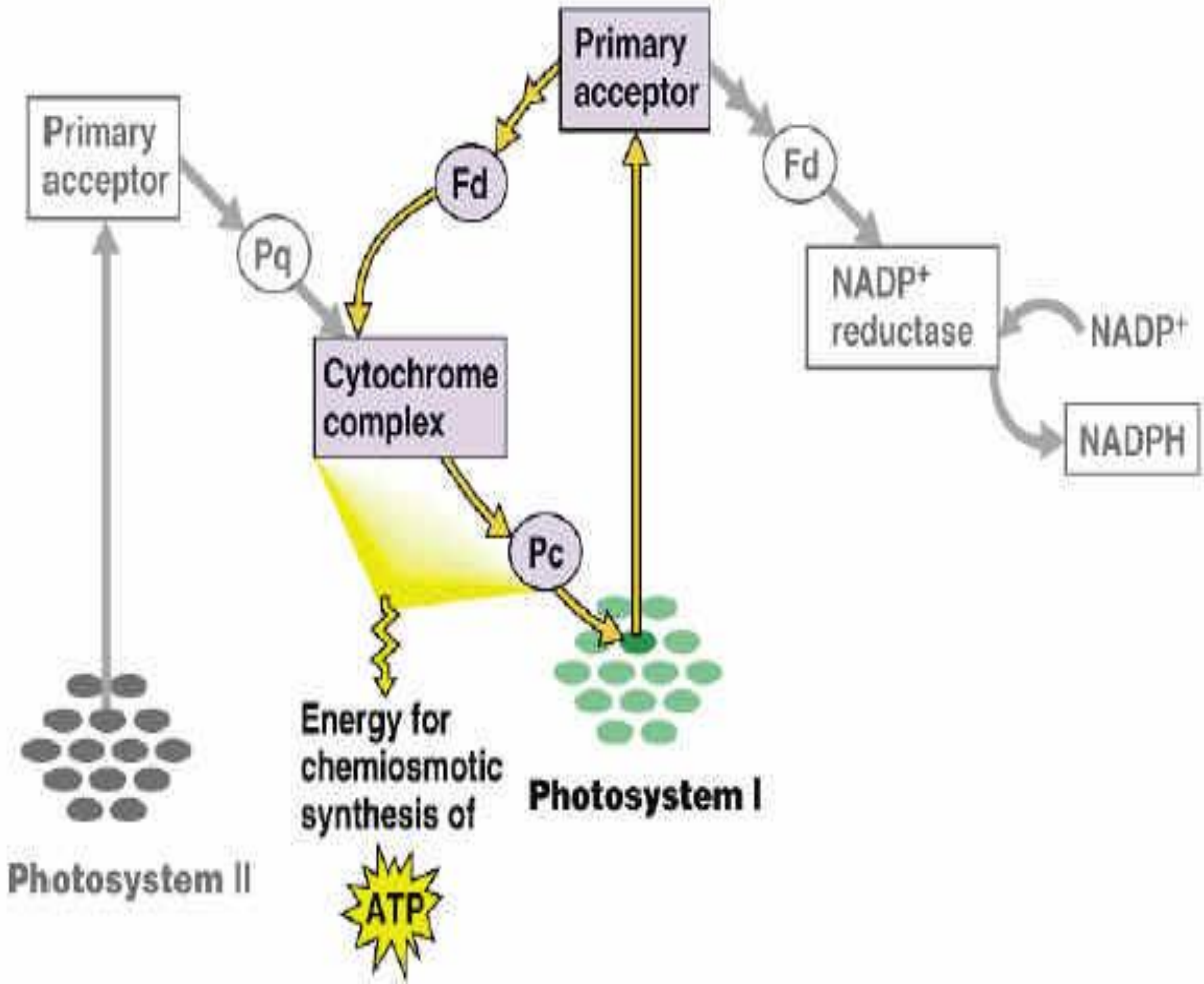
- The mechanism of **noncyclic photophosphorylation** is similar to the process on oxidative phosphorylation.

5. At the bottom of this electron transport chain, the electrons fill an electron "vacancy"

6. This "vacancy" is created when photons (light) excite electrons on the photosystem I complex.

- The excited electrons are captured by a **second** primary electron acceptor which transmits them to a **second** electron transport chain.
- Ultimately, these electrons are passed from the transport chain to NAD**P**$^+$, creating NAD**P**H.
  - NAD**P**H will carry the high-energy electrons to the Calvin cycle.

- Under certain conditions, photoexcited electrons from photosystem I, but not photosystem II, can take an alternative pathway, **cyclic electron flow**.
  - Excited electrons cycle from their reaction center to a primary acceptor, along an electron transport chain, and returns to their reaction center.
  - As electrons flow along the electron transport chain, they generate ATP by **cyclic photophosphorylation**.

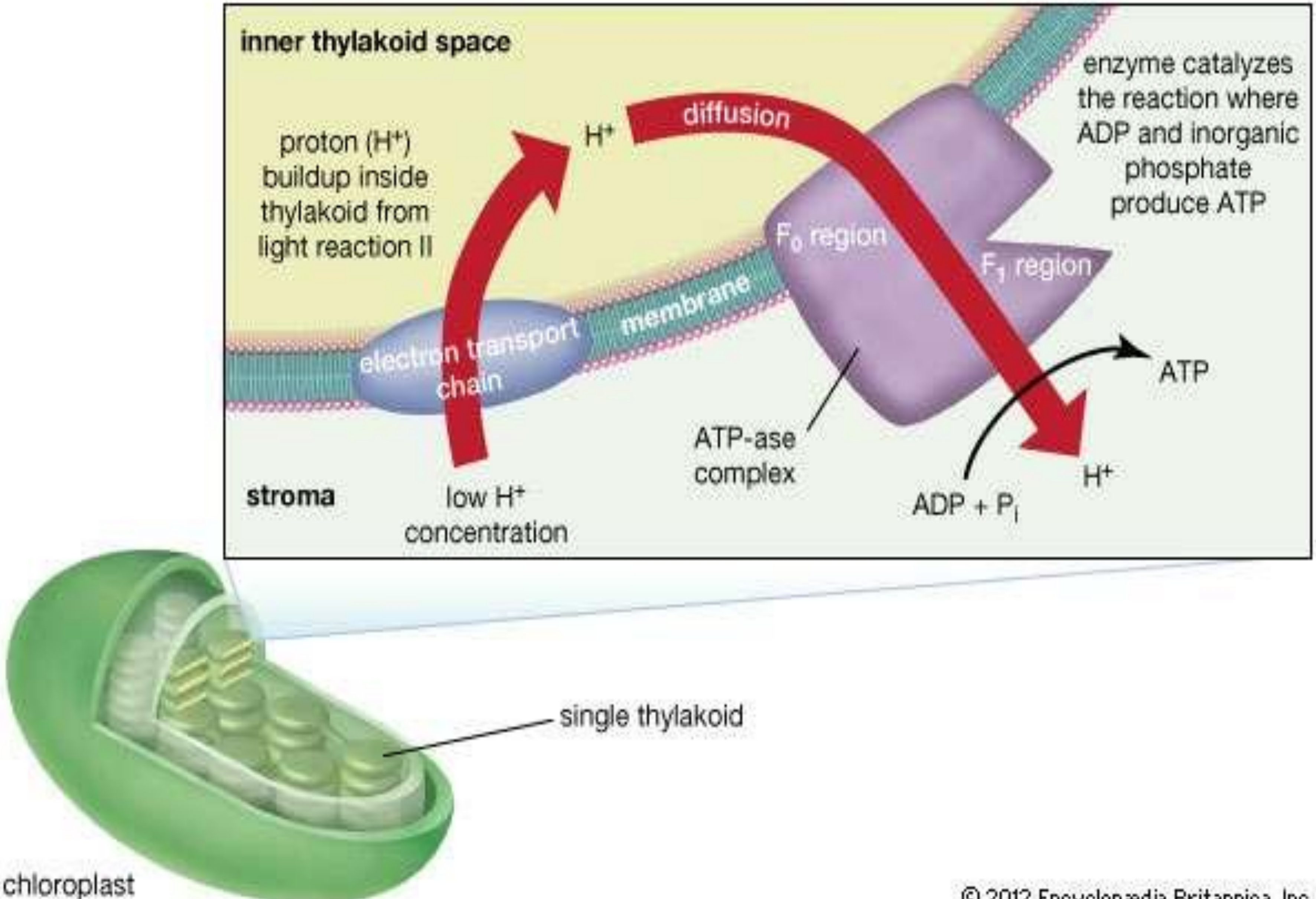


Primary acceptor
Pq
Cytochrome complex
Fd
Primary acceptor
Fd
NADP+ reductase
NADP+
NADPH
Pc
Energy for chemiosmotic synthesis of
ATP
Photosystem I
Photosystem II

- Noncyclic electron flow produces ATP and NADPH in roughly equal quantities.
- However, the Calvin cycle consumes more ATP than NADPH. What does this mean?
- Cyclic electron flow allows the chloroplast to generate enough surplus ATP to satisfy the higher demand for ATP in the Calvin cycle.

- Chloroplasts and mitochondria generate ATP by the same mechanism: chemiosmosis.
  - An electron transport chain pumps protons across a membrane as electrons are passed along a series of more electronegative carriers.
  - This builds the proton-motive force in the form of an H^+ gradient across the membrane.
  - ATP synthase molecules harness the proton-motive force to generate ATP as H^+ diffuses back across the membrane.
- Mitochondria transfer chemical energy from food molecules to ATP and chloroplasts transform light energy into the chemical energy of ATP.

Chemiosmosis in chloroplasts



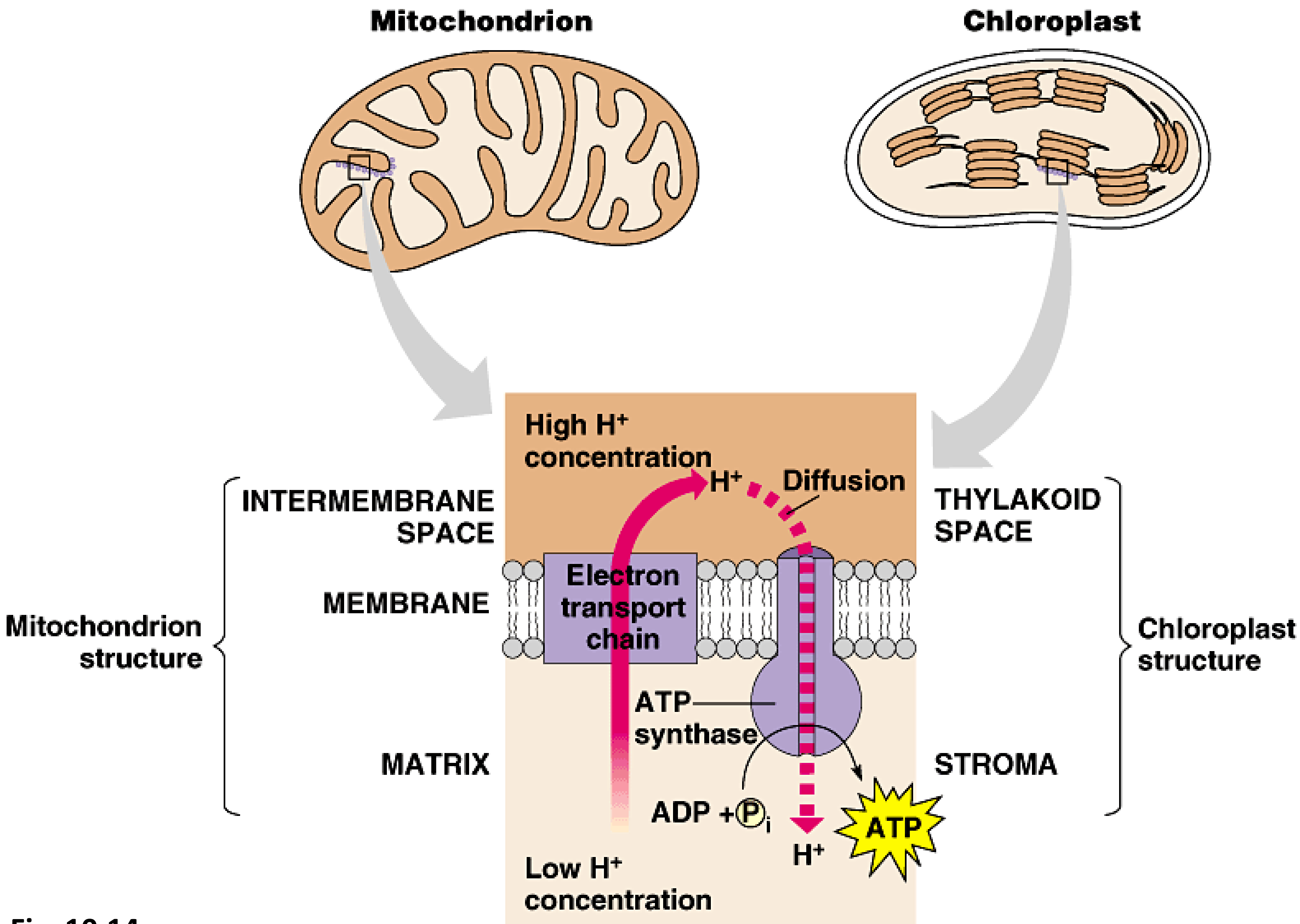
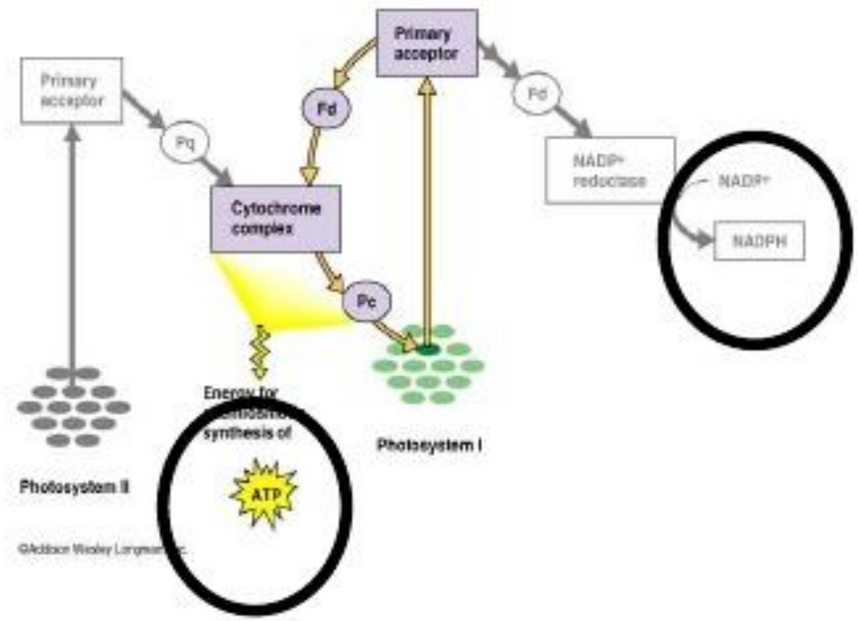

Mitochondrion
Chloroplast
High H+ concentration
H+
Diffusion
INTERMEMBRANE SPACE
THYLAKOID SPACE
MEMBRANE
Electron transport chain
Mitochondrion structure
Chloroplast structure
ATP synthase
MATRIX
STROMA
ADP + Pi
ATP
H+
Low H+ concentration

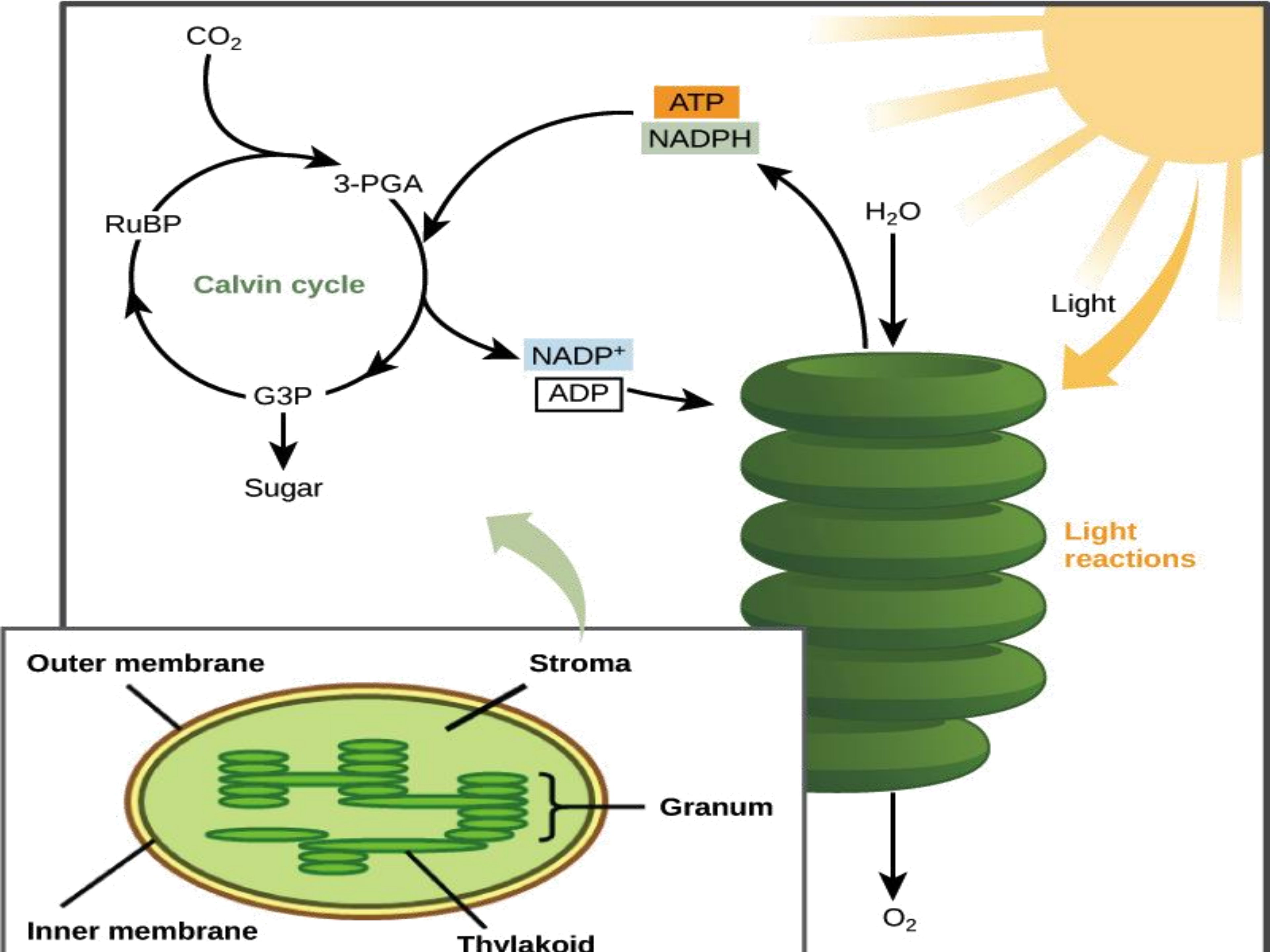
Fig. 10.14

- Noncyclic electron flow pushes electrons from water, where they are at low potential energy, to NADPH, where they have high potential energy.
  - This process also produces ATP.
  - Oxygen is a by-product.
- Cyclic electron flow converts light energy to chemical energy in the form of ATP.

Photosystems I & II work together

- Both photosystems absorb light
- Electron Transport Chain = electrons go down an energy hill = lose energy at each step - this energy is stored in ATP or NADPH
- Electrons released from PSI is replaced by electrons coming from PSII





CO_2
ATP
NADPH
3-PGA
RuBP
H_2O
Calvin cycle
Light
$NADP^+$
ADP
G3P
Sugar
Light reactions
Outer membrane
Stroma
Granum
Inner membrane
Thylakoid
O_2

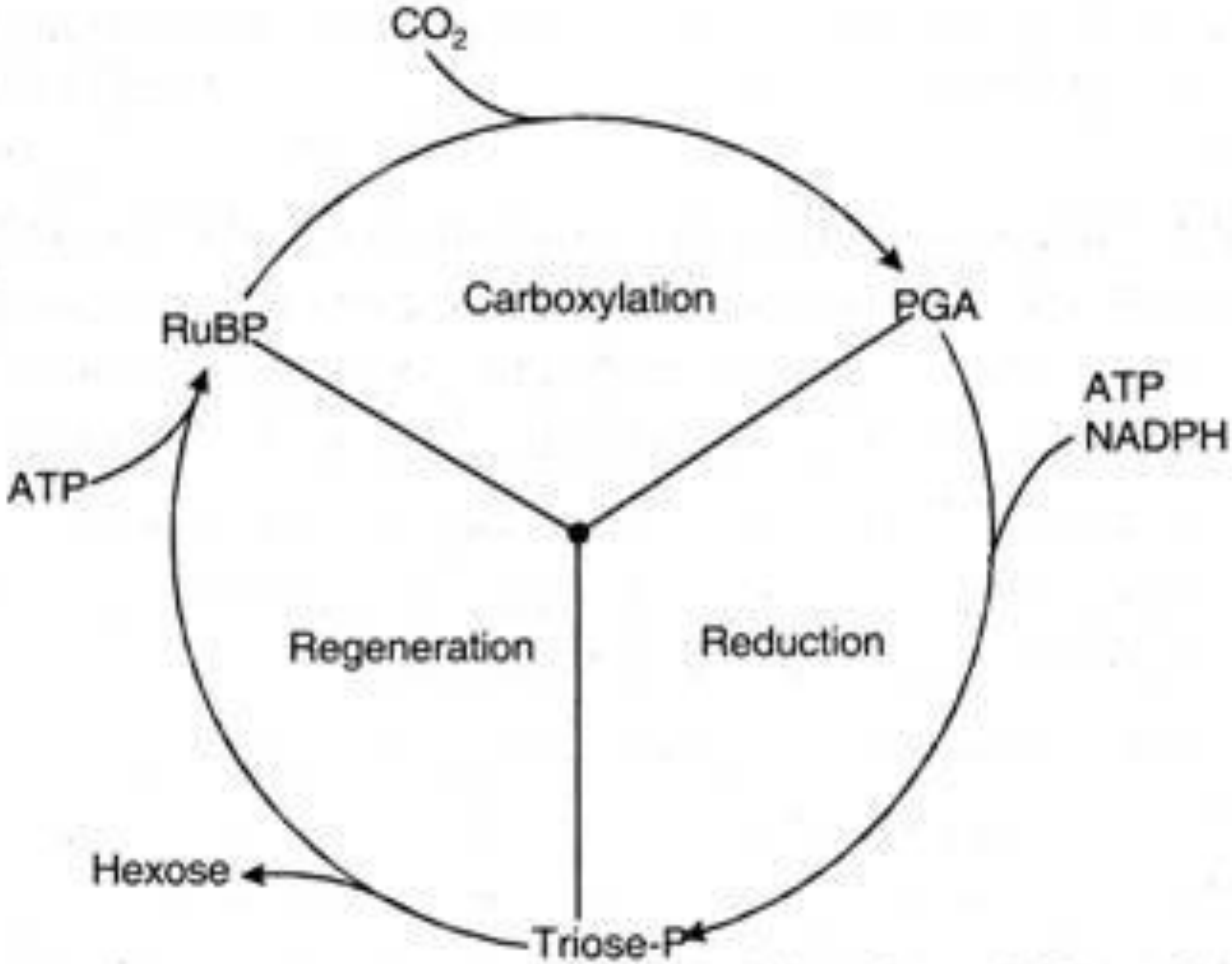
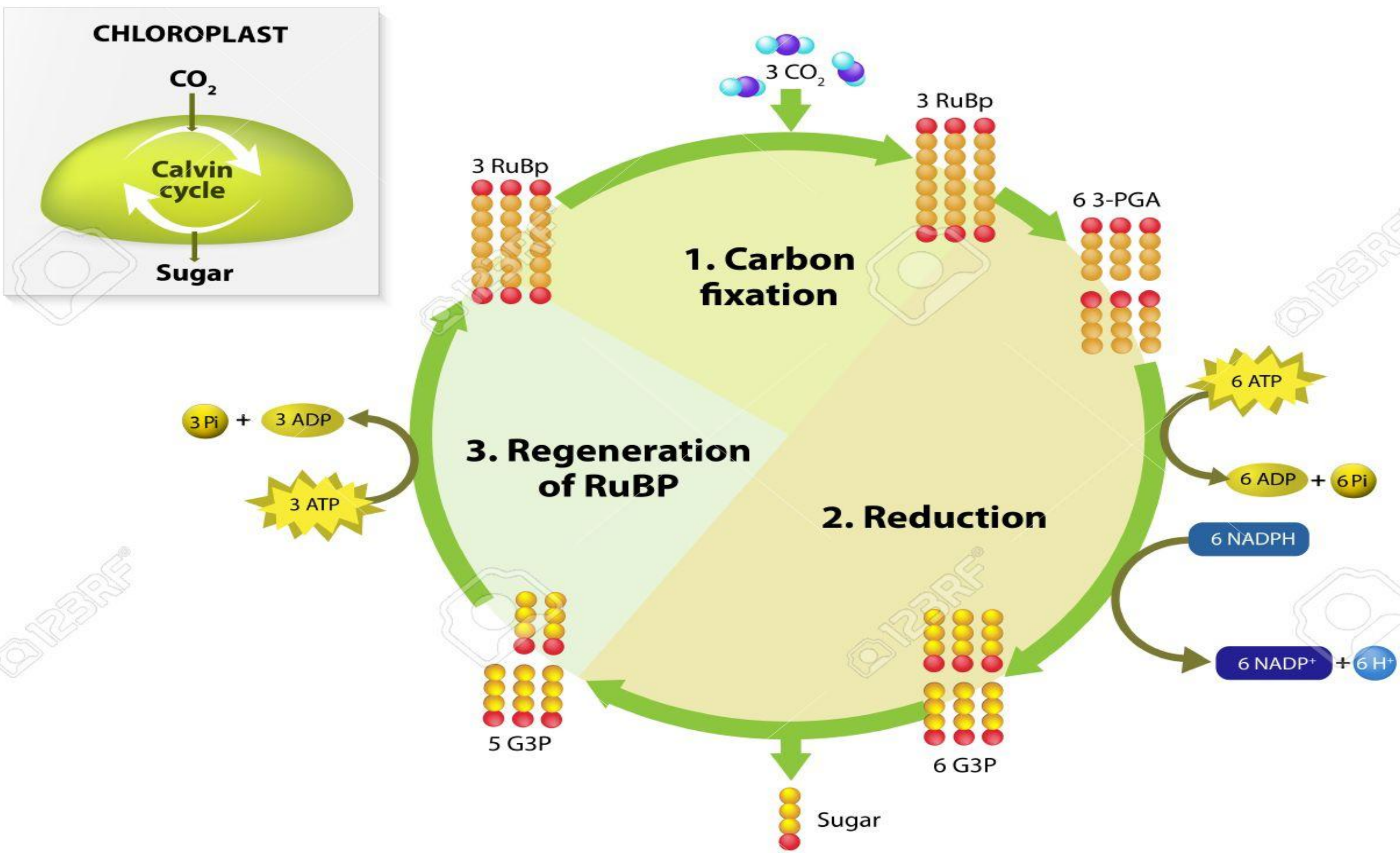
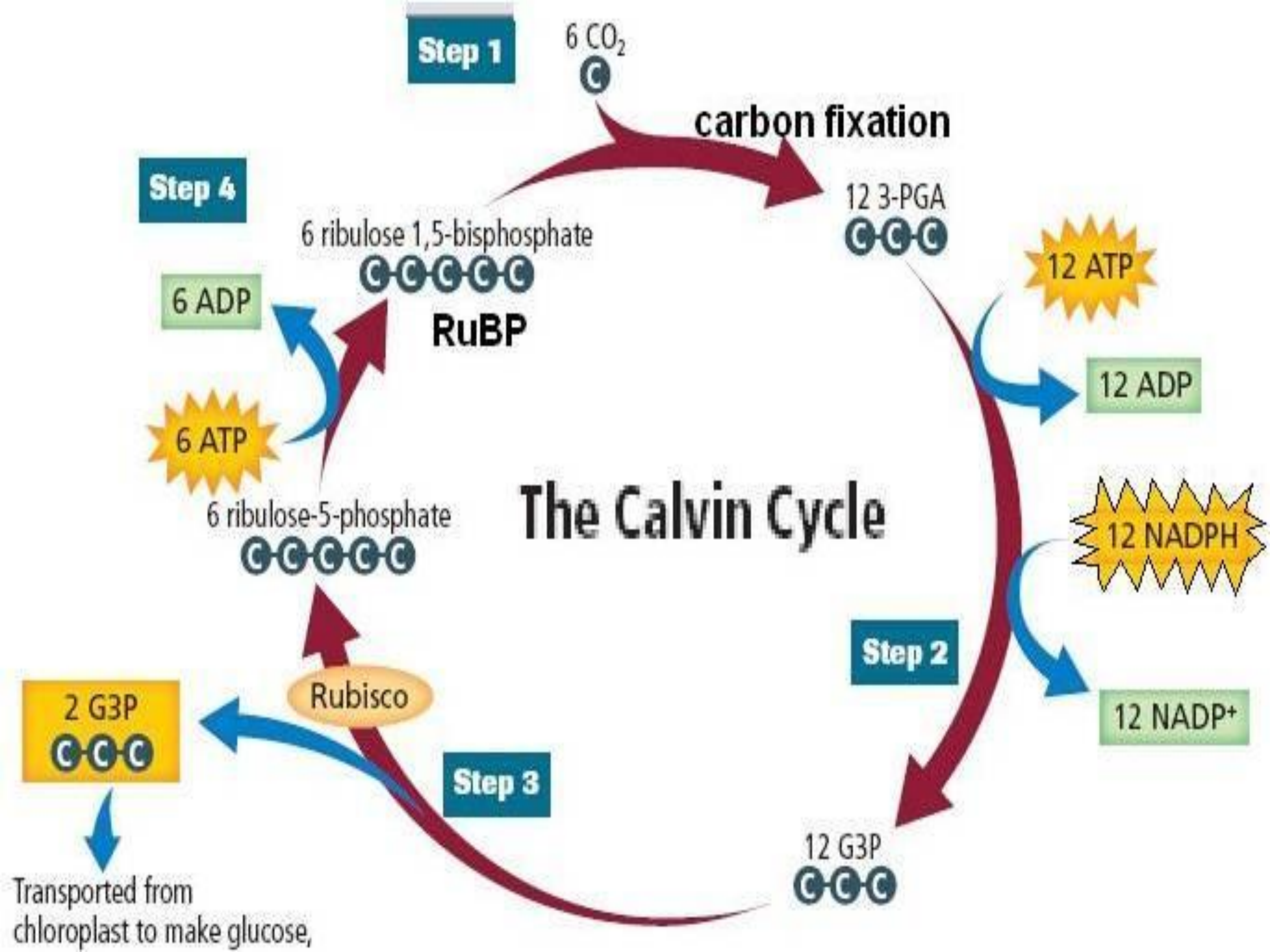


Fig. 11.18. The three stages the Calvin-cycle or PCR-cycle.

CALVIN CYCLE




Step 1
6 CO_2
C
carbon fixation
12 3-PGA
C-C-C
12 ATP
12 ADP
12 NADPH
12 NADP+
Step 2
12 G3P
C-C-C
Step 3
Rubisco
2 G3P
C-C-C
Transported from
chloroplast to make glucose,
6 ribulose-5-phosphate
C-C-C-C-C
The Calvin Cycle
6 ATP
6 ADP
Step 4
6 ribulose 1,5-bisphosphate
C-C-C-C-C
RuBP

The Calvin cycle (C_3-cycle) or PCR-cycle can be divided into three stages:

(a) Carboxylation, during which atmospheric CO_2 combines with 5-C acceptor molecule ribulose 1, 5-bisphosphate (RuBP) and converts it into 3-phosphoglyceric acid (3-PGA);

(b) Reduction, which consumes ATP + NADPH (produced during primary photochemical reaction) and converts 3-PGA into 3-phosphoglyceraldehyde (3PGAld) or triose phosphate (TRI- OSE-P); and

(c) Formation of hexose sugar and regeneration of RuBP which consumes additional ATP, so that the cycle continues