Photosynthesis: using light to make food

生科系李鳳鳴

Figure 7.0-1

Poison ivy常春藤

Introduction

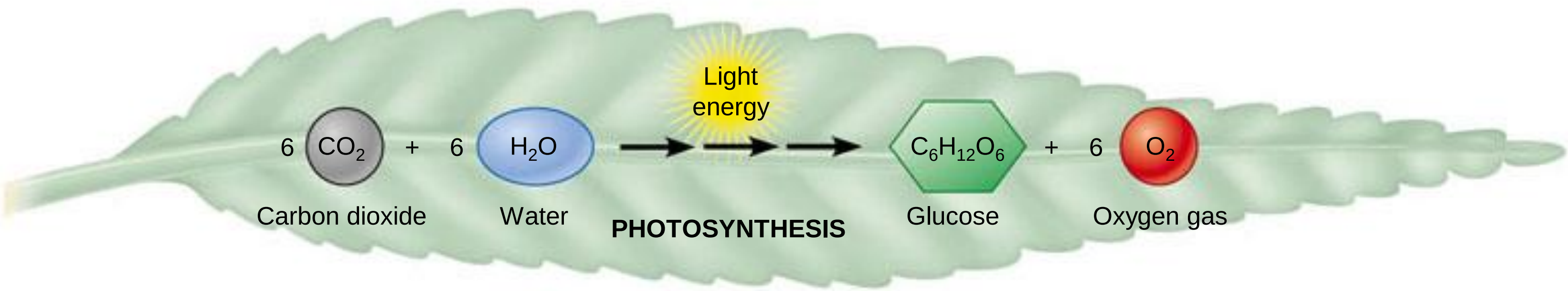
- Poison ivy contains urushiol漆酚, a chemical that may cause itchy and oozing blisters that can last for weeks.
- Like all plants, poison ivy produces energy for its growth by photosynthesis, the process that converts light energy to the chemical energy of sugar.

Introduction

- Photosynthesis
  - removes CO_2 from the atmosphere and
  - stores it in plant matter.
- The burning of sugar in the cellular respiration of almost all organisms releases CO_2 back to the environment.
- Directly or indirectly, photosynthesis nourishes almost the entire living world

– Photosynthesis is the process by which certain organisms use light energy

- To make sugar and oxygen gas from carbon dioxide and water



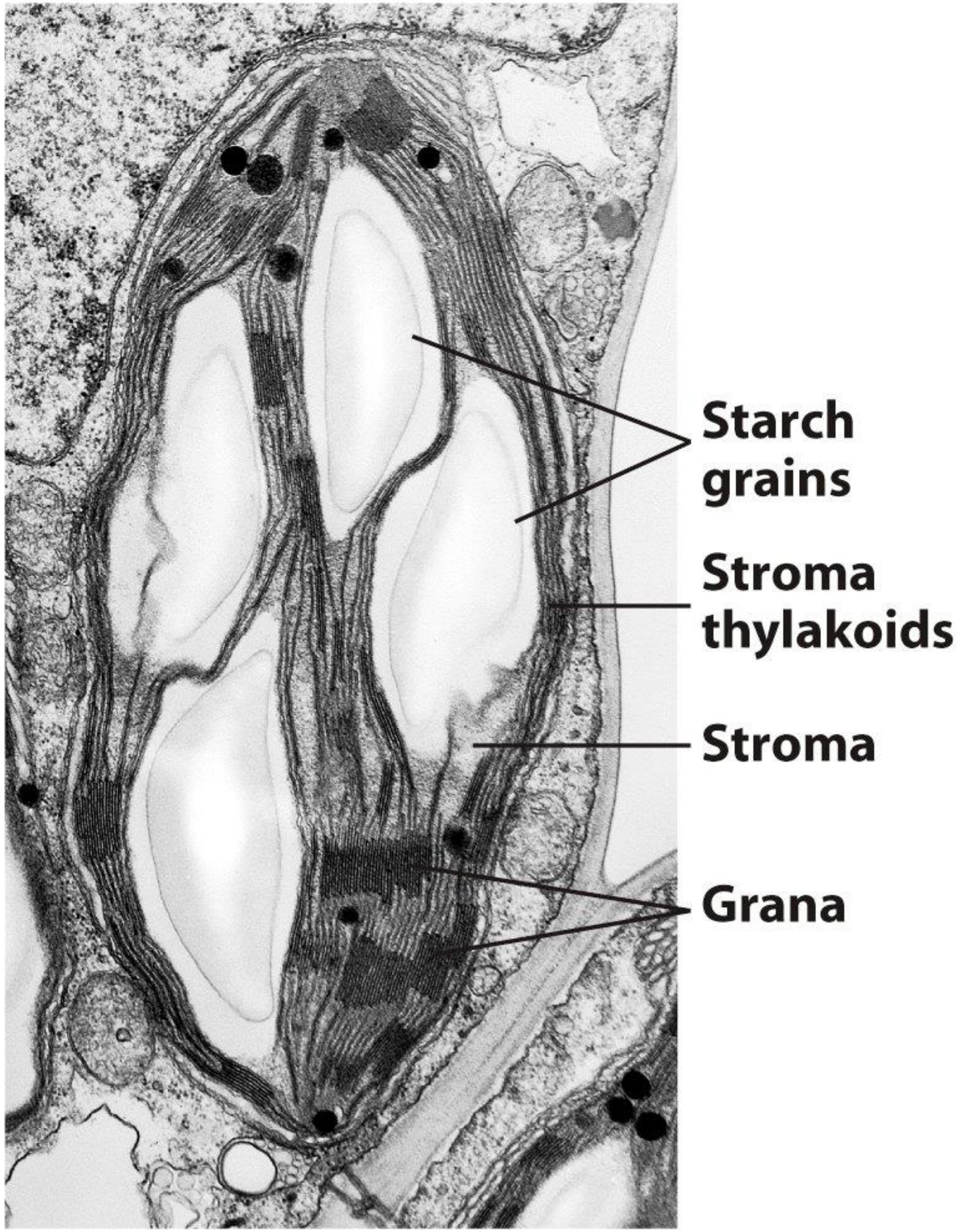


Figure 7-1
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- The Earth's supply of fossil fuels was formed from the remains of organisms that died hundreds of millions of years ago
- In a sense, fossil fuels represent stores of solar energy from the distant past

- As the human demand for energy grows
    - Fossil fuel supplies are dwindling
- Energy plantations
    - Are being planted to serve as a renewable energy source

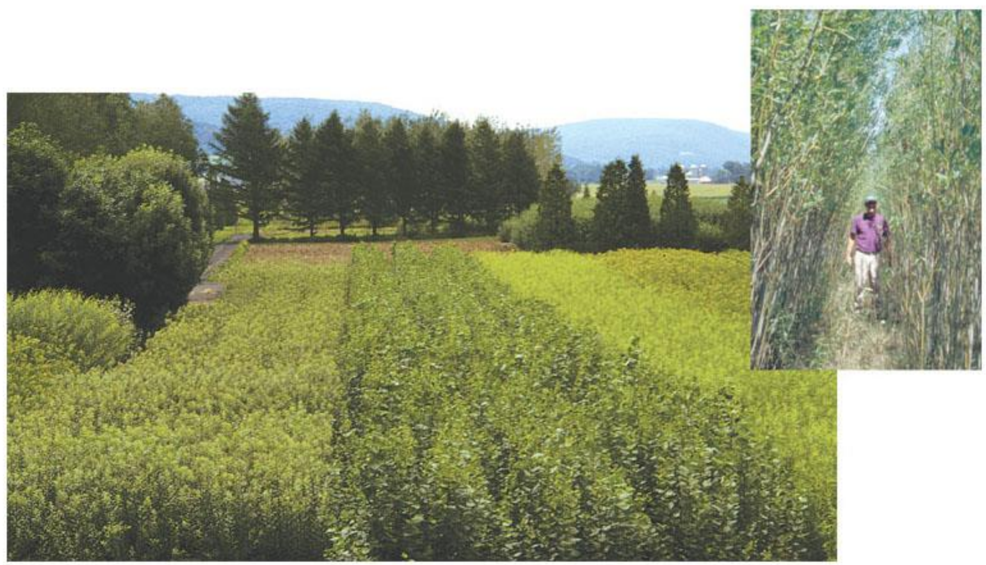


Figure 10.3

Figure 7.3

- English scientist Joseph Priestly
  burning candles - mint, mouse
- Dutch physician Jan Ingenhousz
  air was “restored” only in the presence of sunlight and only by the green parts of plants
- 1796 $CO_2 \rightarrow O_2$

$$CO_2 + H_2O \xrightarrow{\text{light energy}} (CH_2O) + O_2$$

- O_2 given off by plants is derived from H_2O not from CO_2
- 1930 C. B. van Niel

$$CO_2 + 2H_2S \rightarrow CH_2O + H_2O + 2S$$

$$CO_2 + 2H_2O \rightarrow CH_2O + H_2O + O_2$$

7.3 Scientists traced the process of photosynthesis using isotopes

- 1941 Samuel Ruben & Martin Kamen

  Oxygen-18 (^{18}O) a heavy isotope

Scientists traced the process of photosynthesis using isotopes

- Experiment 1:

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

- Experiment 2:

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

- Plants produce O_2 gas by splitting water
  - The O_2 liberated by photosynthesis
    - Is made from the oxygen in water

Experiment 1

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

Not labeled

Experiment 2

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

Labeled

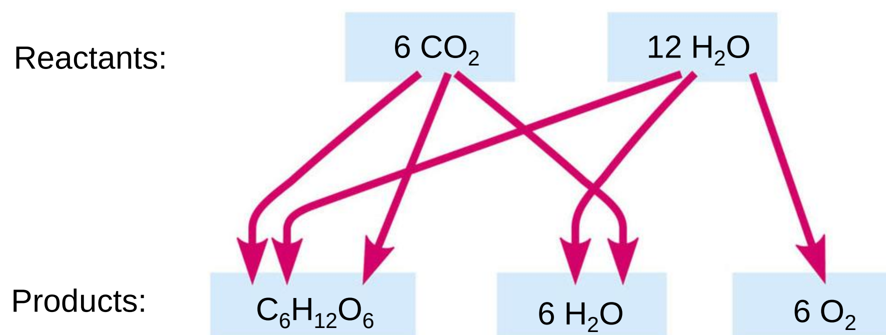


Figure 7.3A–C

Figure 10.5

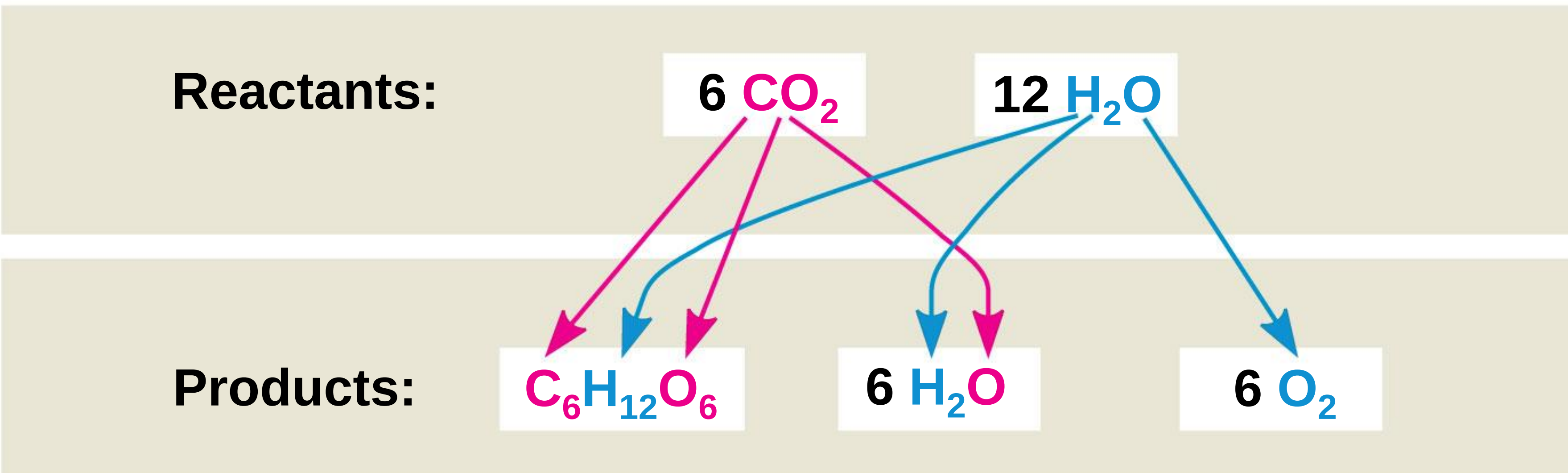
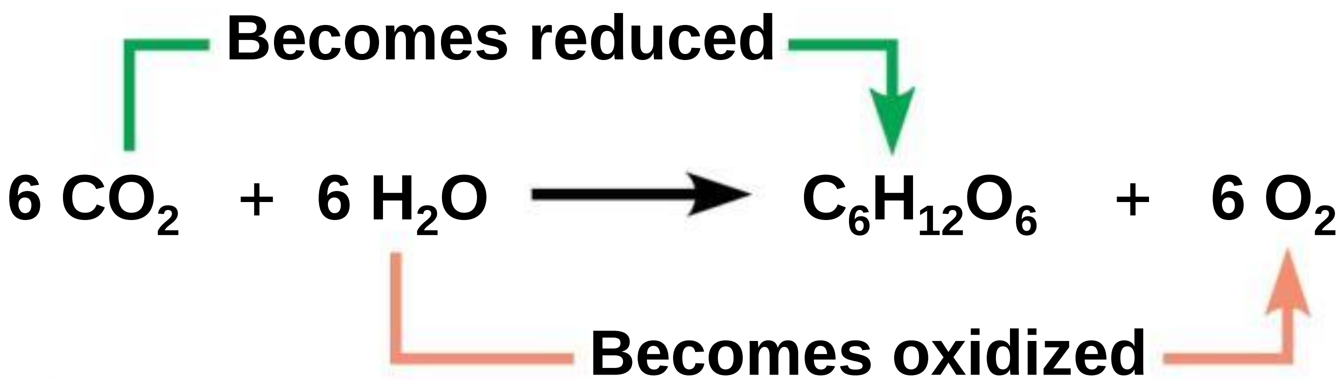


Figure 7.4a

In photosynthesis

H_2O is oxidized and CO_2 is reduced



光合作用

Reduction

$$6\,CO_2 + 6\,H_2O \longrightarrow C_6H_{12}O_6 + 6\,O_2$$

Oxidation

Oxidation

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O$$

Reduction

呼吸作用

- **Autotrophic nutrition**

  Auto: self, trophos: feed

- **Producers生產者**

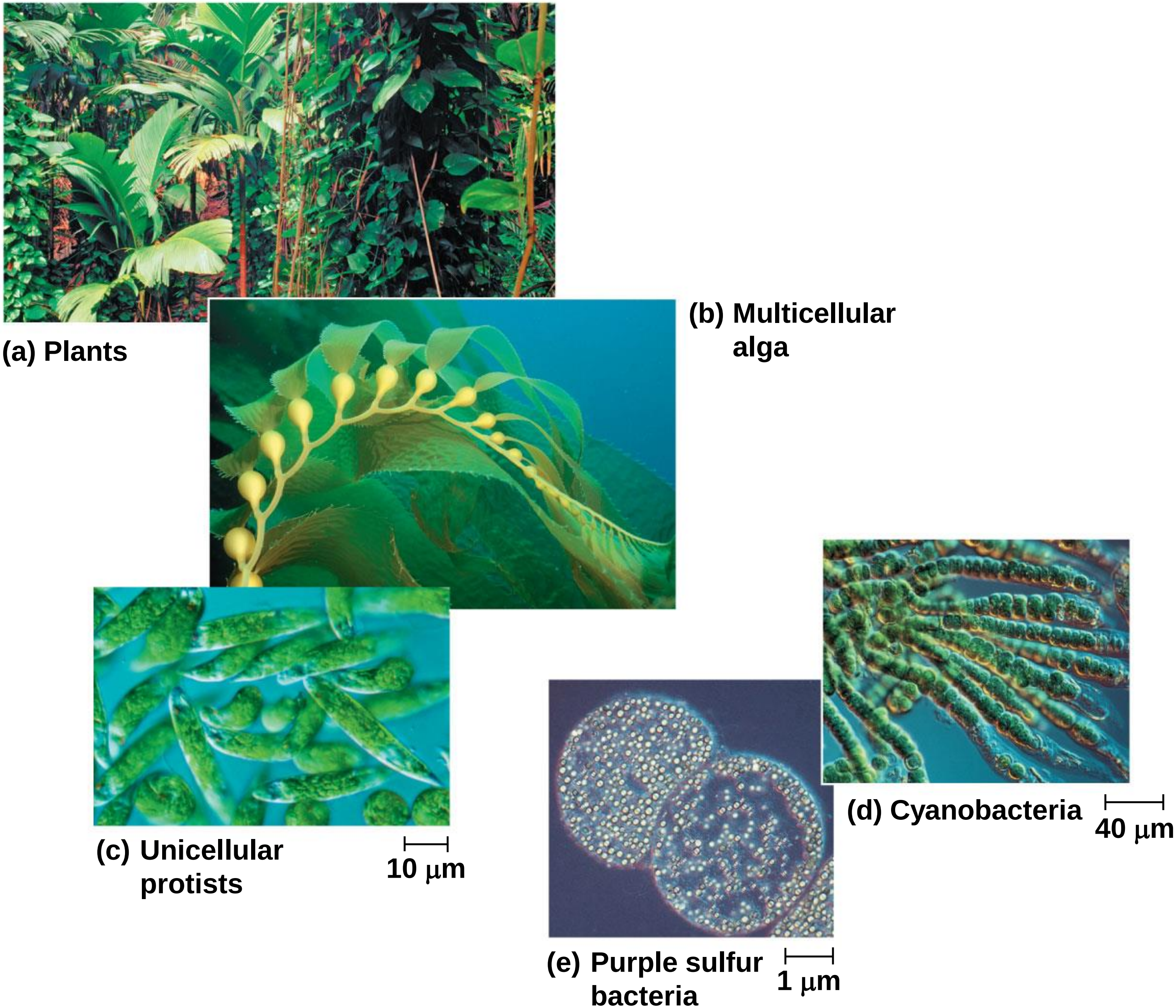
  - Without eating or decomposing other organisms
  - They make their organic molecules from inorganic raw materials

- **Photoautotrophs光自營性**
- Chemoautotrophs化學自營性

Photoautotrophs光自營性

- Organisms that use **light as a source of energy** to synthesize carbohydrates lipid, proteins and other organic substances. ex. Plant, algae, protista and prokaryotes
- Plants are photoautotrophs光自營性生物
  - They use the energy of sunlight to make organic molecules from water and carbon dioxide
  - 每年光合作用固定250 billion 公噸醣類

Figure 10.2


(a) Plants
(b) Multicellular alga
(c) Unicellular protists
10 μm
(d) Cyanobacteria
40 μm
(e) Purple sulfur bacteria
1 μm

Heterotrophic nutrition異營

Hetero: other, different

Consumers消費者 e.g. Animal

Decomposers分解者 e.g. Fungi真菌, many types of bacteria

Figure 7.2-0

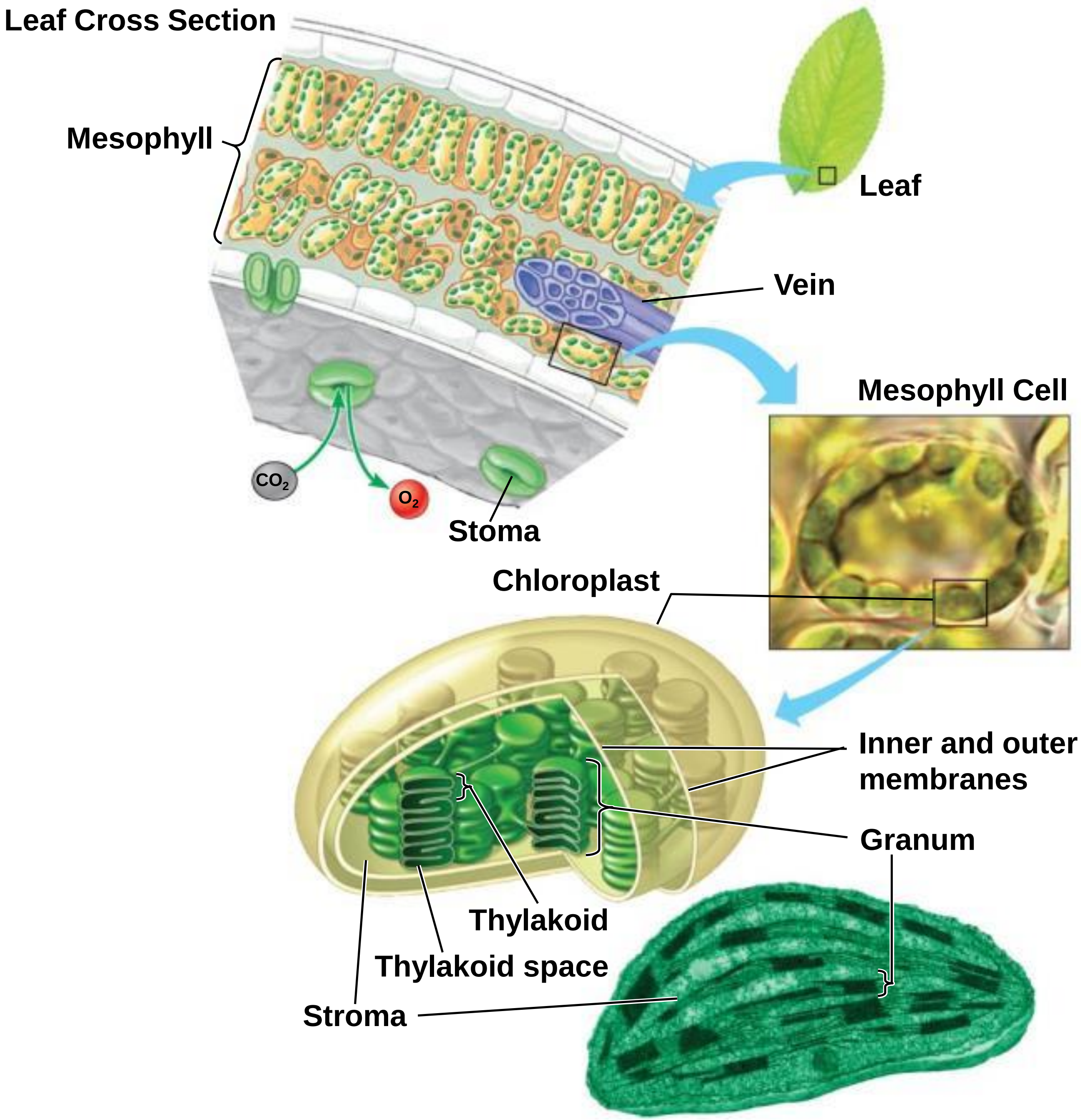
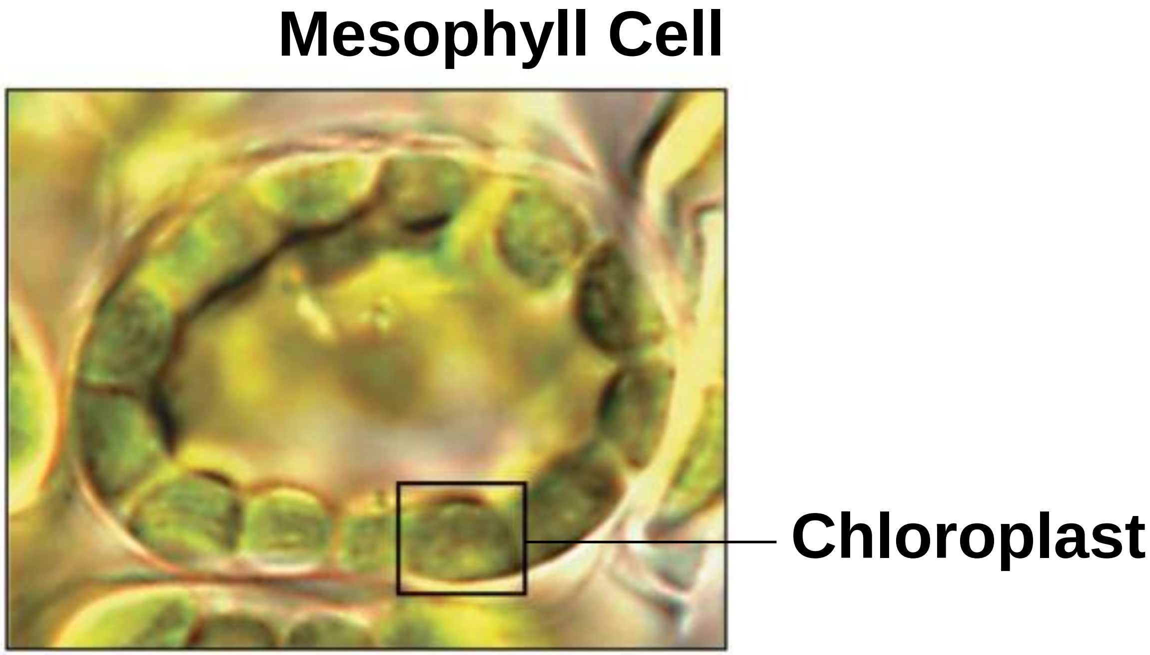

Leaf Cross Section
Mesophyll
Leaf
Vein
CO2
O2
Stoma
Mesophyll Cell
Chloroplast
Inner and outer membranes
Granum
Thylakoid
Thylakoid space
Stroma

Figure 7.2-3



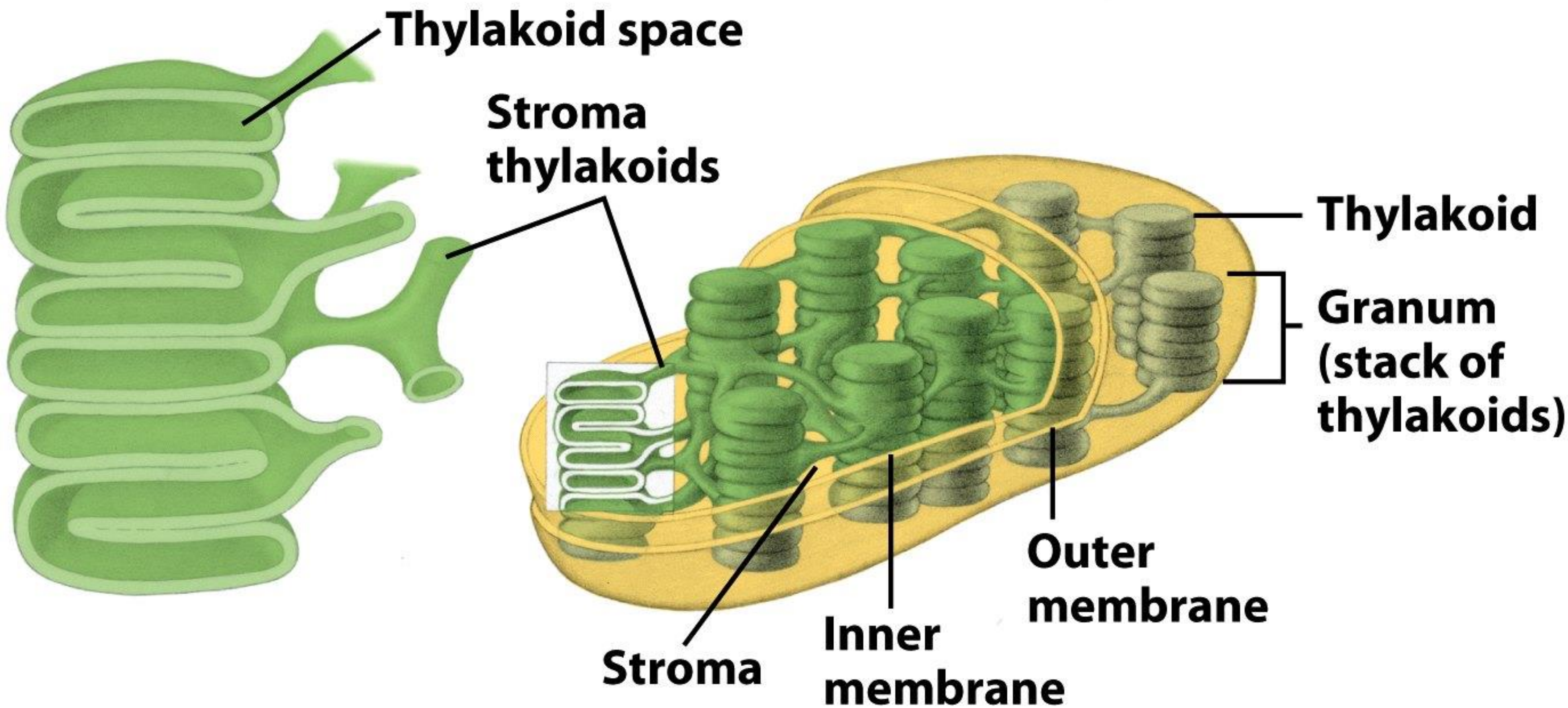


Figure 7-7c,d
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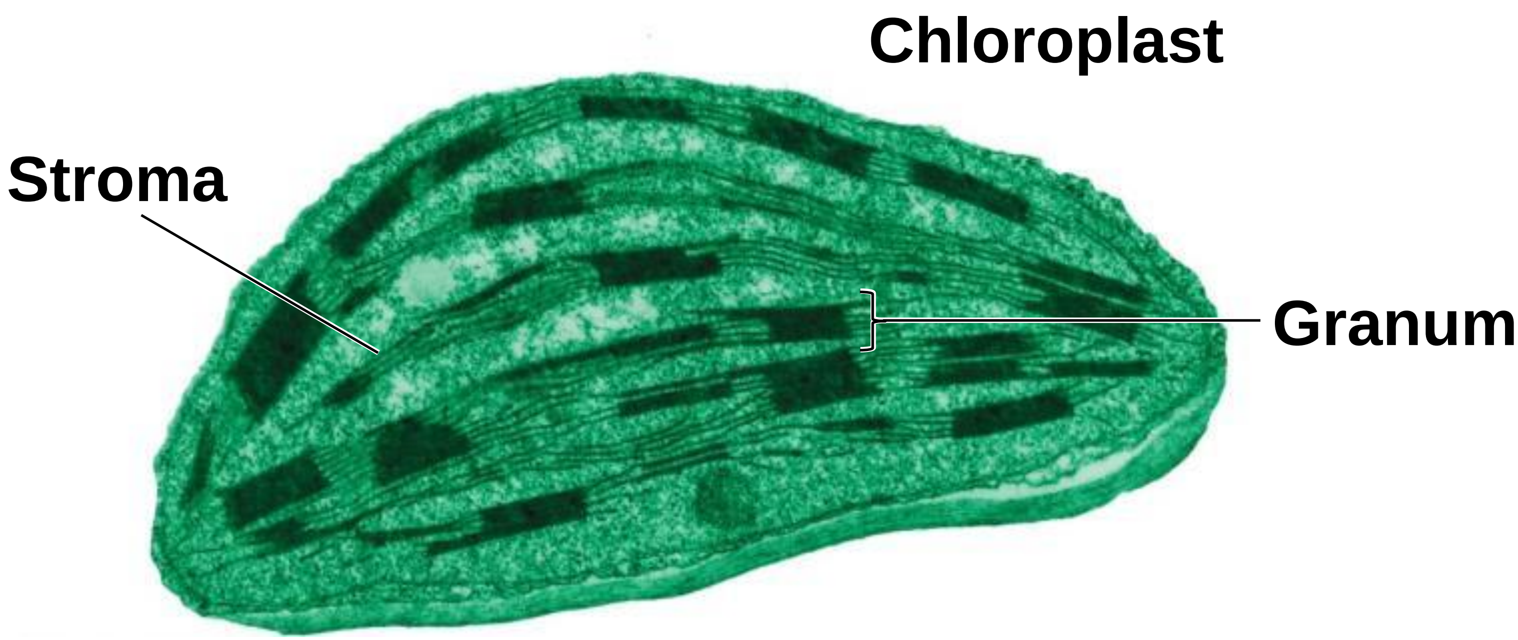
Figure 7.2-4



Overview: Photosynthesis occurs in two stages linked by ATP and NADPH

- The complete process of photosynthesis consists of two linked sets of reactions
  - **The light reactions** and the **Calvin cycle**

- The light reactions
  - Convert light energy to chemical energy and produce O_2
- The Calvin cycle assembles sugar molecules from CO_2
  - Using ATP and NADPH from the light reactions

7.5 The two stages of photosynthesis are linked by ATP and NADPH

- Photosynthesis occurs in two stages.
  1. The **light reactions** occur in the thylakoid membranes. In these reactions
     - water is split, providing a source of electrons and giving off oxygen as a by-product,
     - ATP is generated from ADP and a phosphate group, and
     - light energy is absorbed by the chlorophyll molecules to drive the transfer of electrons and H^+ from water to the electron acceptor **$NADP^+$**, reducing it to NADPH.
     - NADPH, produced by the light reactions, provides the "reducing power" to the Calvin cycle.

The two stages of photosynthesis are linked by ATP and NADPH

2. The second stage is the **Calvin cycle**, which occurs in the stroma of the chloroplast.
   - The Calvin cycle is a cyclic series of reactions that assembles sugar molecules using CO_2 and the energy-rich products of the light reactions.
   - During the Calvin cycle, CO_2 is incorporated into organic compounds in a process called **carbon fixation**.
   - After carbon fixation, the carbon compounds are reduced to sugars.
   - The Calvin cycle is often called the dark reactions, or light-independent reactions, because none of the steps requires light directly.

Figure 10.6-1

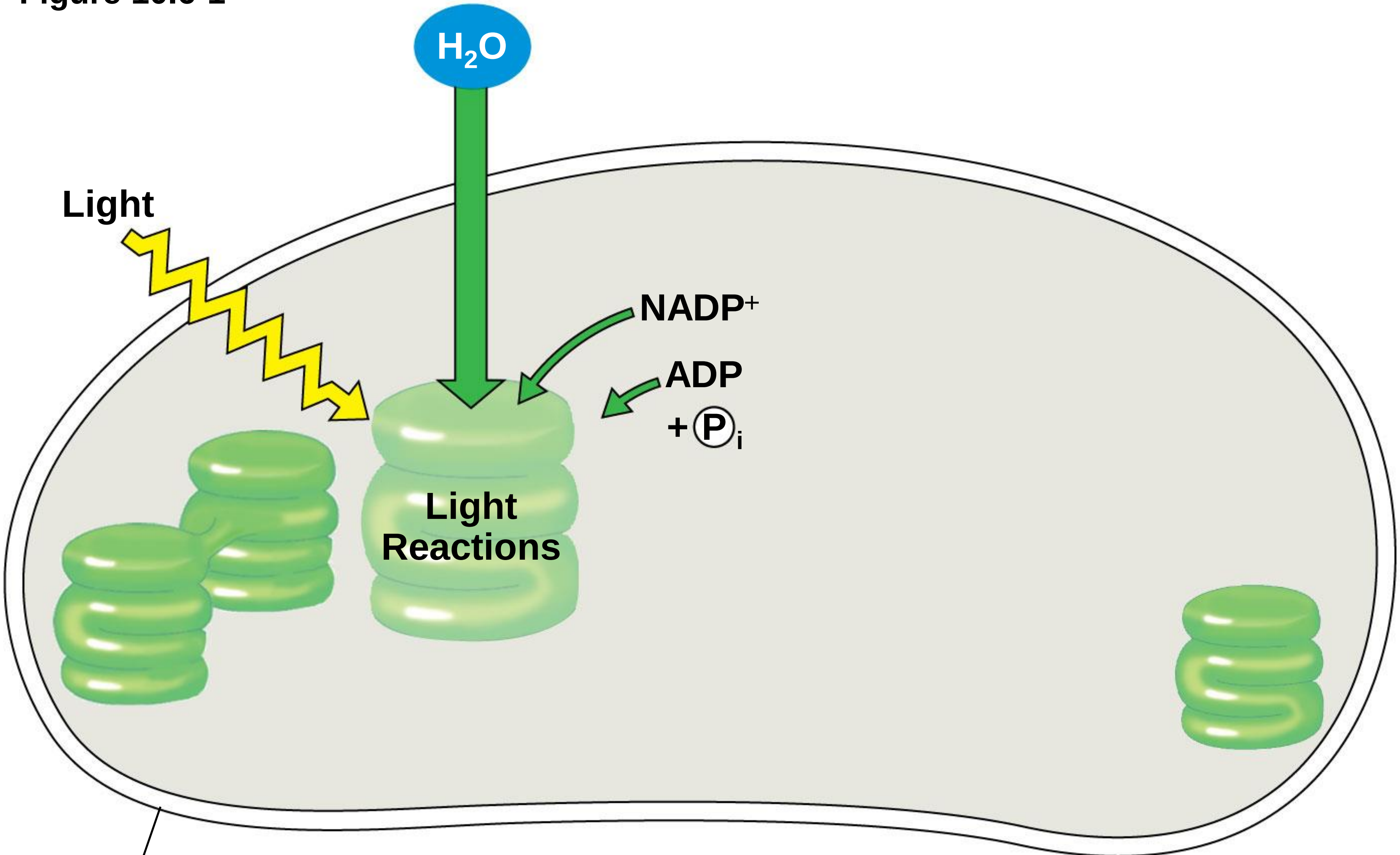
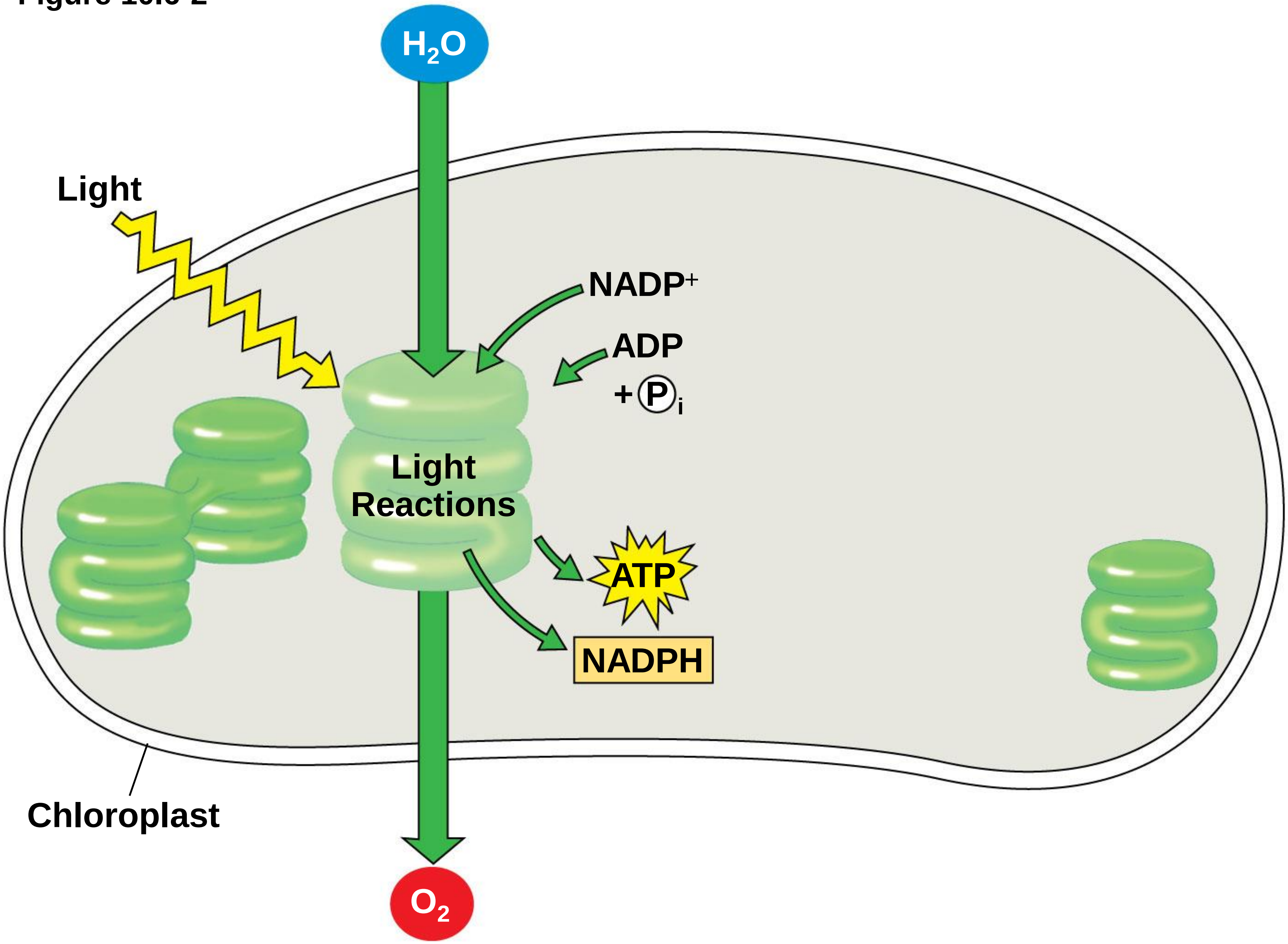
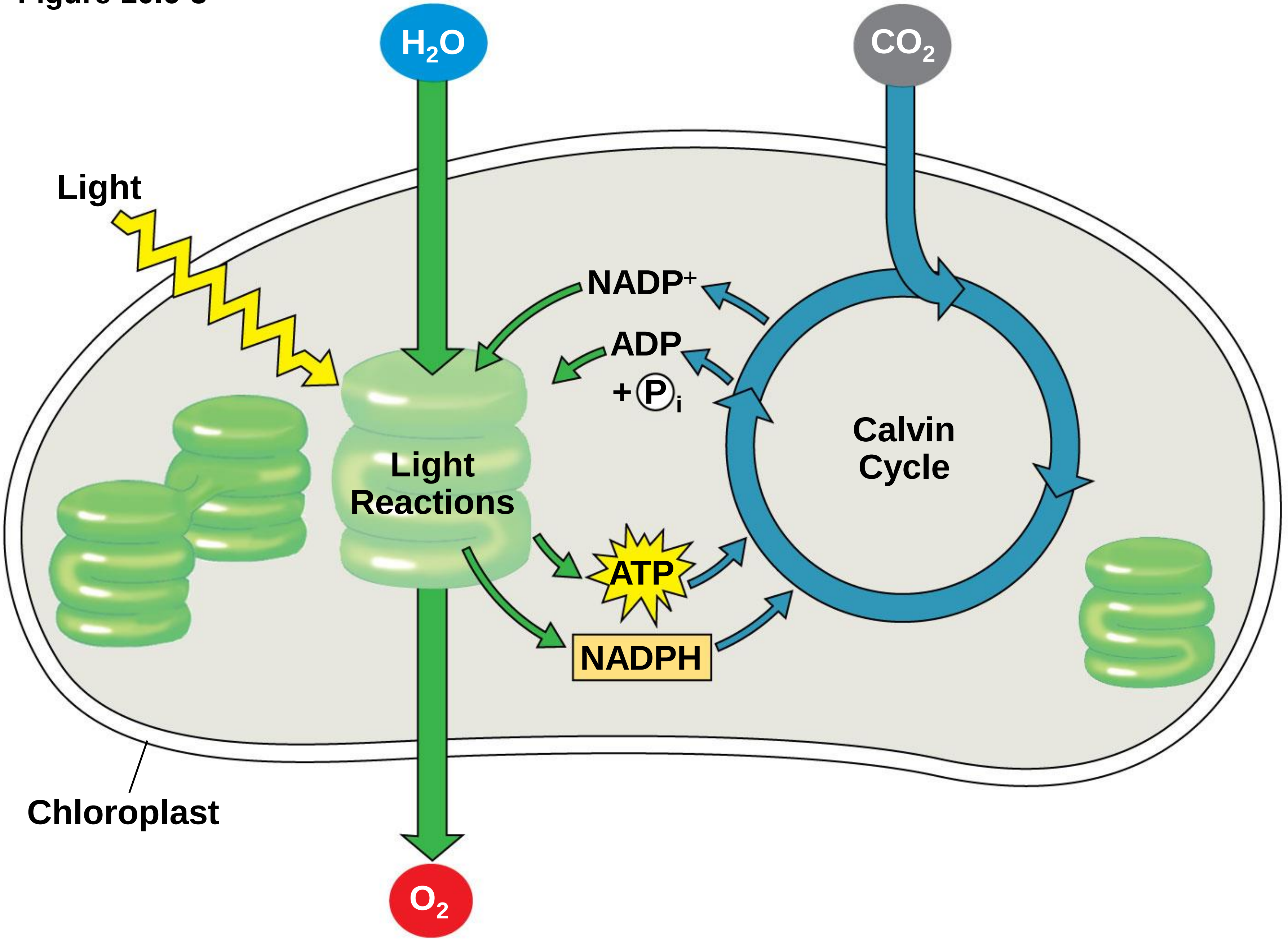


Figure 10.6-2



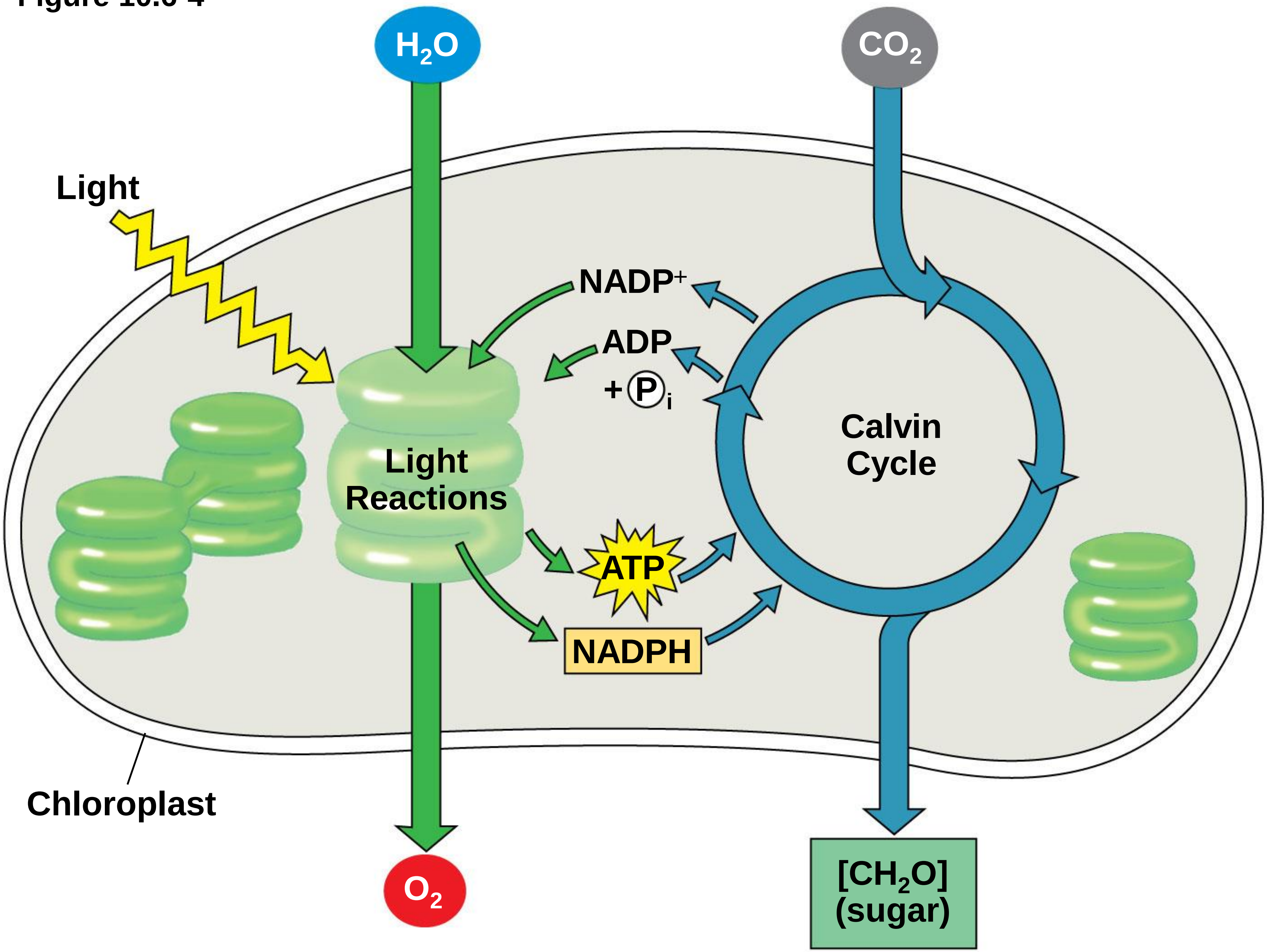
H_2O
Light
$NADP^+$
ADP
+ P i
Light Reactions
ATP
NADPH
Chloroplast
O_2

Figure 10.6-3



H_2O
CO_2
Light
NADP+
ADP
+ P i
Light Reactions
Calvin Cycle
ATP
NADPH
Chloroplast
O_2

Figure 10.6-4



H_2O
CO_2
Light
$NADP^+$
ADP
+ (P)$_i$
Calvin
Cycle
Light
Reactions
ATP
NADPH
Chloroplast
O_2
$[CH_2O]$
(sugar)

The Light Reactions:

Converting Solar Energy to Chemical Energy

7.6 Visible radiation absorbed by pigments drives the light reactions

- Sunlight contains energy called electromagnetic energy or radiation.
  - Visible light is only a small part of the **electromagnetic spectrum**電磁光譜, the full range of electromagnetic wavelengths.
  - Electromagnetic energy travels in waves.
  - The **wavelength**波長 is the distance between the crests of two adjacent waves.

The Light Reactions: Converting Solar Energy to Chemical Energy

Figure 10.1

Electronmagnetic spectrum電磁光譜

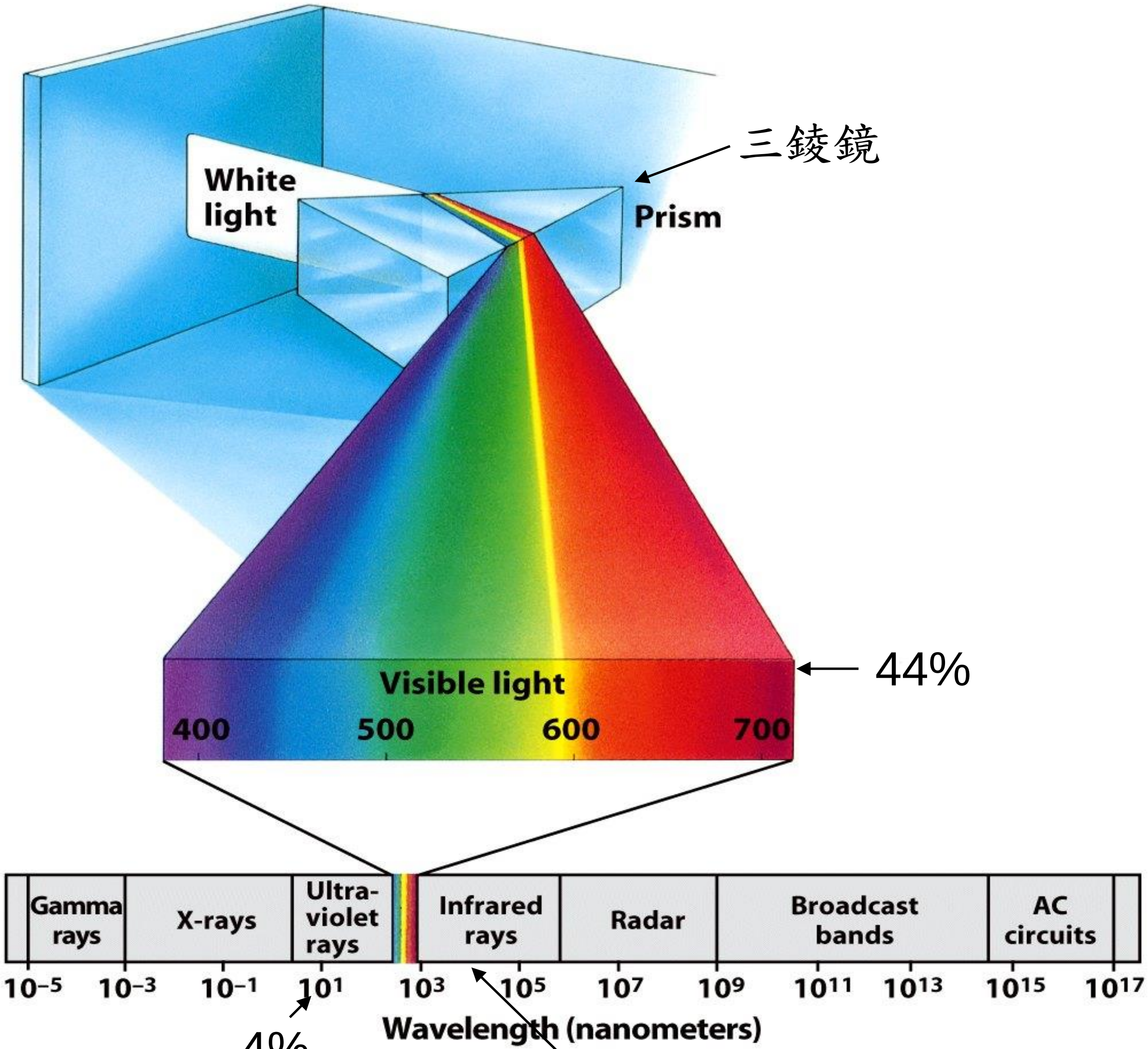


Figure 7-4
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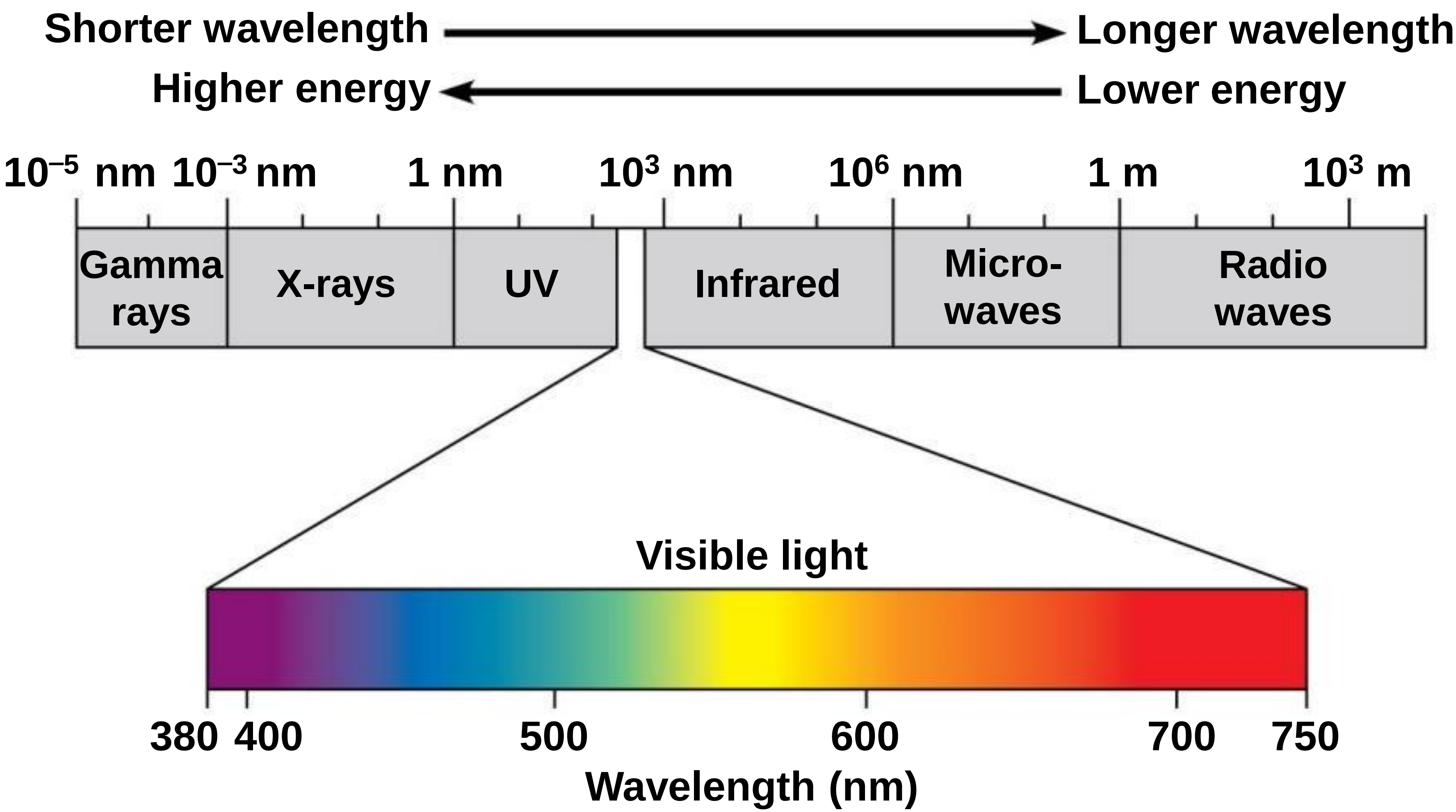
- The electromagnetic spectrum
  - Is the entire range of electromagnetic energy, or radiation

Figure 7.6a



Shorter wavelength
Longer wavelength
Higher energy
Lower energy
10–5 nm
10–3 nm
1 nm
103 nm
106 nm
1 m
103 m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
400
500
600
700
750
Wavelength (nm)

7.6 Visible radiation absorbed by pigments drives the light reactions

- Light behaves as discrete packets of energy called photons.
  - A **photon**光子 is a fixed quantity of light energy.
  - The shorter the wavelength, the greater the energy.

1905 Einstein : light consists of packets of energy called photon 光子

- the intensity of light depends on the number of photons absorbed per unit of time

- each photon carries a fixed amount of energy

The nature of light

- the different wavelengths as different colors
- the energy of a photon is a **quantum**
  (pl. quanta)光量子.
- the longer the wavelength, the less
  energy per photon
- Sunlight consists of about 4% ultraviolet radiation,
  52% infrared radiation, 44% visible light.

The nature of light

- About 1/3 of the light hitting the atmosphere is reflected back to space, and only about 1% of the light is used for photosynthesis
- Light is the part of the electromagnetic spectrum having wavelengths visible to the human eye (380-760 nm)

The nature of light

- the slower the vibration, the less energy carried by the photon
- the distance moved by the photon during a complete vibration is referred to as the photon's wavelength (λ)
- 單位 nm (10^{-9})

Ultraviolet radiation (uv)

- contains too much energy for most biological

  system its high-energy photons often drive

  electrons from molecules so called **ionizing radiation**
- UV breaks week bonds & cause sunburn

  absorbed by O_2, O_3 & glass

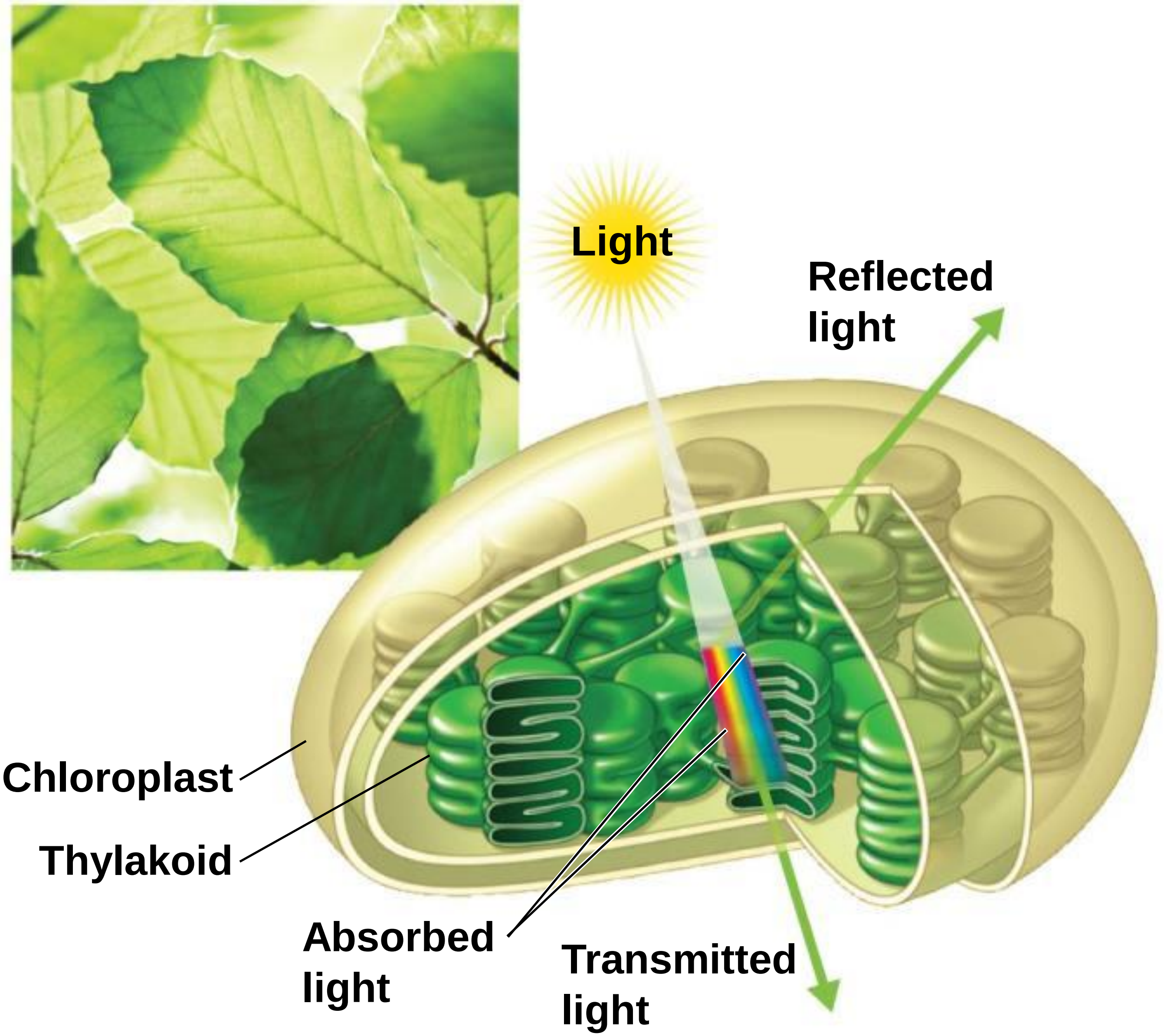
Infrared radiation (IR)

- Doesn’t contain enough energy per photon to be useful to living systems.
- Cell absorb IR, but this energy is insufficient to excite electrons
- Most of the energy of IR is converted immediately to heat.
- IR is absorbed by water & CO_2, but goes through glass.

7.6 Visible radiation absorbed by pigments drives the light reactions

- Plant pigments色素
  - are built into the thylakoid membrane,
  - absorb some wavelengths of light, and
  - reflect or transmit other wavelengths.
- We see the color of the wavelengths that are transmitted. For example, chlorophyll transmits green wavelengths.

Figure 7.6b-0



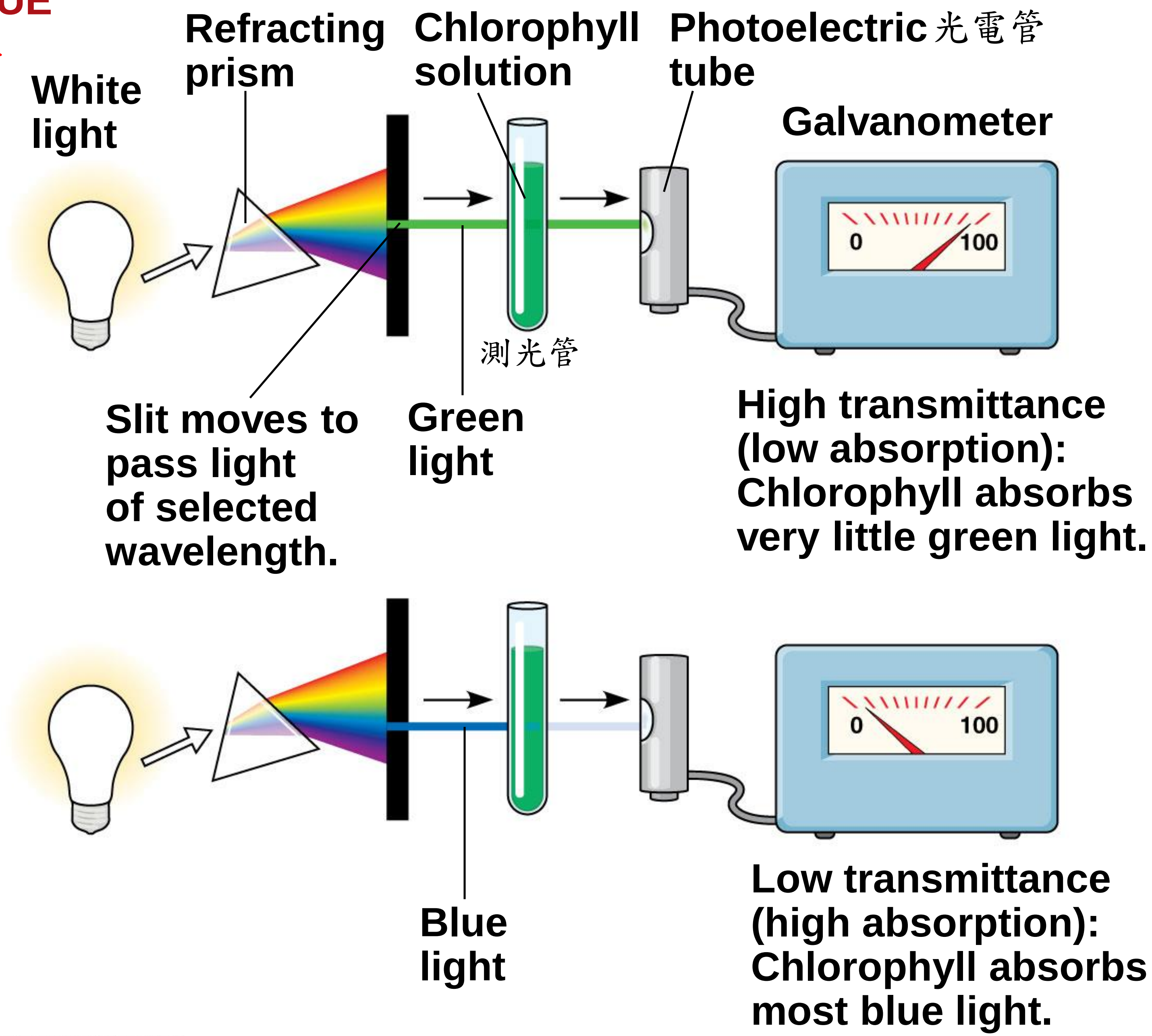
Light
Reflected light
Chloroplast
Thylakoid
Absorbed light
Transmitted light

- An **absorption spectrum**吸收光譜
  - Is a graph plotting light absorption versus wavelength

Figure 10.9

TECHNIQUE

分光光度計



Visible radiation absorbed by pigments drives the light reactions

- Chloroplasts contain several different pigments, which absorb light of different wavelengths.
  - **Chlorophyll *a*** absorbs blue-violet and red light and reflects green.
  - **Chlorophyll *b*** absorbs blue and orange and reflects yellow-green.

- **Carotenoids類胡蘿蔔素**
  - broaden the spectrum of colors that can drive photosynthesis and
  - **provide photoprotection**, absorbing and dissipating excessive light energy that would otherwise damage chlorophyll or interact with oxygen to form reactive oxidative molecules.

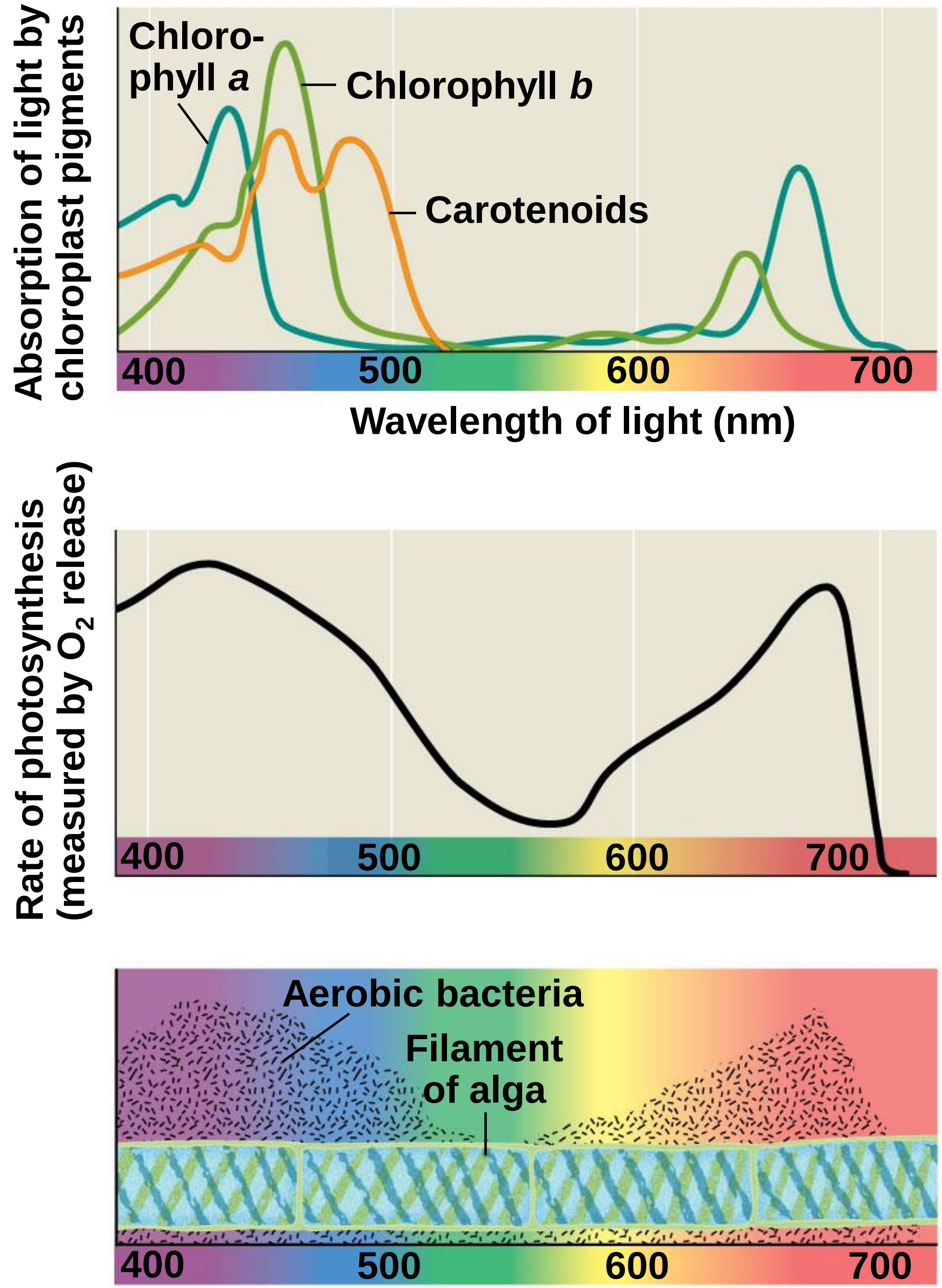
Figure 10.10

RESULTS

(a) Absorption spectra

(b) Action spectrum

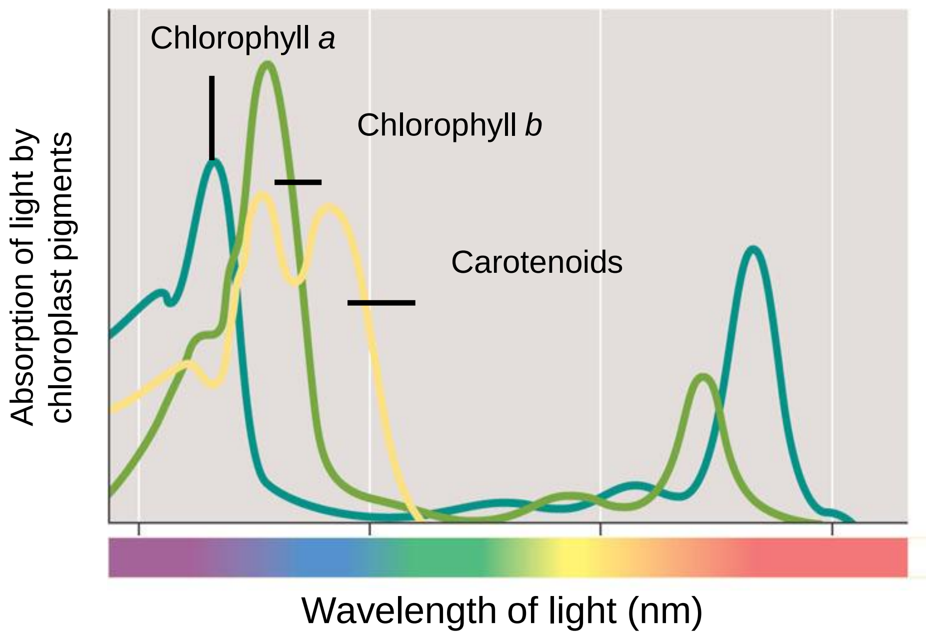
(c) Engelmann's experiment



- The absorption spectra吸收光譜 of three types of pigments in chloroplasts

EXPERIMENT periments helped reveal which wavelengths of light are photosynthetically important. The results are shown below.

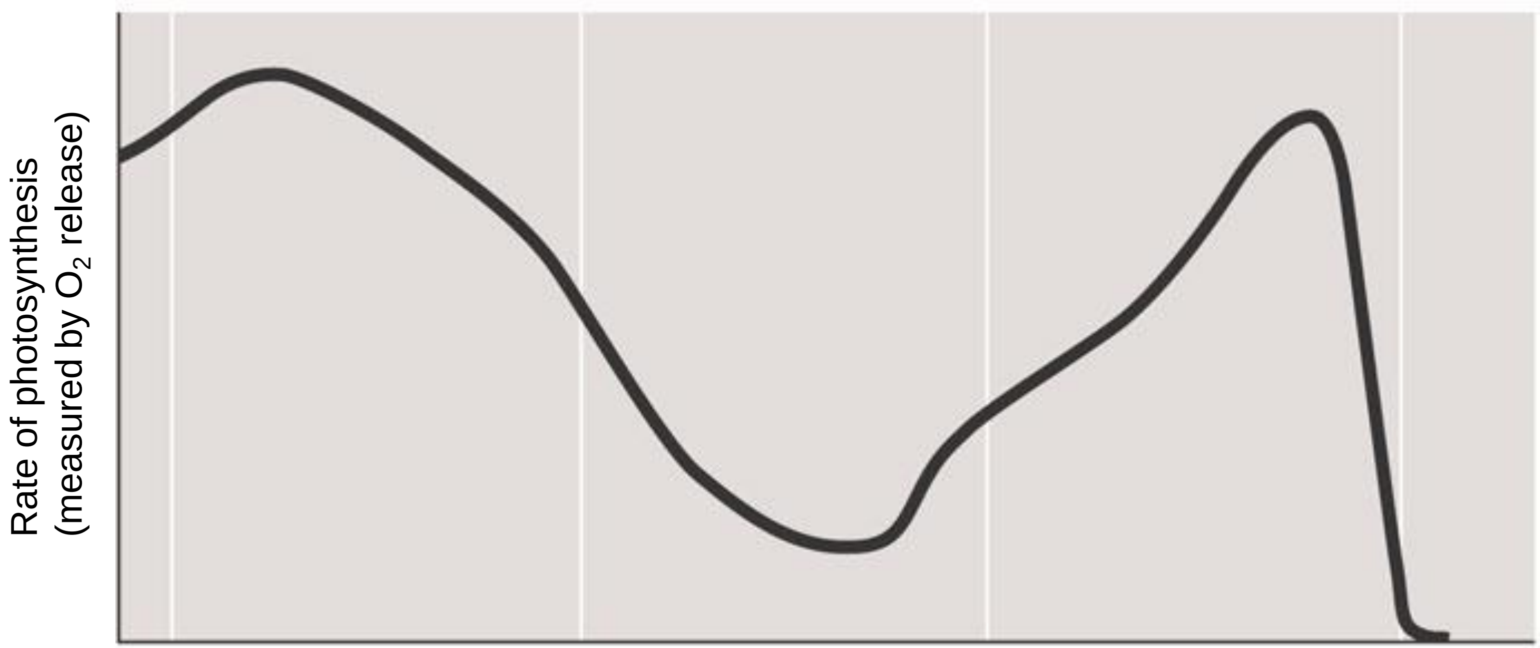
RESULTS



(a) Absorption spectra. The three curves show the wavelengths of light best absorbed by three types of chloroplast pigments.

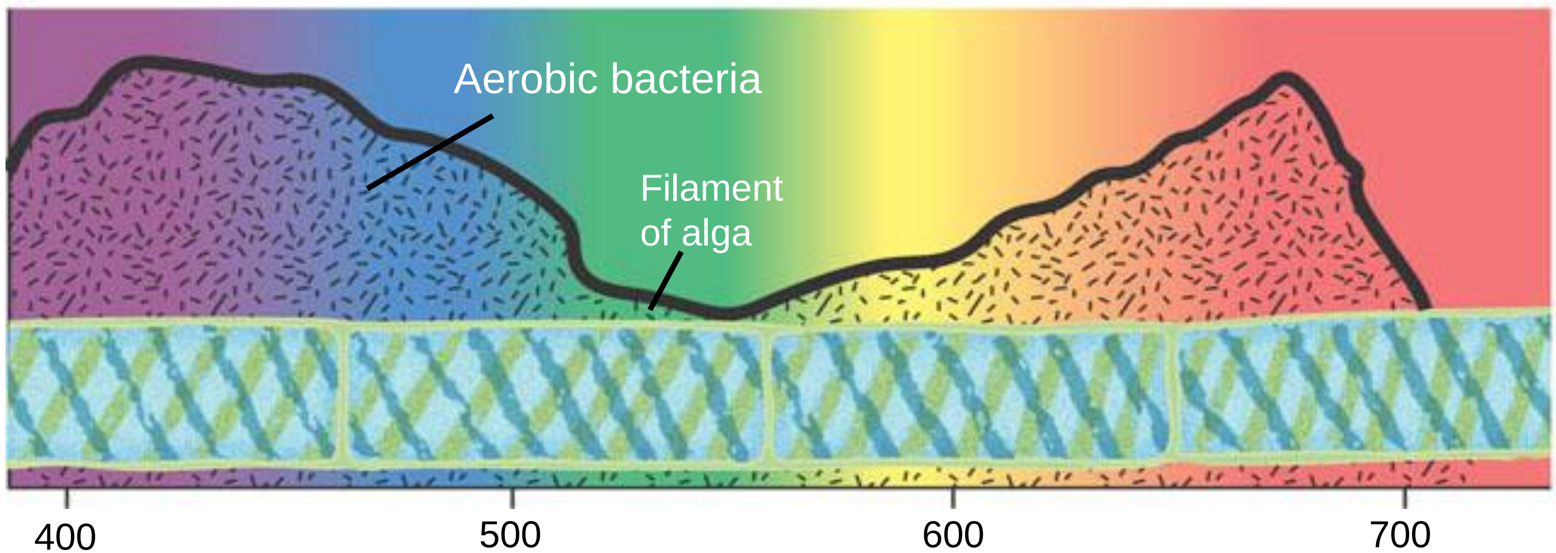
Figure 10.9

- The action spectrum of a pigment
  - Profiles the relative effectiveness of different wavelengths of radiation in driving photosynthesis



(b) Action spectrum. This graph plots the rate of photosynthesis versus wavelength. The resulting action spectrum resembles the absorption spectrum for chlorophyll *a* but does not match exactly (see part a). This is partly due to the absorption of light by accessory pigments such as chlorophyll b and carotenoids.

- The action spectrum作用光譜 for photosynthesis
  - Was first demonstrated by Theodor W. Engelmann



(c) Engelmann's experiment. In 1883, Theodor W. Engelmann illuminated a filamentous alga with light that had been passed through a prism, exposing different segments of the alga to different wavelengths. He used aerobic bacteria, which concentrate near an oxygen source, to determine which segments of the alga were releasing the most O_2 and thus photosynthesizing most.
Bacteria congregated in greatest numbers around the parts of the alga illuminated with violet-blue or red light. Notice the close match of the bacterial distribution to the action spectrum in part b.

CONCLUSION Light in the violet-blue and red portions of the spectrum are most effective in driving photosynthesis.

The photochemical reaction:

- Oxidize water
- Release O_2
- Produce ATP
- Reduced $NADP^+$

- Chlorophyll a

  Is the main photosynthetic pigment

- Chlorophyll b

  Is an **accessory pigment輔助色素**

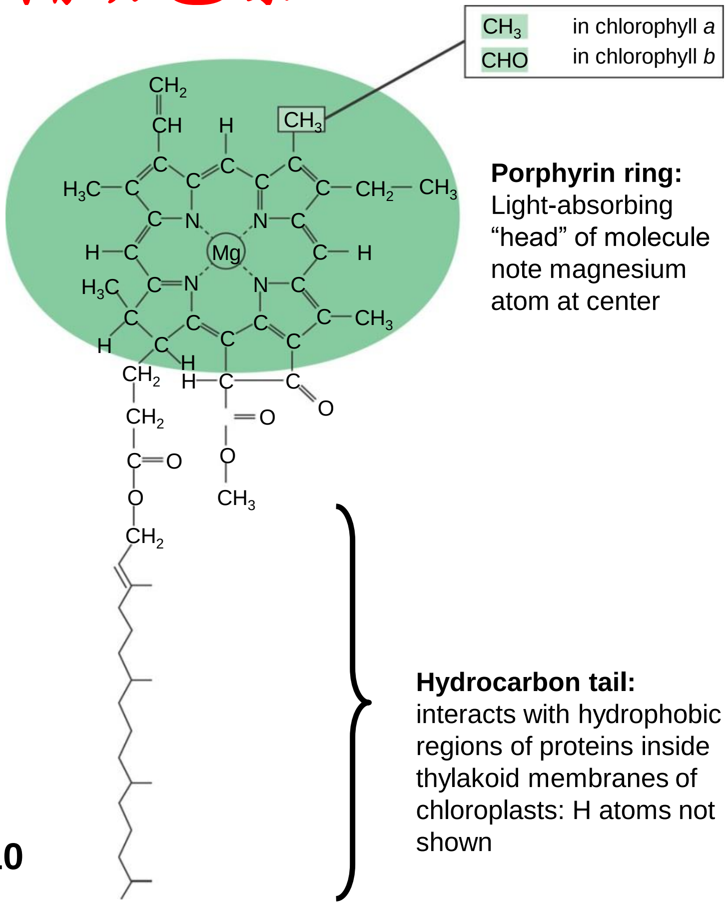
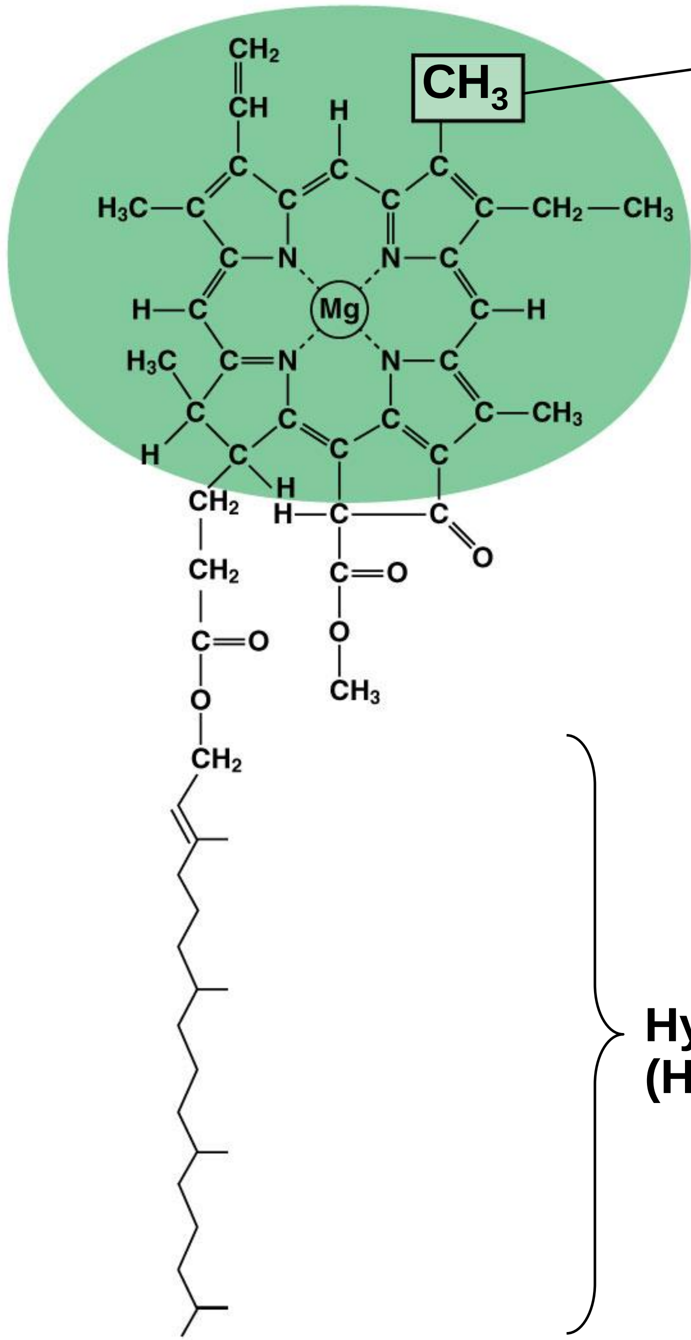


Figure 10.10

Figure 10.11



CH_3 in chlorophyll *a*

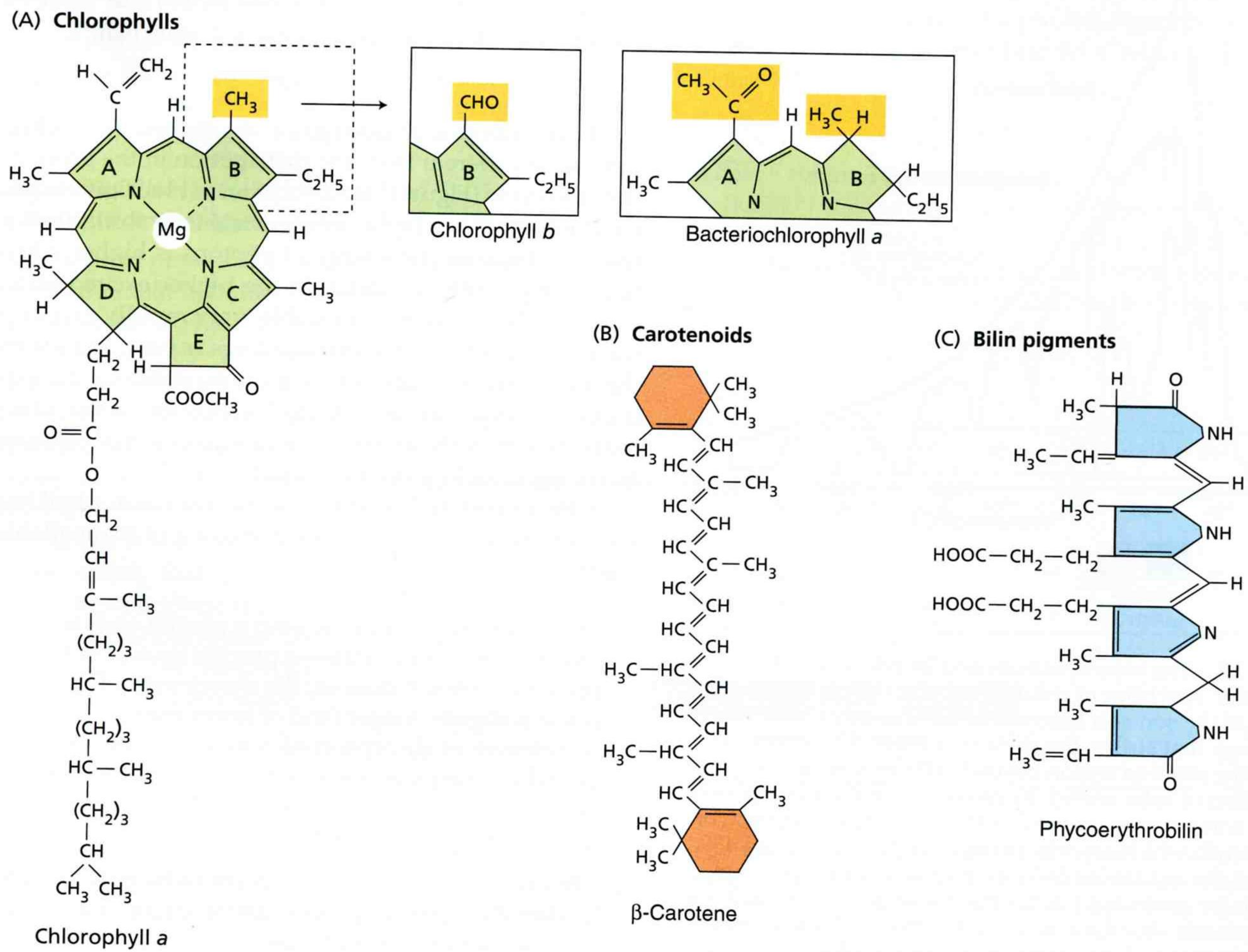
CHO in chlorophyll *b*

Porphyrin ring

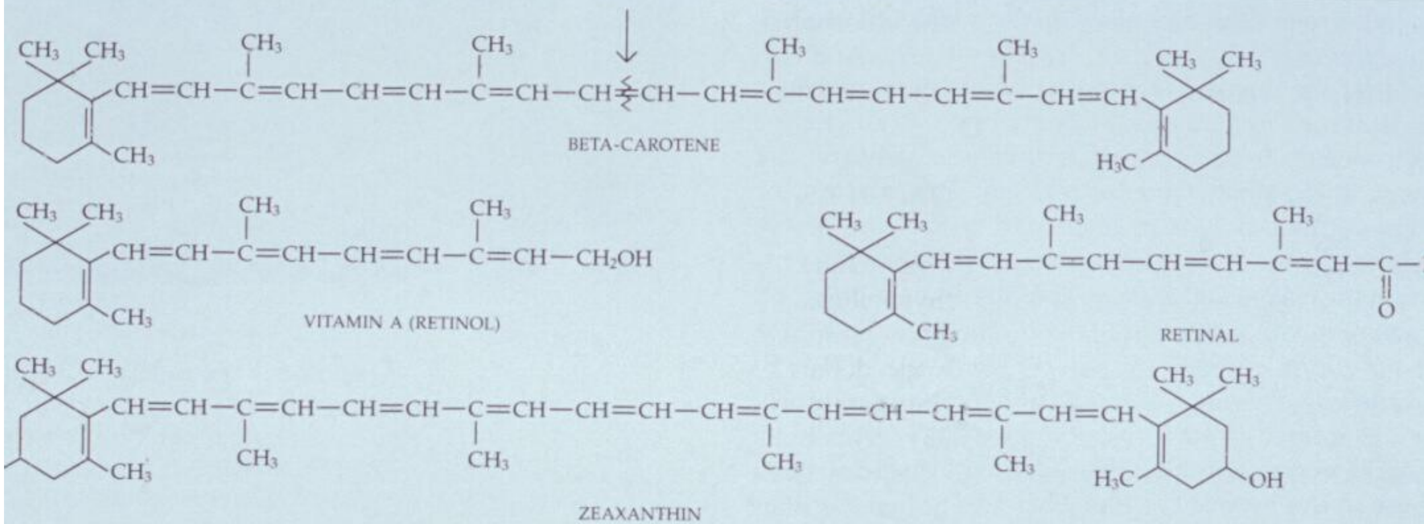
卟啉

Hydrocarbon tail
(H atoms not shown)

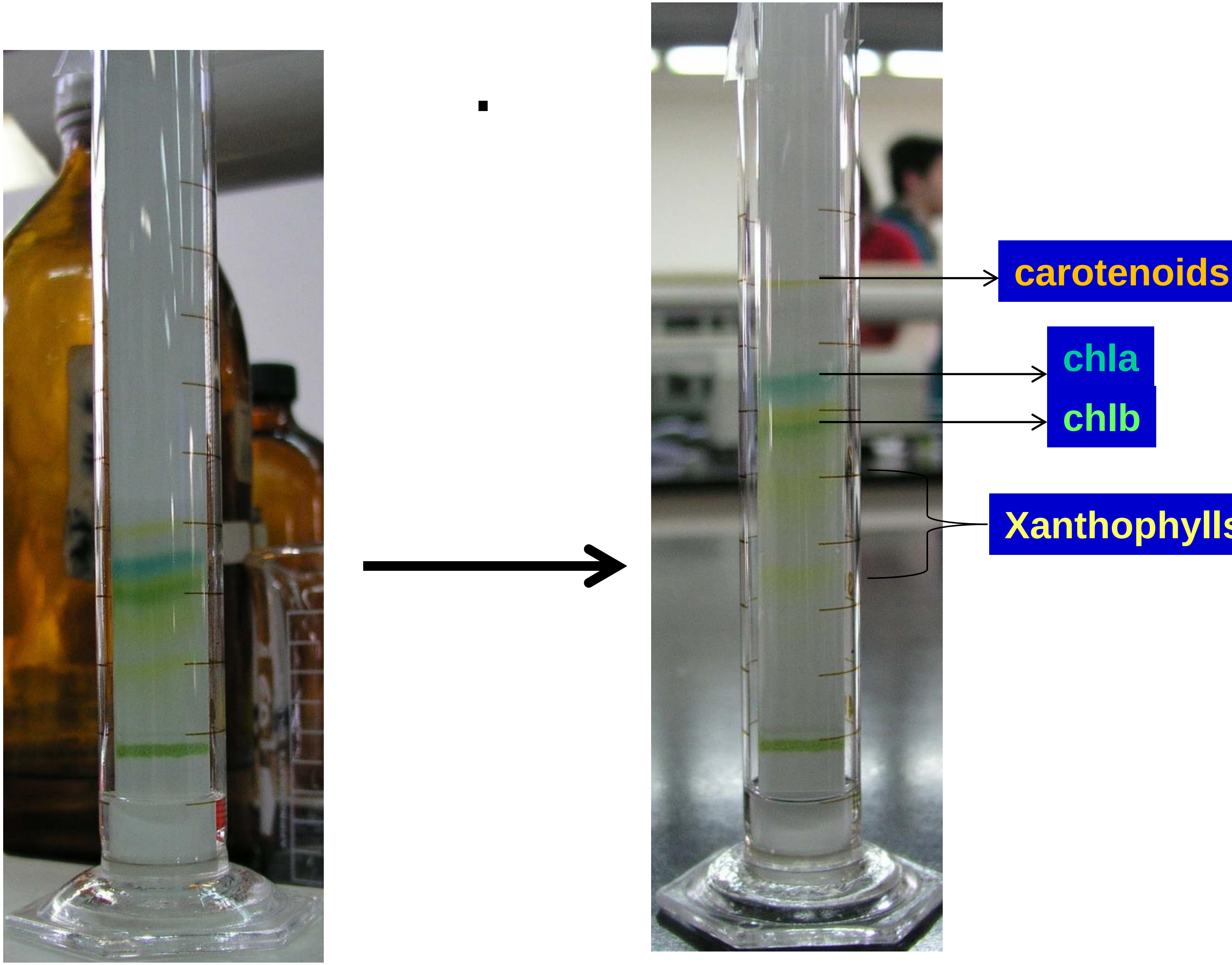
- Other accessory pigments
  - Absorb different wavelengths of light and pass the energy to **chlorophyll a**


(A) Chlorophylls
Chlorophyll a
Chlorophyll b
Bacteriochlorophyll a
(B) Carotenoids
β-Carotene
(C) Bilin pigments
Phycoerythrobilin

類胡蘿蔔素



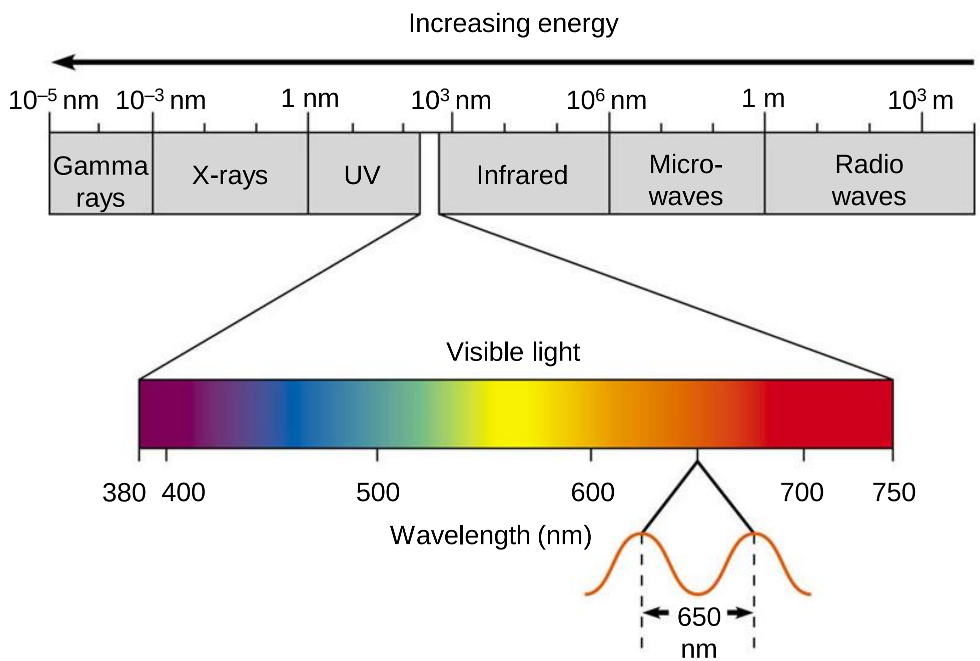
ited carotenoids. Cleavage of the -carotene molecule at the point indi- d by the arrow yields two molecules itamin A (retinol). Oxidation of vitamin A yields retinal, the pigment involved in vision. Note the conjugated bonds (alternating single and double bonds) in the carbon chains. Zeaxanthin (a xanthophyll) is the pigment responsib for the yellow color of corn (Zea mays) kernels.



carotenoids
chla
chlb
Xanthophylls

THE LIGHT REACTIONS: CONVERTING SOLAR ENERGY TO CHEMICAL ENERGY

- Visible radiation drives the light reactions
  - Certain wavelengths of visible light, absorbed by pigments
    - Drive the light reactions of photosynthesis



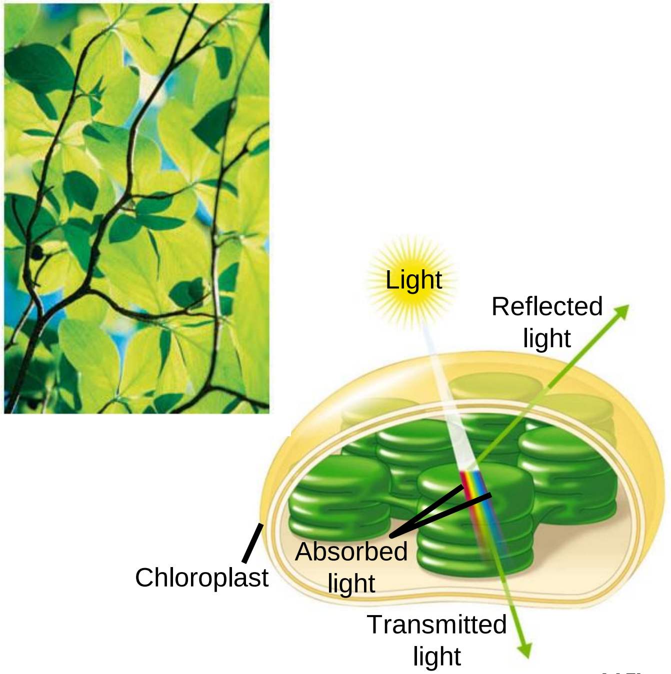


Figure 7.6A, B

7.7 Photosystems capture solar energy

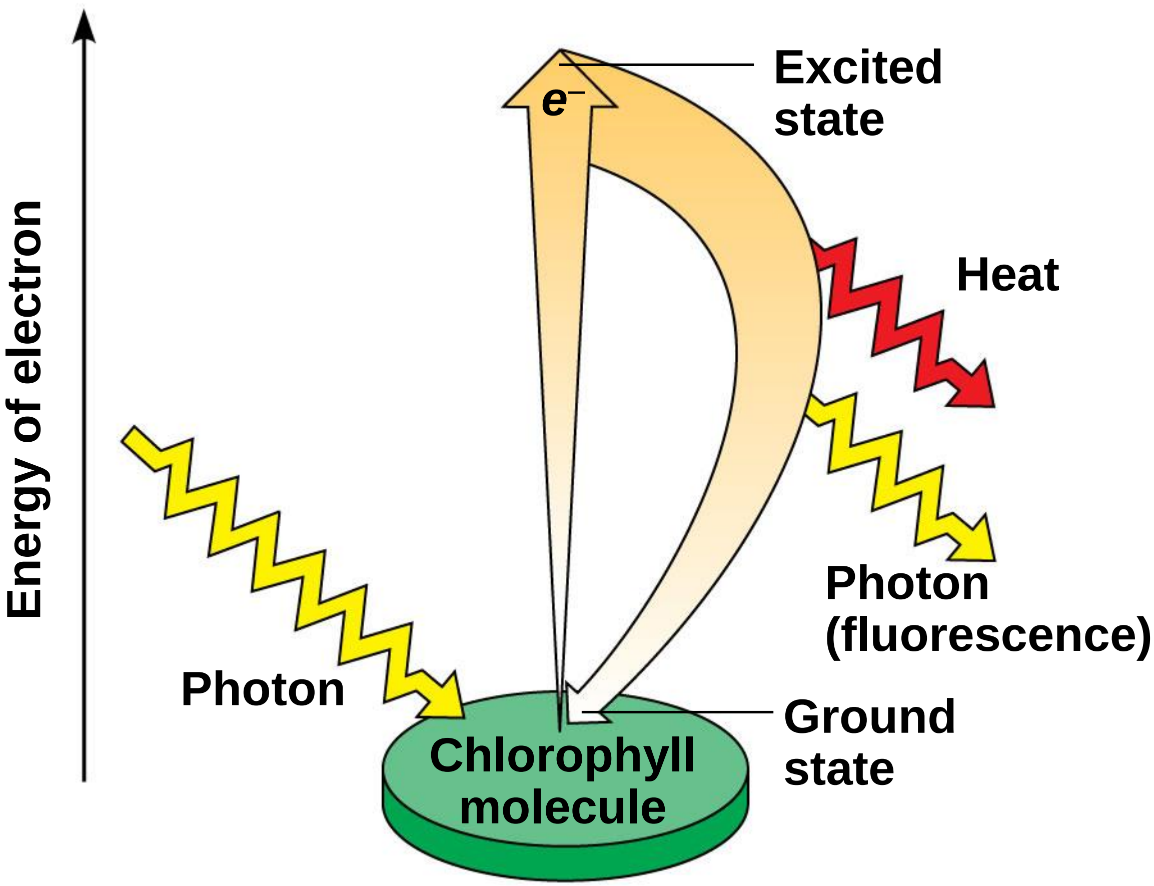
- Pigments in chloroplasts absorb photons (capturing solar power), which
  - increases the potential energy of the pigments' electrons and
  - sends the electrons into an unstable state.

- Generally, when isolated pigment molecules absorb light, their excited electrons drop back down to the ground state and release their excess energy as heat.

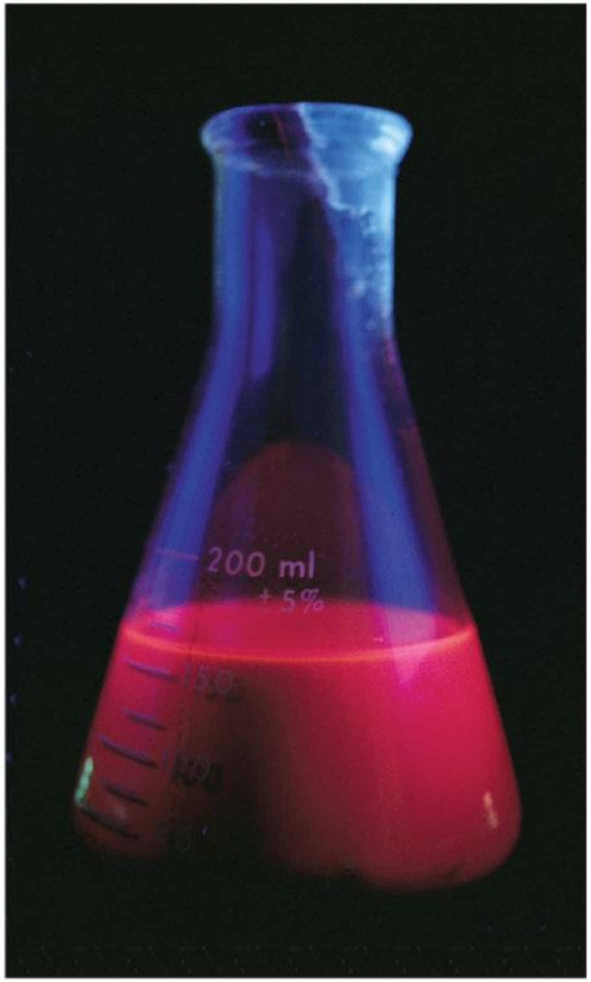
Excitation of Chlorophyll by Light

- When a pigment absorbs light, it goes from a ground state to an excited state, which is unstable
- When excited electrons fall back to the ground state, photons are given off, an afterglow called **fluorescence**螢光
- If illuminated, an isolated solution of chlorophyll will fluoresce, **giving off light and heat**

Figure 10.12



(a) Excitation of isolated chlorophyll molecule



(b) Fluorescence

Excitation of Chlorophyll by Light

- When a pigment absorbs light
  - It goes from a **ground state**基態 to an **excited state**激發態, which is unstable

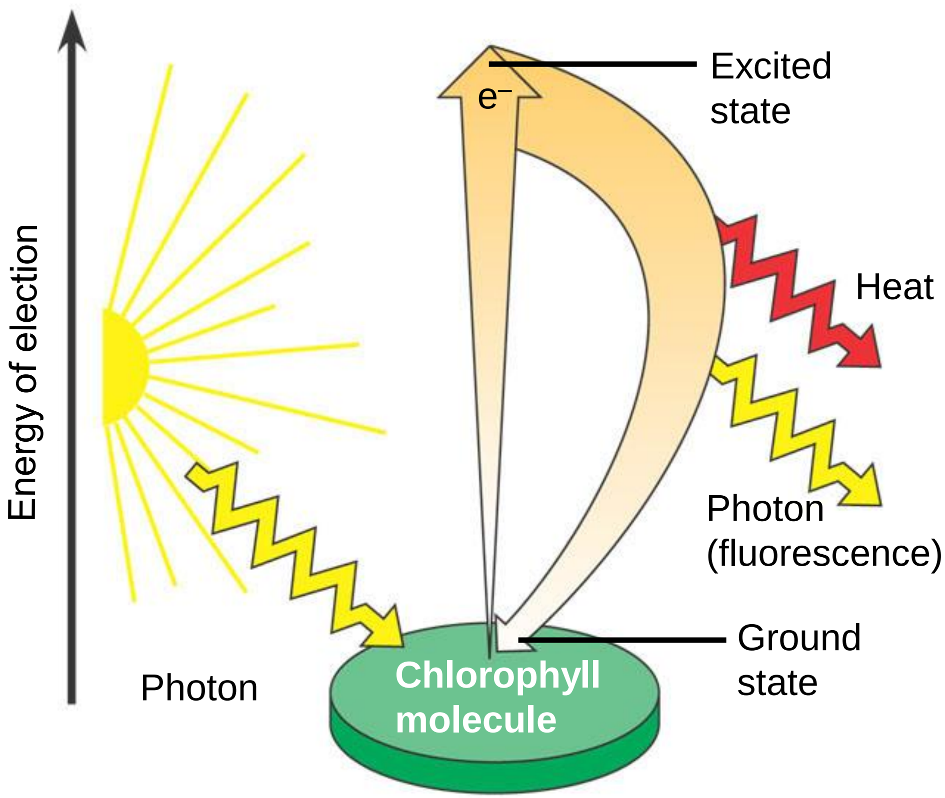


Figure 10.11 A

- If an isolated solution of chlorophyll is illuminated
  - It will **fluoresce**螢光, giving off **light and heat**

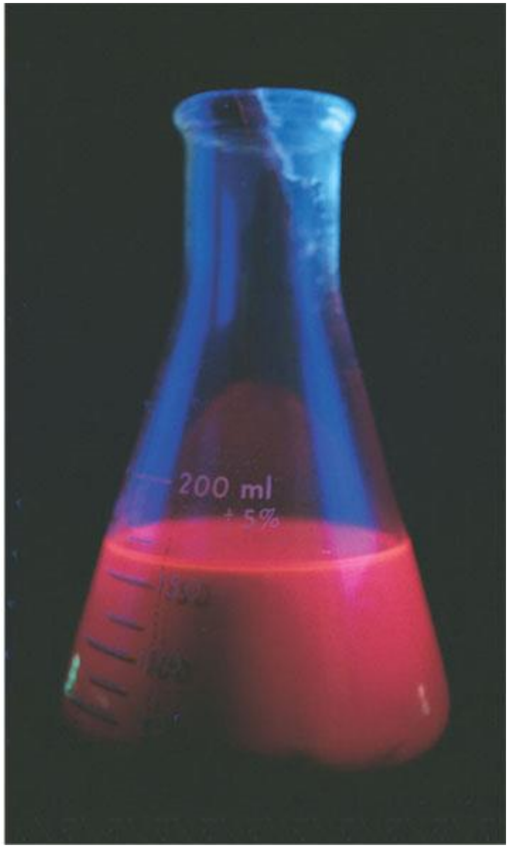


Figure 10.11 B

- Other accessory pigments
  - Absorb different wavelengths of light and pass the energy to **chlorophyll a**

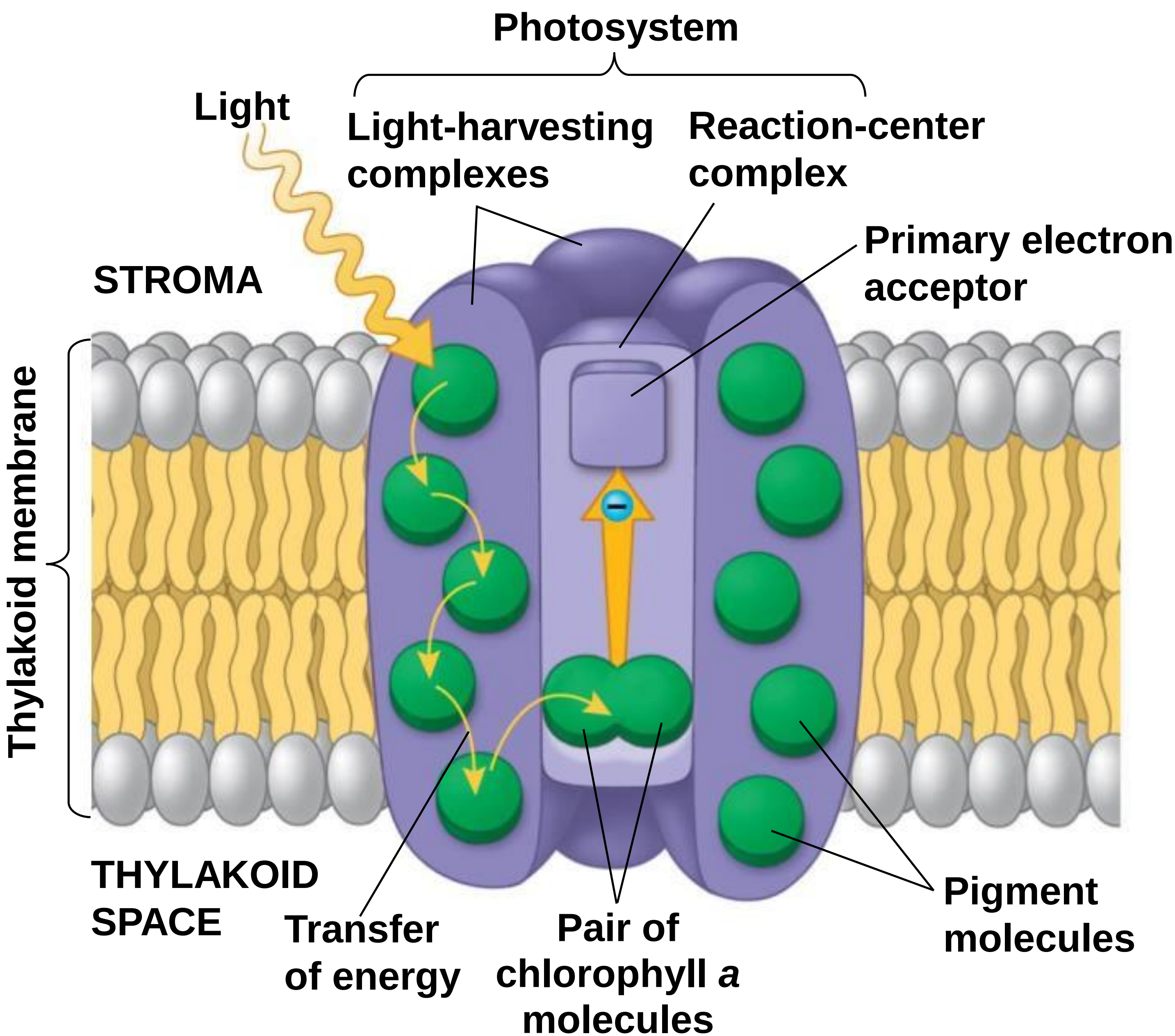
Photosystems capture solar energy

- Within a thylakoid membrane, chlorophyll and other pigment molecules
  - absorb photons and
  - transfer the energy to other pigment molecules.
- In the thylakoid membrane, chlorophyll molecules are organized along with other pigments and proteins into photosystems.

Photosystems capture solar energy

- A **photosystem** consists of a number of light-harvesting complexes surrounding a reaction-center complex.
- A light-harvesting complex contains various pigment molecules bound to proteins.
- Collectively, the light-harvesting complexes function as a light-gathering antenna.

Figure 7.7b



Photosystem
Light
Light-harvesting complexes
Reaction-center complex
Primary electron acceptor
STROMA
Thylakoid membrane
THYLAKOID SPACE
Transfer of energy
Pair of chlorophyll *a* molecules
Pigment molecules

- 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.

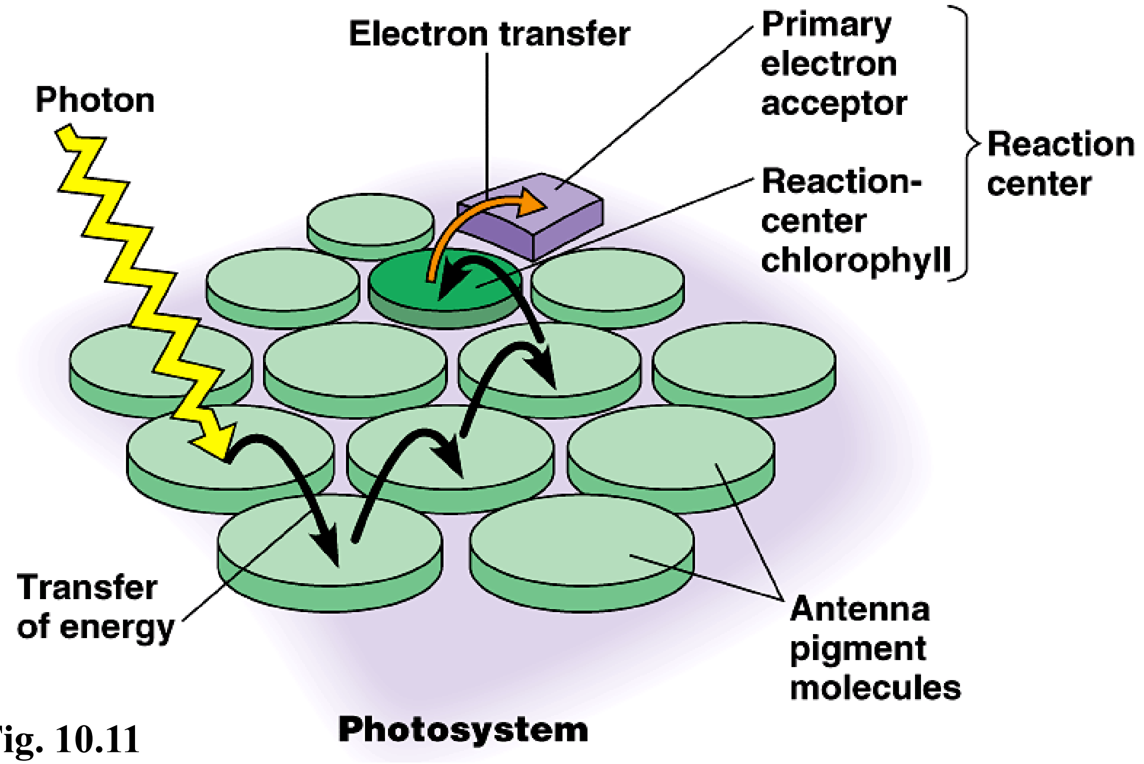


Fig. 10.11

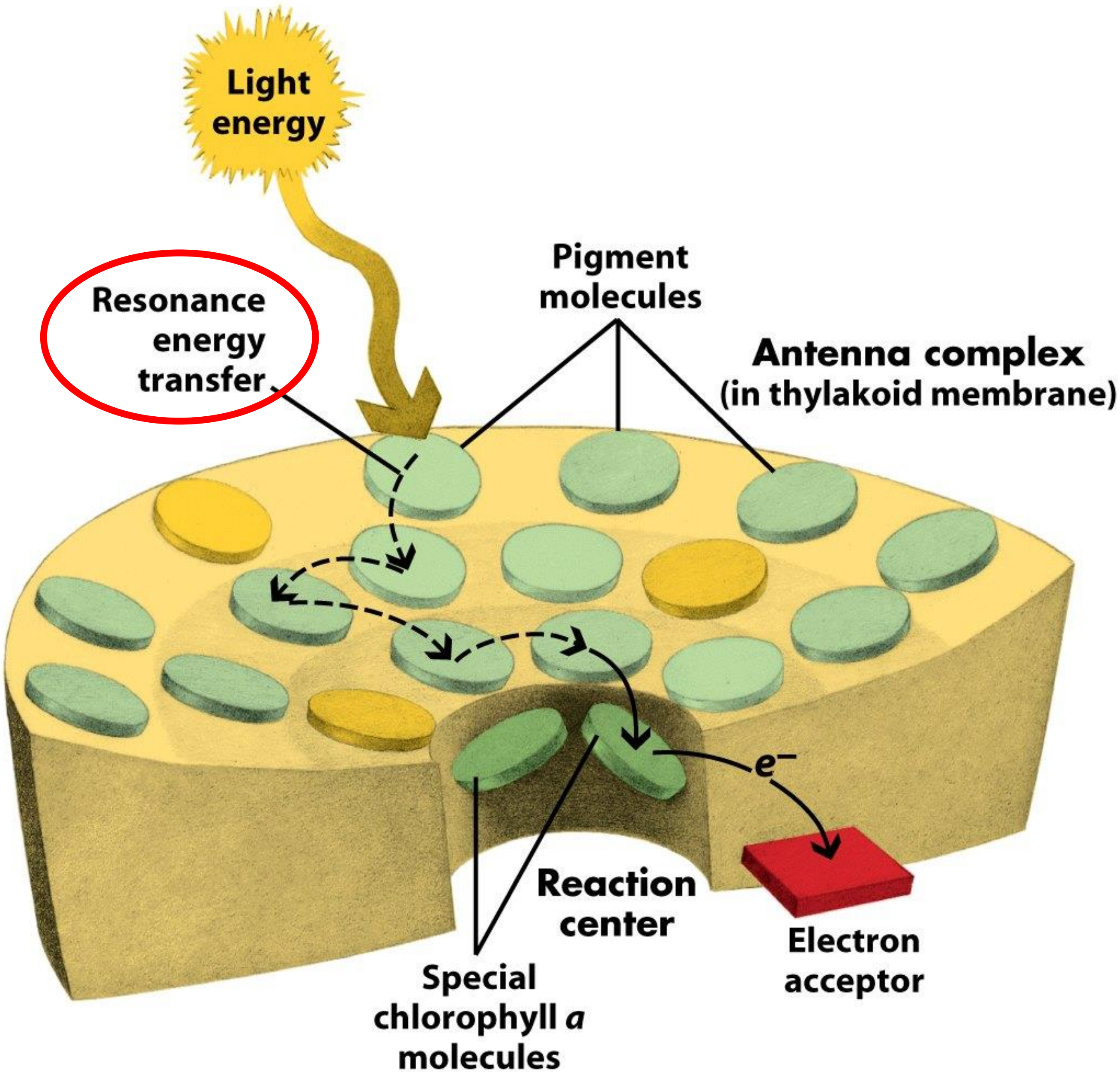


Figure 7-10
Biology of Plants, Seventh Edition

- When a reaction-center chlorophyll molecule absorbs energy
  - One of its electrons gets bumped up to a primary electron acceptor

- The thylakoid membrane
  - Is populated by two types of **photosystems, I and II**

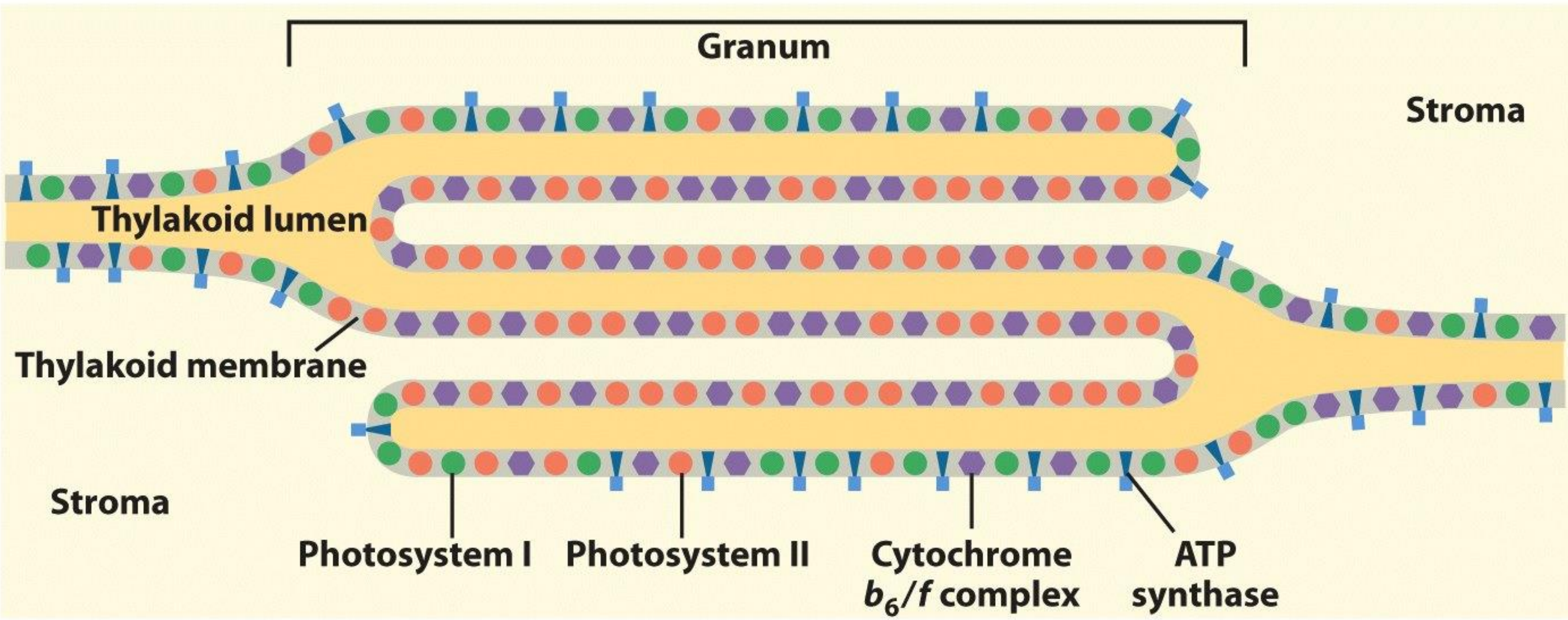


Figure 7-13
Biology of Plants, Seventh Edition

- In the light reactions, electron transport chains generate ATP and NADPH
  - Two connected photosystems absorb photons of light
    - And transfer the energy to chlorophyll P680 and P700

Photosystems capture solar energy

- The light energy is passed from molecule to molecule within the photosystem.
  - Finally it reaches the reaction center, where a primary electron acceptor accepts these electrons and consequently becomes reduced.
  - The solar-powered transfer of an electron from the reaction-center chlorophyll a pair to the primary electron acceptor is the first step in the transformation of light energy to chemical energy in the light reactions.

Photosystems capture solar energy

- Two types of photosystems (photosystem I and photosystem II) cooperate in the light reactions.
- Each photosystem has a characteristic reaction-center complex, with a special pair of chlorophyll *a* molecules associated with a particular primary electron acceptor.

7.8 Two photosystems connected by an electron transport chain generate ATP and NADPH

- In the light reactions, light energy is transformed into the chemical energy of ATP and NADPH.
- To accomplish this, electrons are
  - removed from water,
  - passed from photosystem II to photosystem I, and
  - accepted by $NADP^+$, reducing it to NADPH.
- Between the two photosystems, the electrons
  - move down an electron transport chain and
  - provide energy for the synthesis of ATP.

Two photosystems connected by an electron transport chain generate ATP and NADPH

- A simple mechanical analogy helps unpack this rather complicated system.
- This construction analogy shows how the coupling of two photosystems and an electron transport chain can transform the energy of light to the chemical energy of ATP and NADPH.

Linear Electron Flow

- Linear electron flow
  - Is the primary pathway of energy transformation in the light reactions

產生1/2 O_2, 6ATP, 6NADPH + $6H^+$

Photolysis光解作用

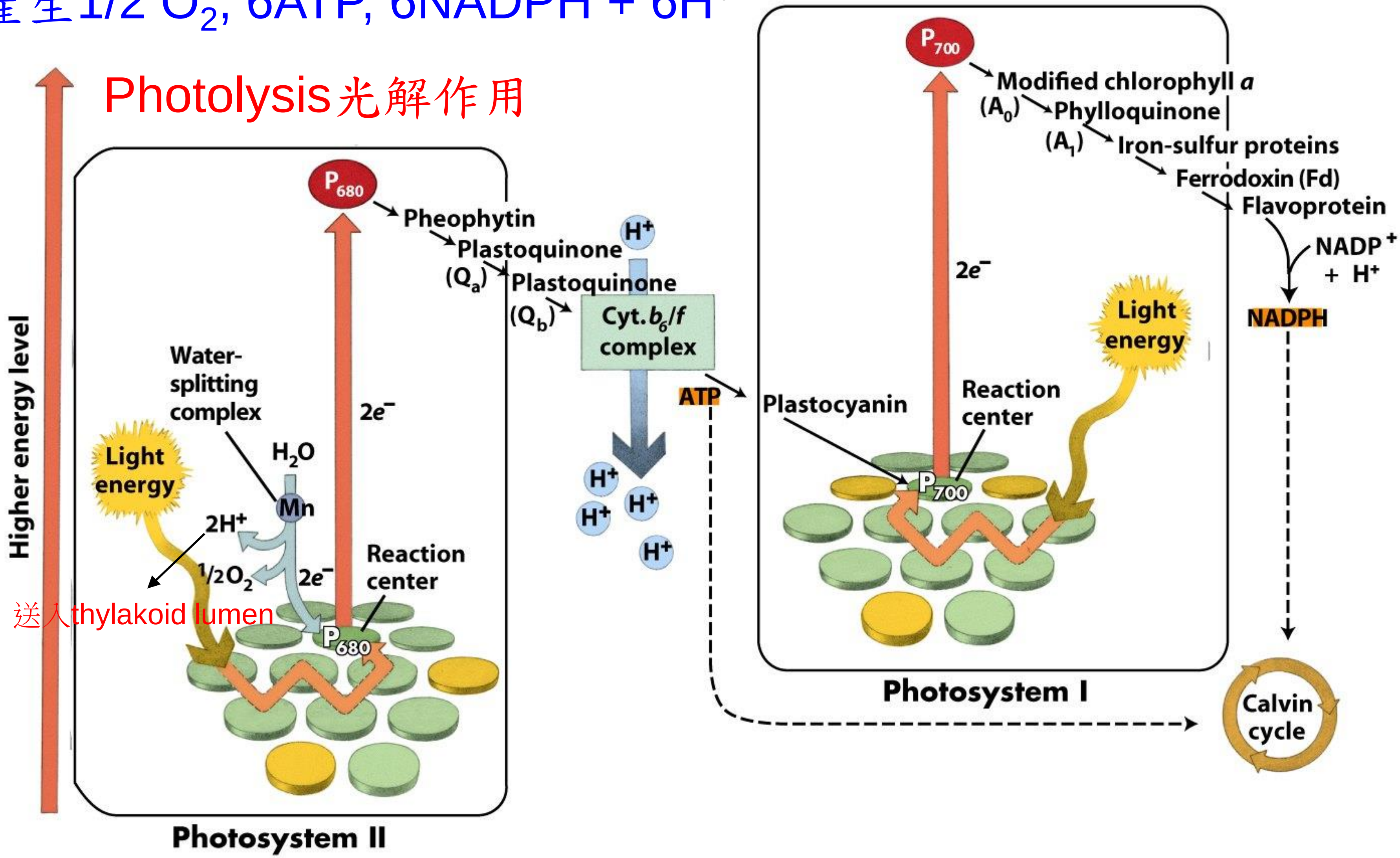


Figure 7-11
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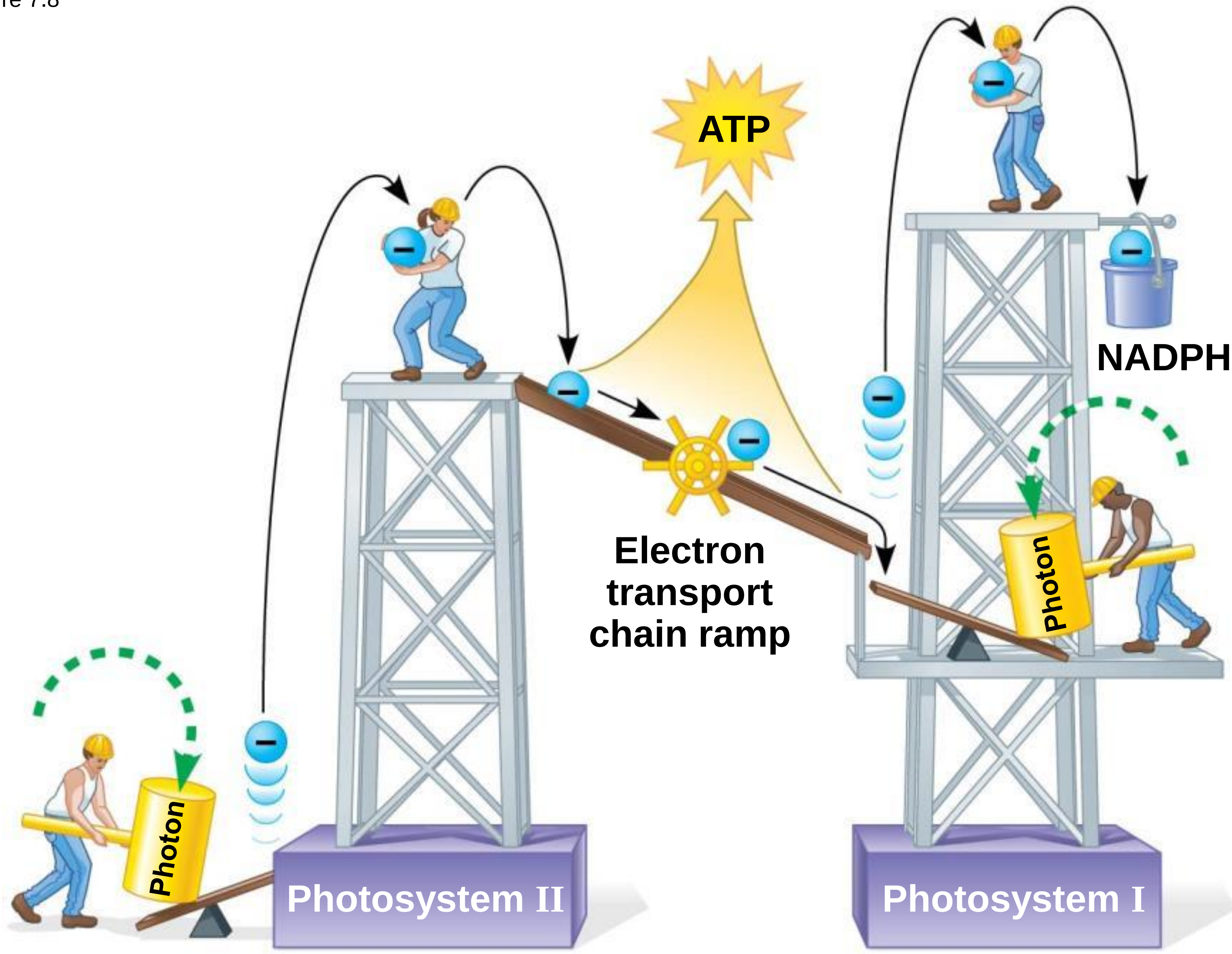
Z protein: Mn–containing protein

- Photosystem II regains electrons by splitting water
  - Releasing O_2

Figure 7.8



ATP
NADPH
Electron transport chain ramp
Photon
Photon
Photosystem II
Photosystem I

Cyclic Electron Flow

- Under certain conditions
  - Photoexcited electrons take an alternative path

- **In cyclic electron flow**
  - Only photosystem I is used
  - Only ATP is produced

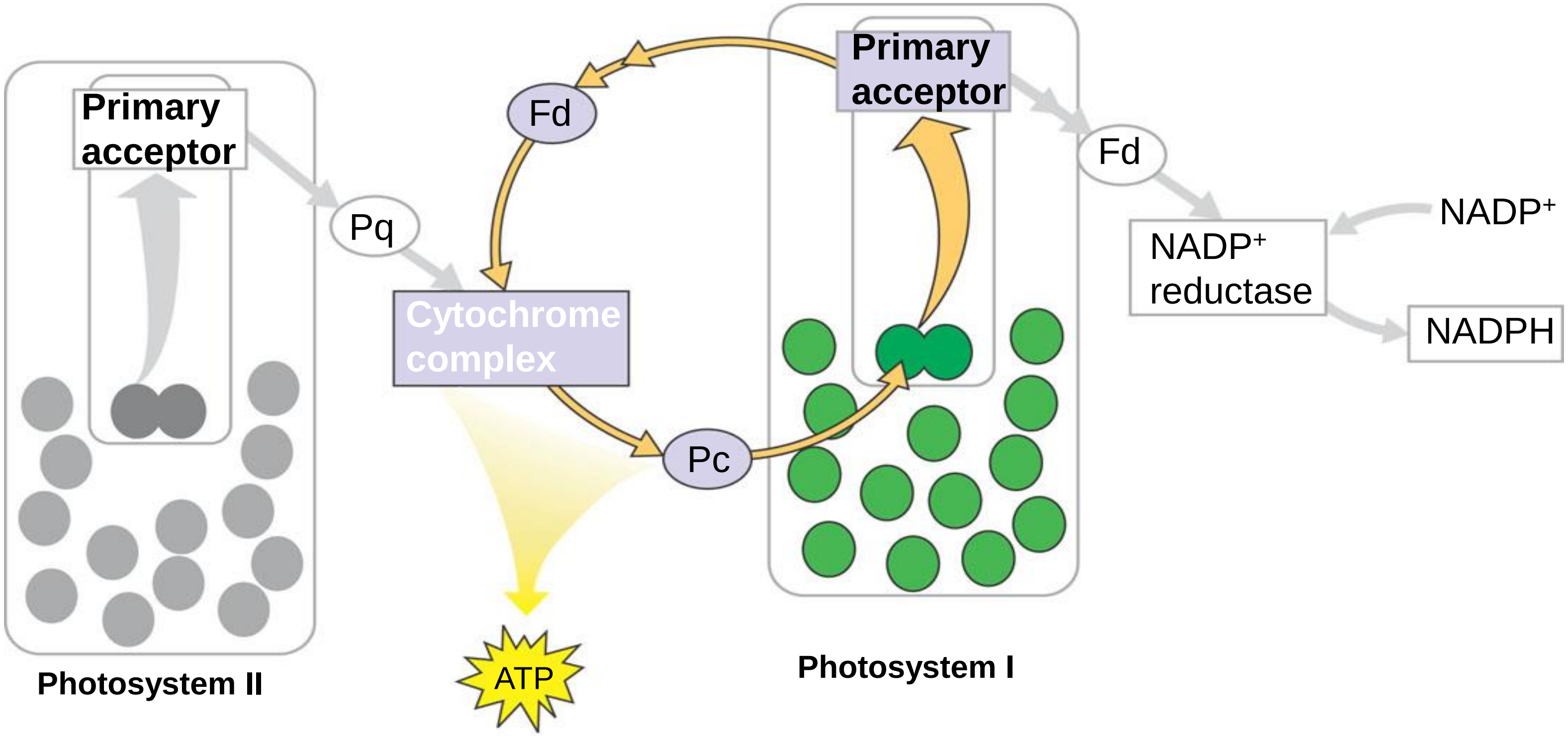
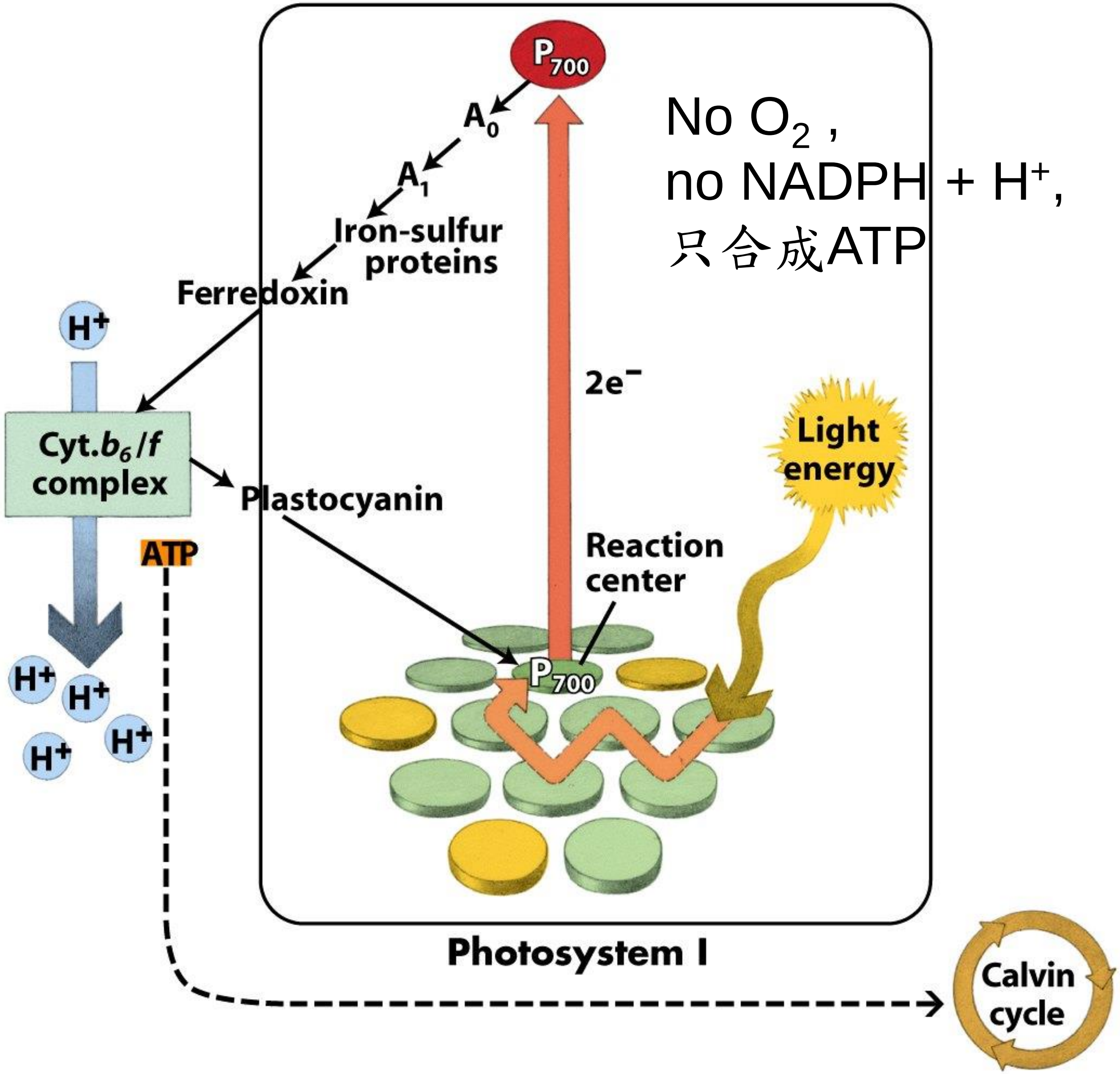


Figure 10.15



No O_2 ,
no NADPH + H^+,
只合成ATP

Figure 7-14
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Cyclic Electron Flow

- Most primitive photosynthetic mechanism
- Bacteria, eukaryotes

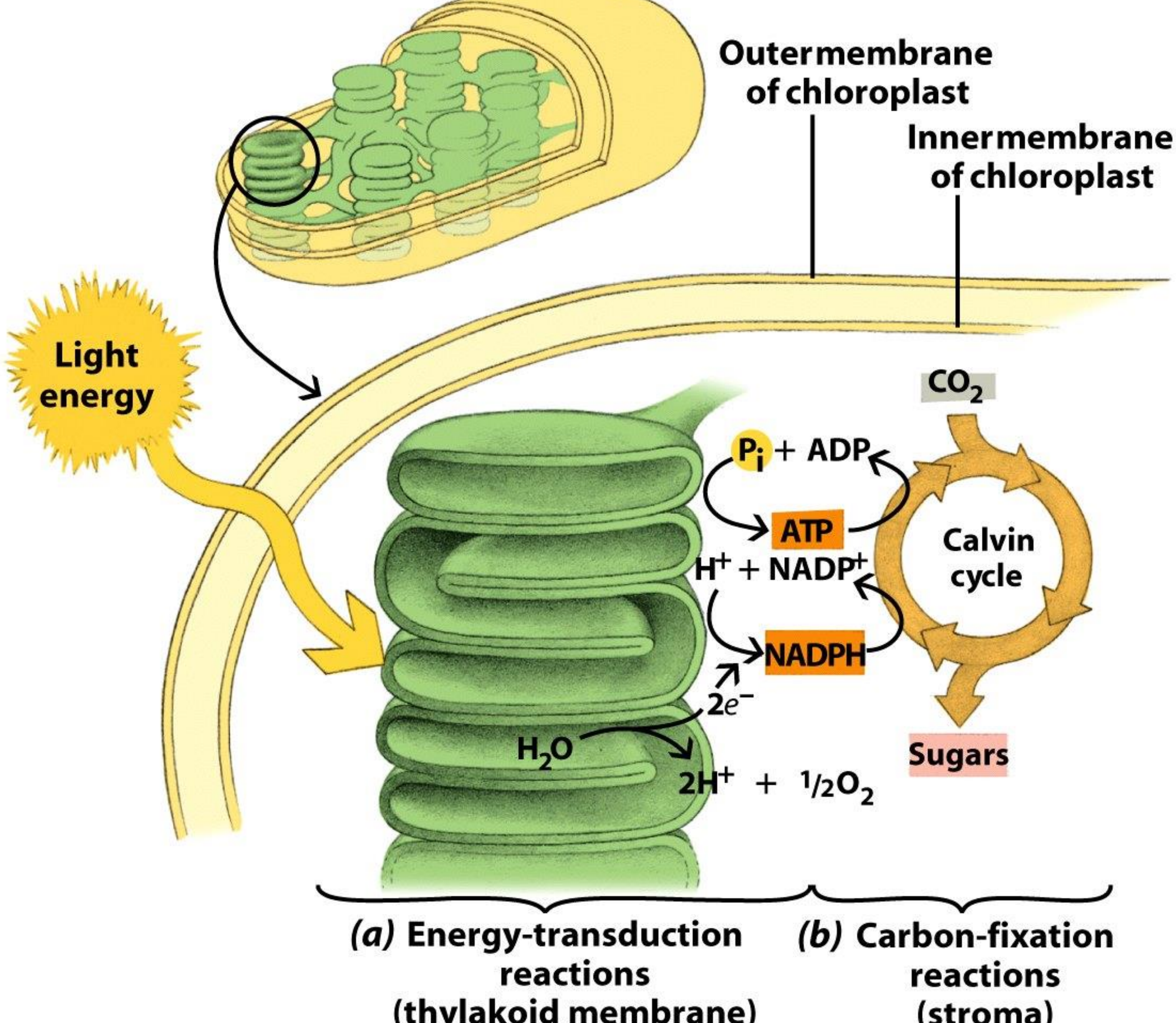

Figure 7-9
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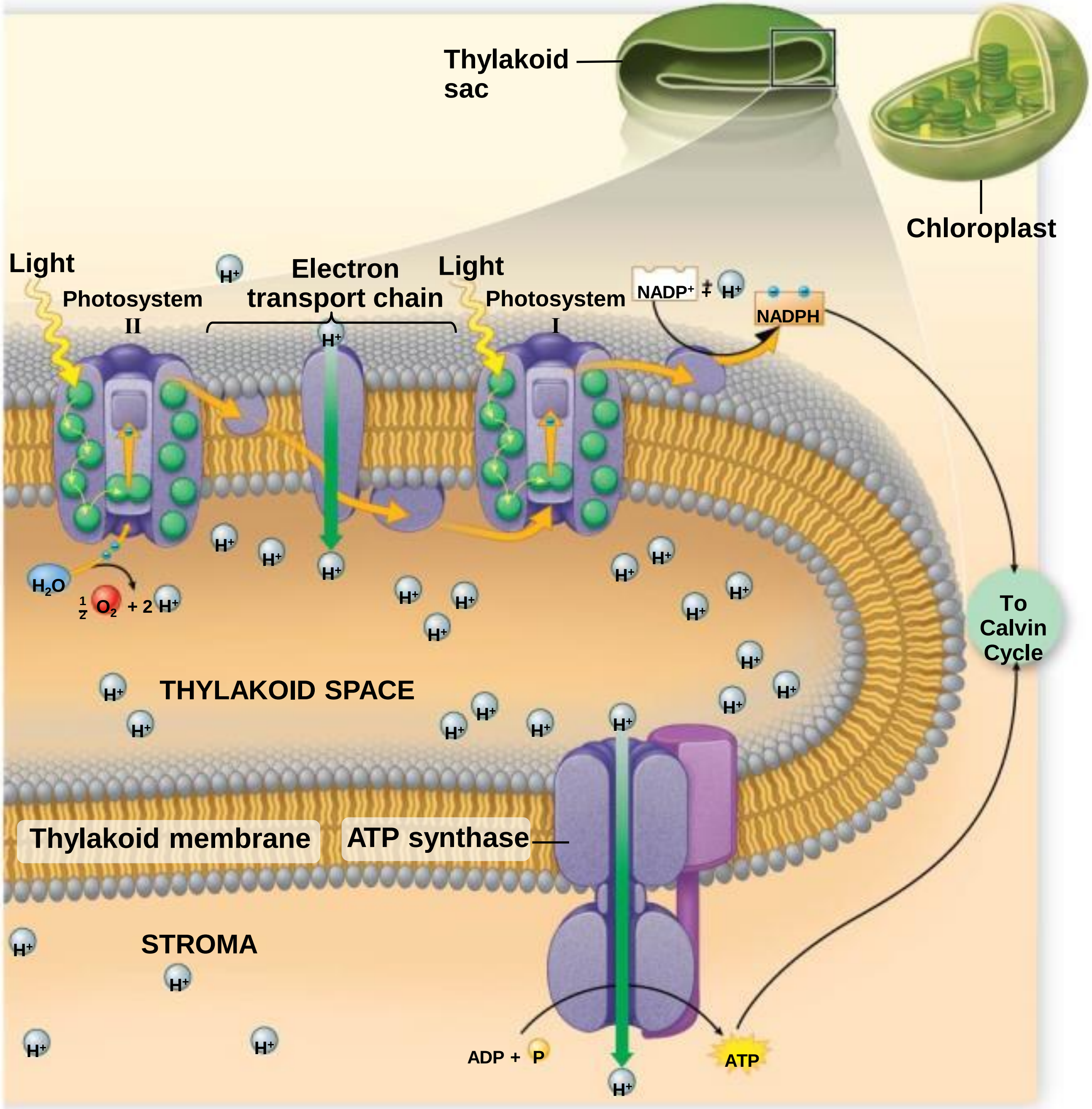
- Chemiosmosis powers ATP synthesis in the light reactions
  - The electron transport chain
    - Pumps H^+ into the thylakoid space

Figure 7.9-0



Thylakoid sac
Chloroplast
Light
Photosystem II
H+
Electron transport chain
Light
Photosystem I
NADP+ + H+
NADPH
H2O
1/2 O2 + 2 H+
THYLAKOID SPACE
To Calvin Cycle
Thylakoid membrane
ATP synthase
STROMA
ADP + P
ATP

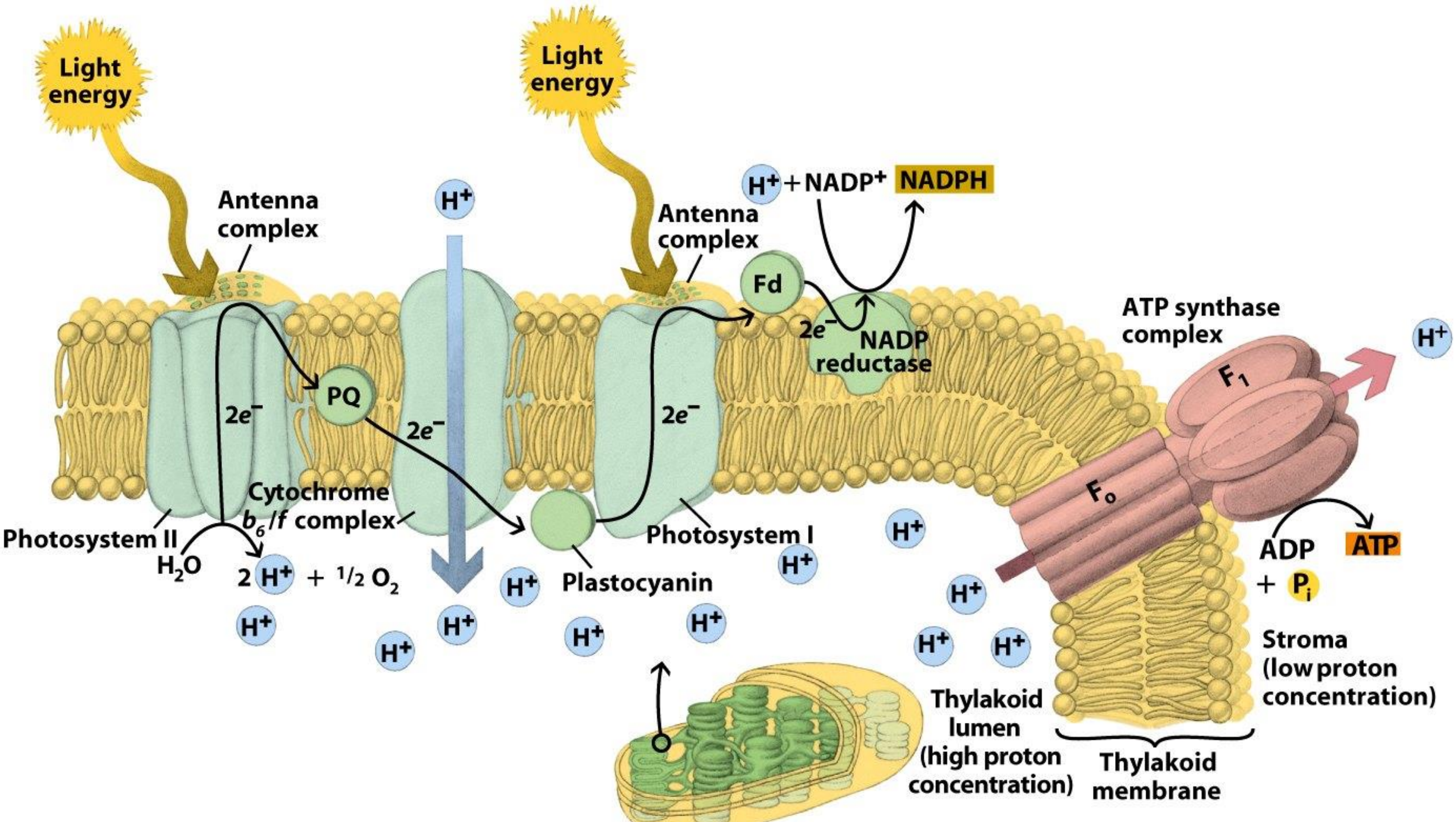


Figure 7-12
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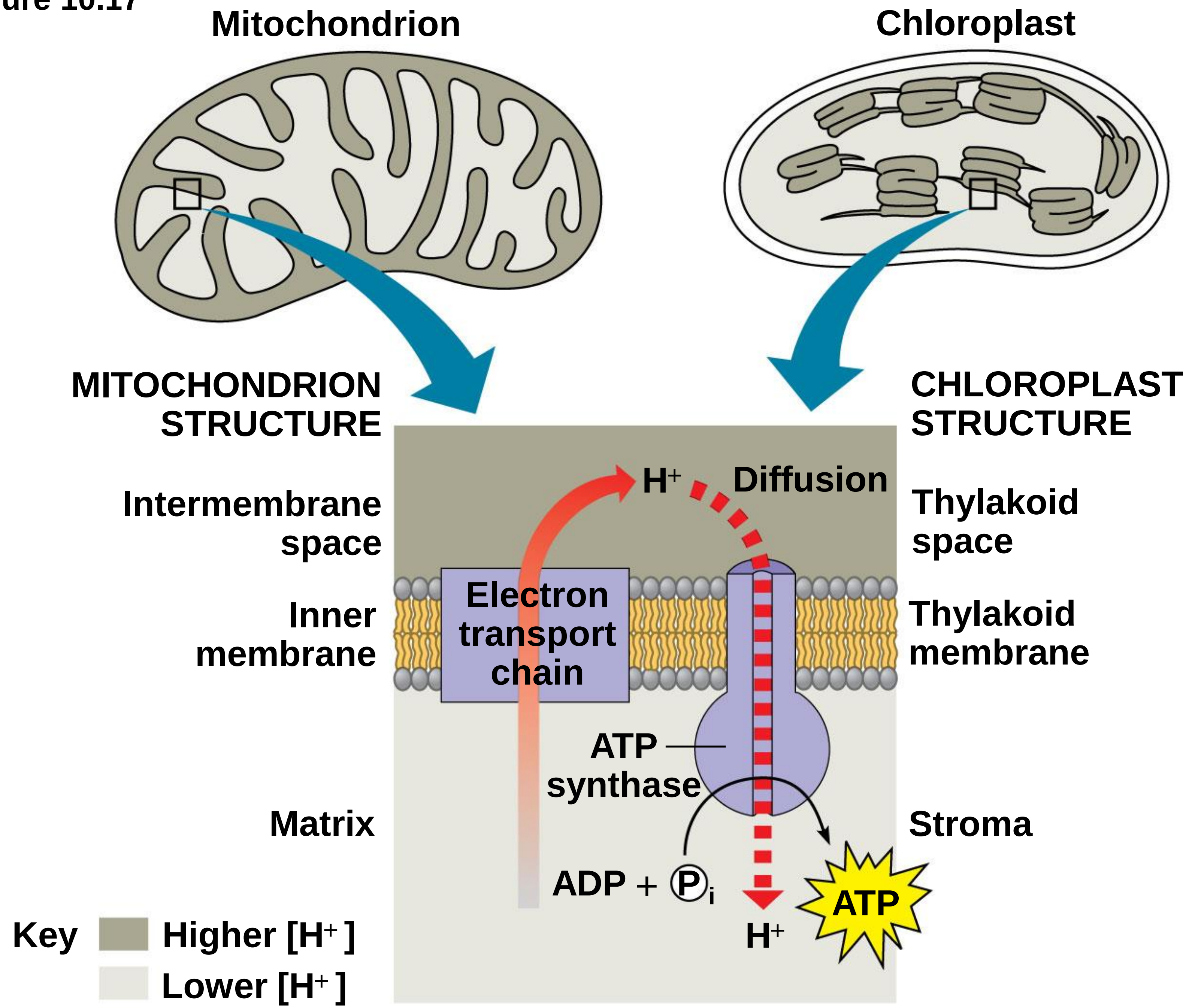
- pH: - log [H^+]
- H^+ conc. = 10^{-5} : pH 5
- H^+ conc. = 10^{-8} : pH 8
- 相差1000 x
- pH gradient

- In both organelles
  - Redox reactions of electron transport chains generate a H^+ gradient across a membrane
- **ATP synthase**
  - Uses this **proton-motive force** to make ATP

A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria
  - Generate ATP by the same basic mechanism: chemiosmosis
  - But use different sources of energy to accomplish this

Figure 10.17



Mitochondrion
Chloroplast
MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Intermembrane space
Inner membrane
Matrix
Thylakoid space
Thylakoid membrane
Stroma
H+
Diffusion
Electron transport chain
ATP synthase
ADP + P i
ATP
H+
Key
Higher [H+]
Lower [H+]

The Calvin Cycle: Reducing CO_2 to Sugar

The biochemical reactions of photosynthesis

- 1950s **Melvin Calvin** and his colleagues
- 1961 Nobel Prize
- C^{14} radioactive carbon
- 7 second exposure – 3*-PGA
- (3-phosphoglyceric acid)
- Ribulose-1,5-bisphosphate (RuBP) - 5C sugar
- RuBP + CO_2 $\longrightarrow$ unstable 6C $\longrightarrow$ 2 3-PGA

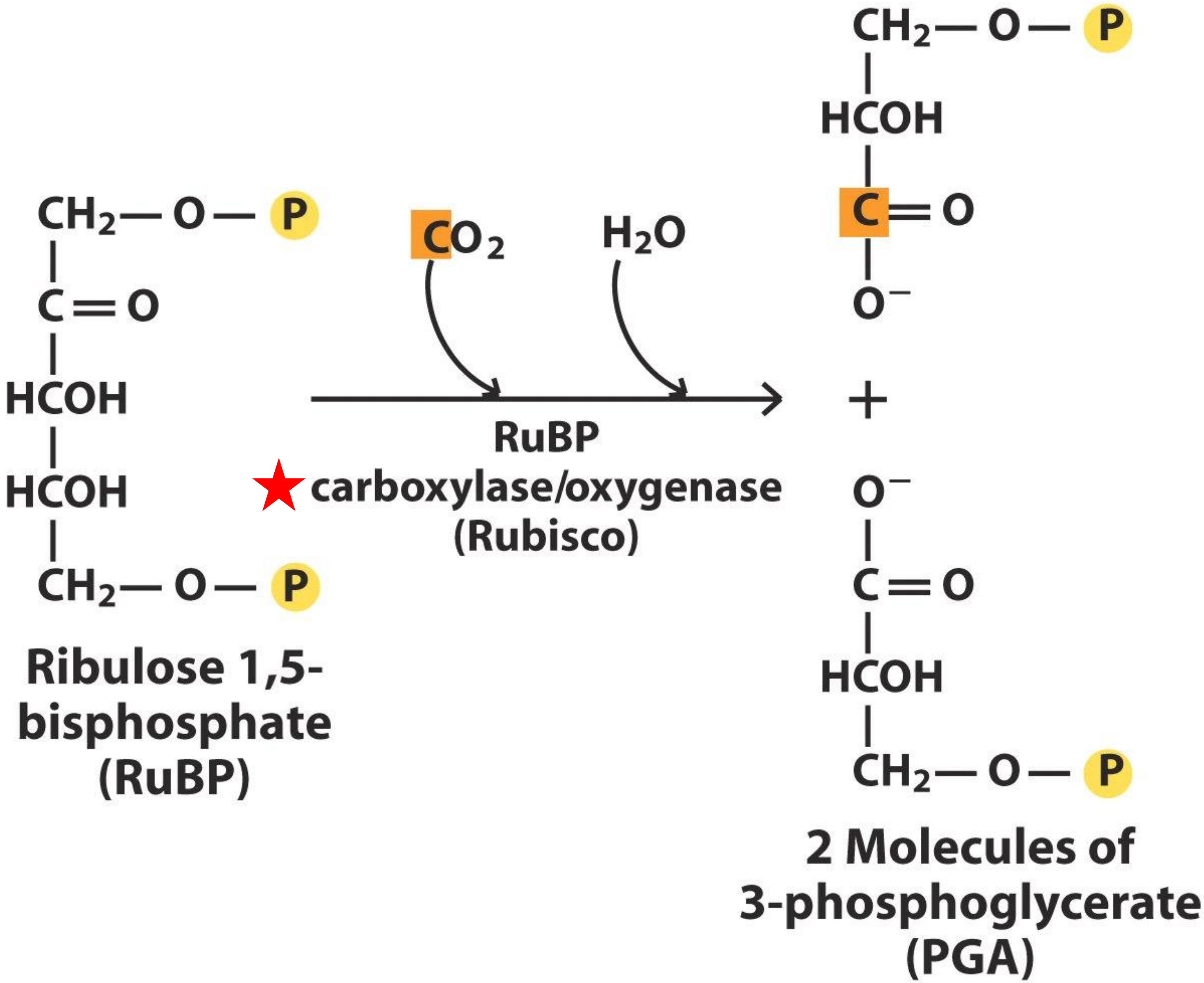


Figure 7-16
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- A large enzyme MW 490,000
- 8 large subunit – coded in the chloroplast
- 8 small subunit – coded in the nucleus
- The assembly of the large and small subunits into rubisco is controlled by light.
- Rubisco occurs in all autotrophs except a few species of bacteria and is the most important and abundant protein on earth. It makes up about 20%~25% of the soluble protein in leaves.

THE CALVIN CYCLE: CONVERTING CO_2 TO SUGARS

- ATP and NADPH power sugar synthesis in the Calvin cycle
  - The Calvin cycle
    - Occurs in the chloroplast's stroma
    - Consists of carbon fixation, reduction, release of G3P, and regeneration of RuBP

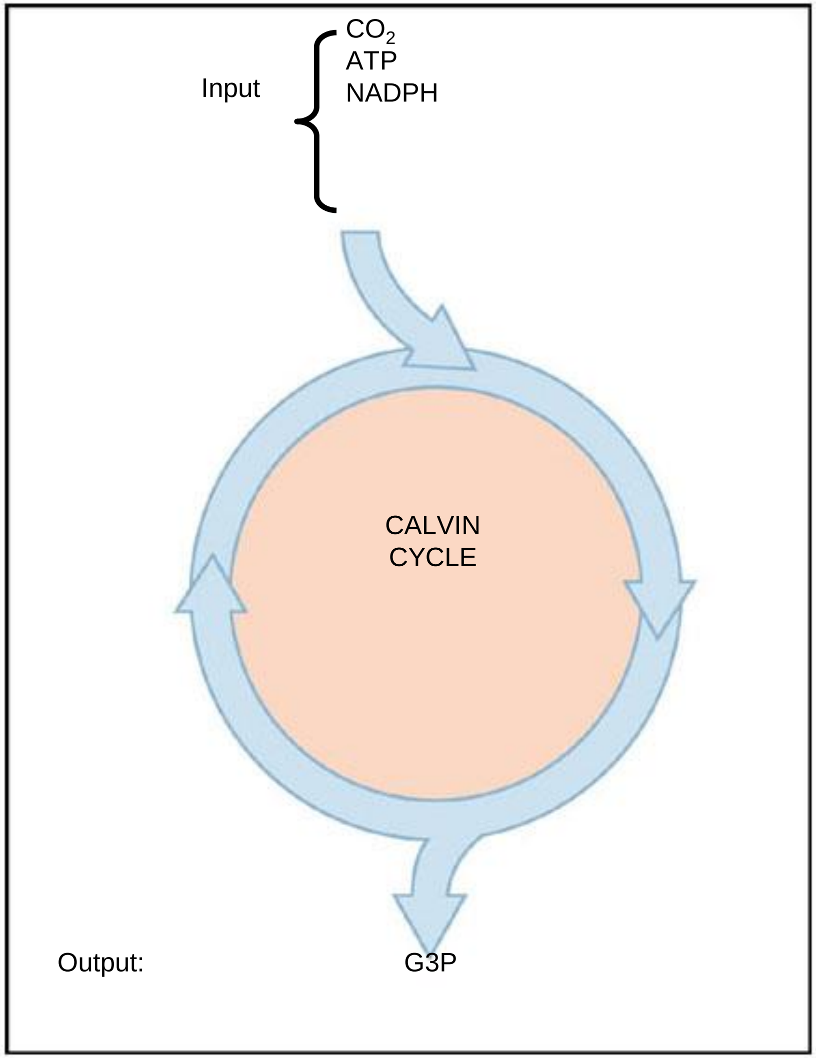
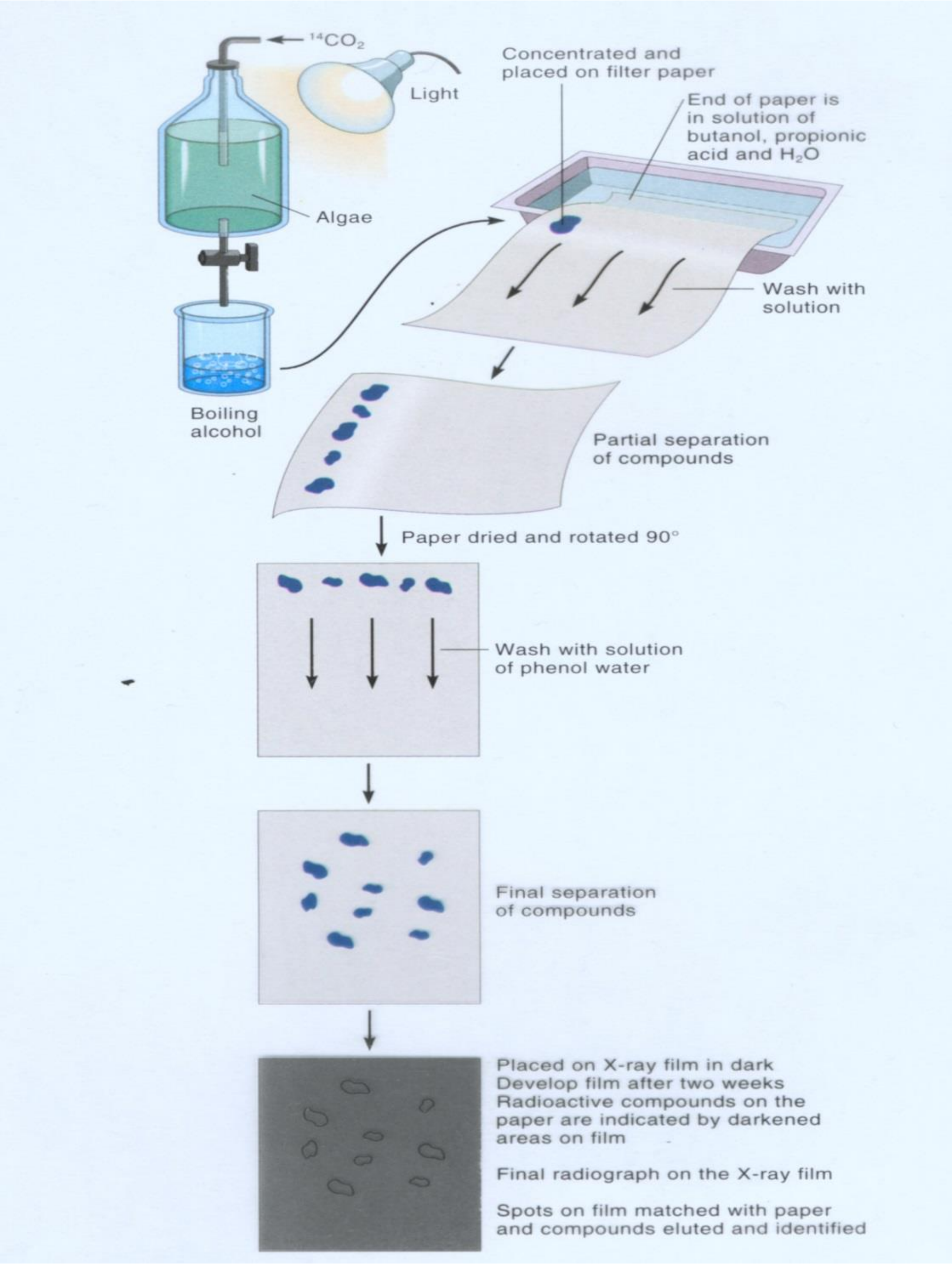


Figure 7.10A

- 利用C^{14}
- Chromatography色層分析
- Autoradiography自動顯影術



$^{14}CO_2$
Light
Concentrated and placed on filter paper
End of paper is in solution of butanol, propionic acid and H_2O
Algae
Wash with solution
Boiling alcohol
Partial separation of compounds
Paper dried and rotated 90°
Wash with solution of phenol water
Final separation of compounds
Placed on X-ray film in dark
Develop film after two weeks
Radioactive compounds on the paper are indicated by darkened areas on film
Final radiograph on the X-ray film
Spots on film matched with paper and compounds eluted and identified

- The Calvin cycle has three phases
  - Carbon fixation
  - Reduction
  - Regeneration of the CO_2 acceptor

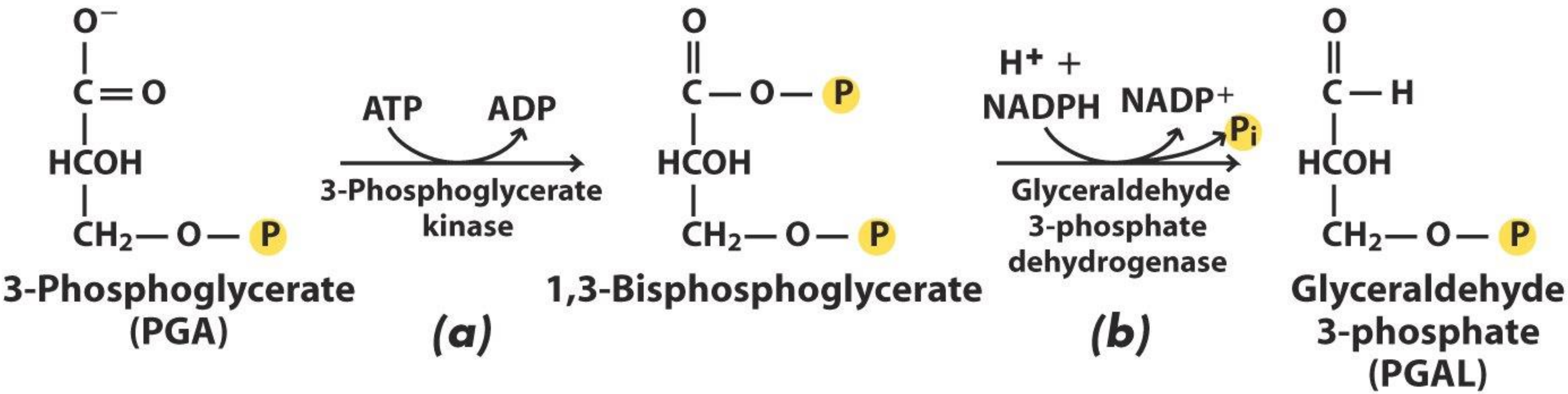


Figure 7-17
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Figure 7.10-2

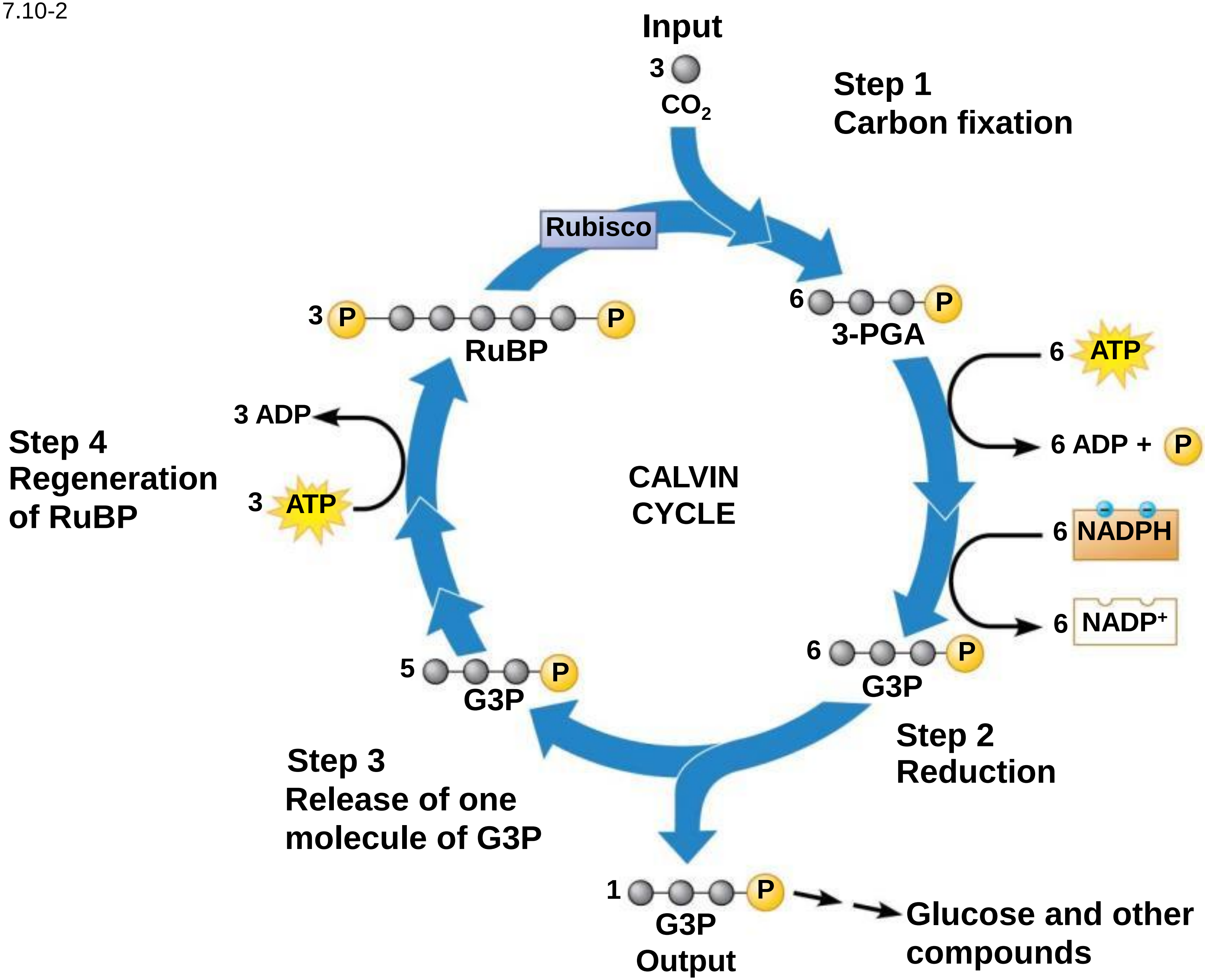
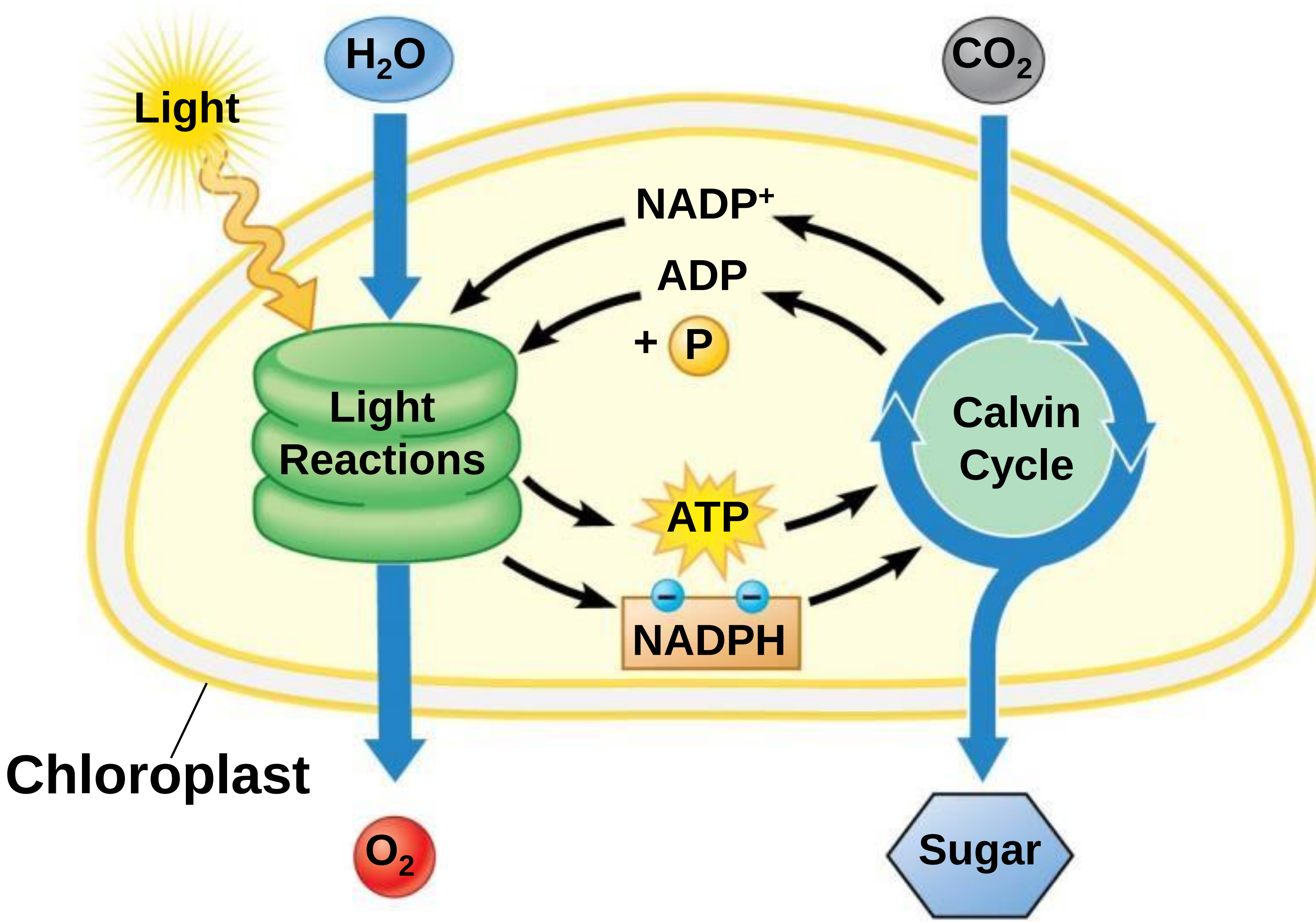

Input
3
CO_2
Step 1
Carbon fixation
Rubisco
6
P
3-PGA
6 ATP
6 ADP + P
6 NADPH
6 $NADP^+$
3
P
P
RuBP
3 ADP
Step 4
Regeneration
of RuBP
3 ATP
CALVIN
CYCLE
6
P
G3P
Step 2
Reduction
5
P
G3P
Step 3
Release of one
molecule of G3P
1
P
G3P
Output
Glucose and other
compounds

Figure 7.10-1

A review of photosynthesis



- Organic compounds produced by photosynthesis
  - Provide the energy and building material for ecosystems

Photorespiration: An Evolutionary Relic?

- In **photorespiration**光呼吸作用
  - O_2 substitutes for CO_2 in the active site of the enzyme rubisco
  - The photosynthetic rate is reduced

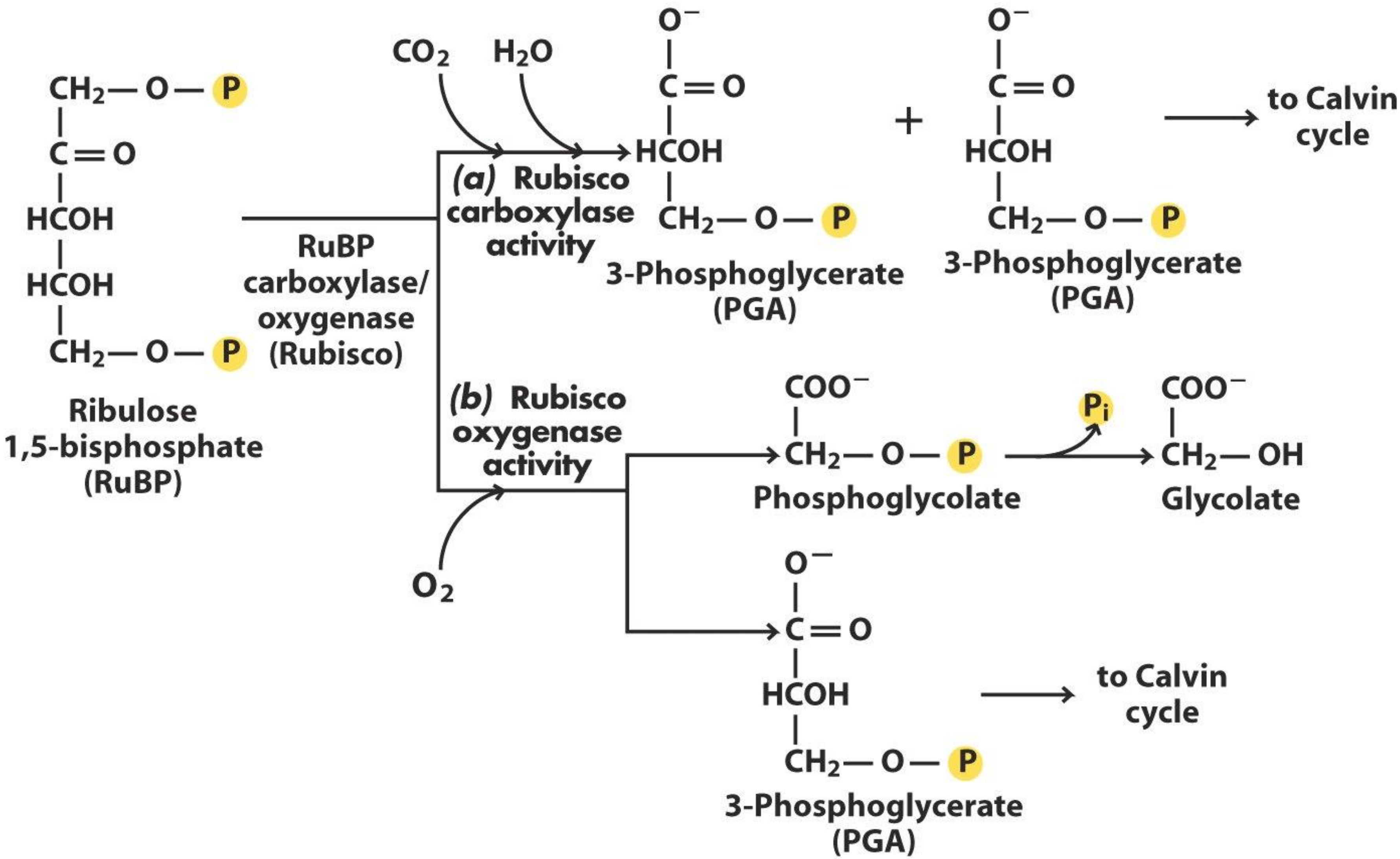


Figure 7-19
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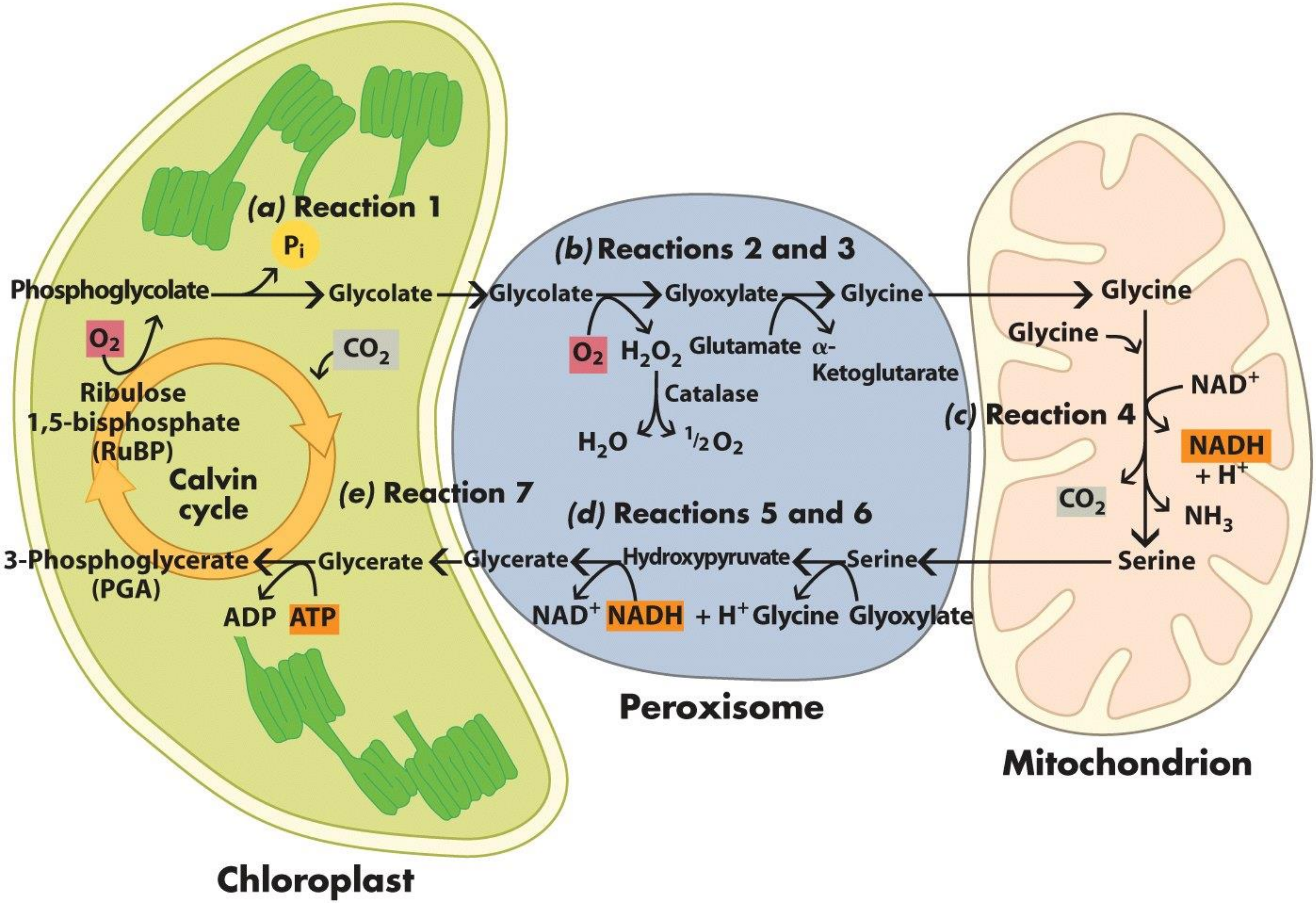

Figure 7-20
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- Concept : Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- On hot, dry days, plants close their stomata
  - Conserving water but limiting access to CO_2
  - Causing oxygen to build up

Figure 10.21a

C4

Sugarcane

C_4 Plants

- **C_4 plants** minimize the cost of photorespiration
  - By incorporating CO_2 into four carbon compounds in mesophyll cells

- These four carbon compounds
  - Are exported to bundle sheath cells, where they release CO_2 used in the Calvin cycle

- C_4 leaf anatomy and the C_4 pathway

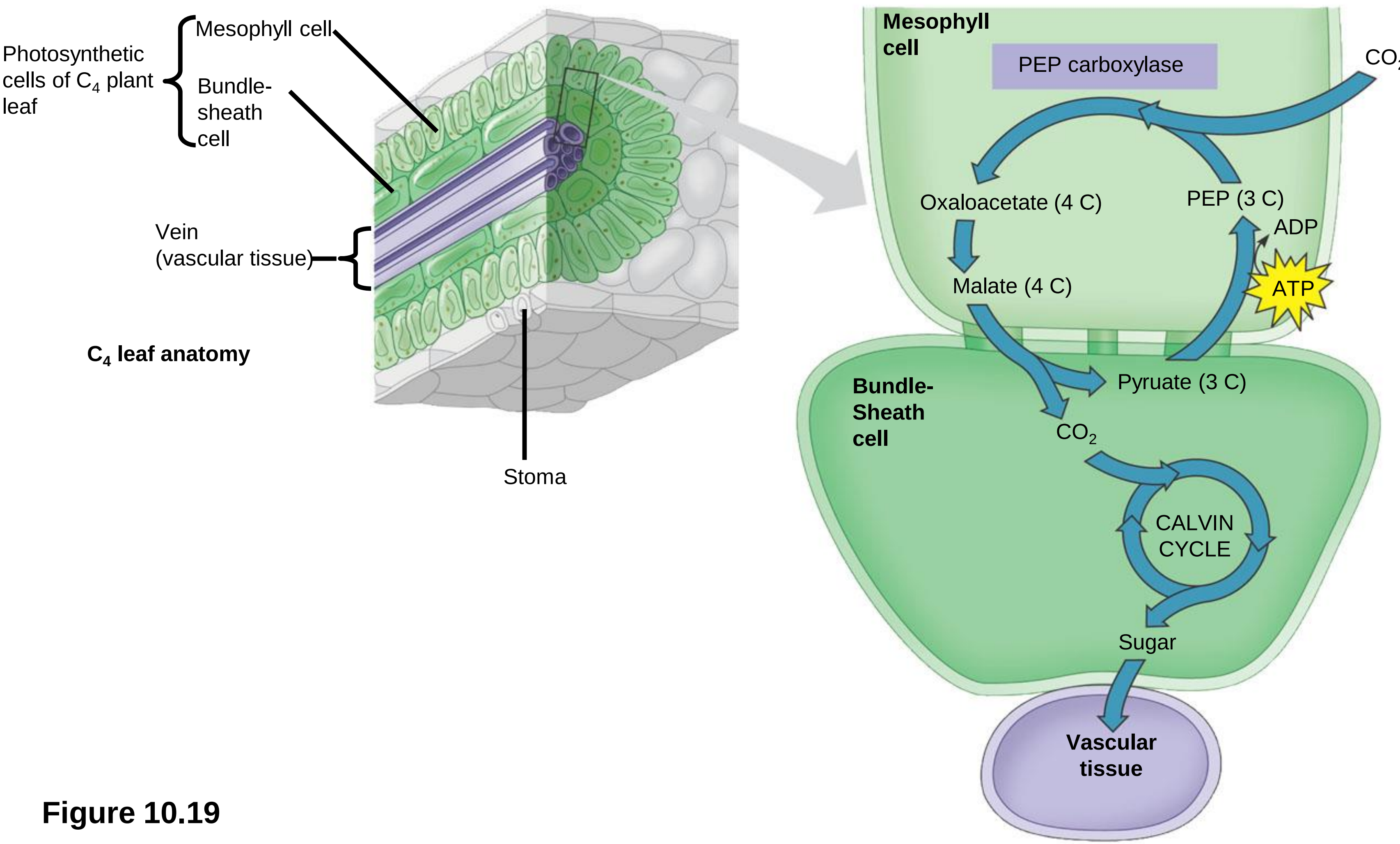

Figure 10.19

- C_4 and CAM plants have special adaptations that save water
  - In C_3 plants a drop in CO_2 and rise in O_2 when stomata close on hot dry days
    - Divert the Calvin cycle to photorespiration

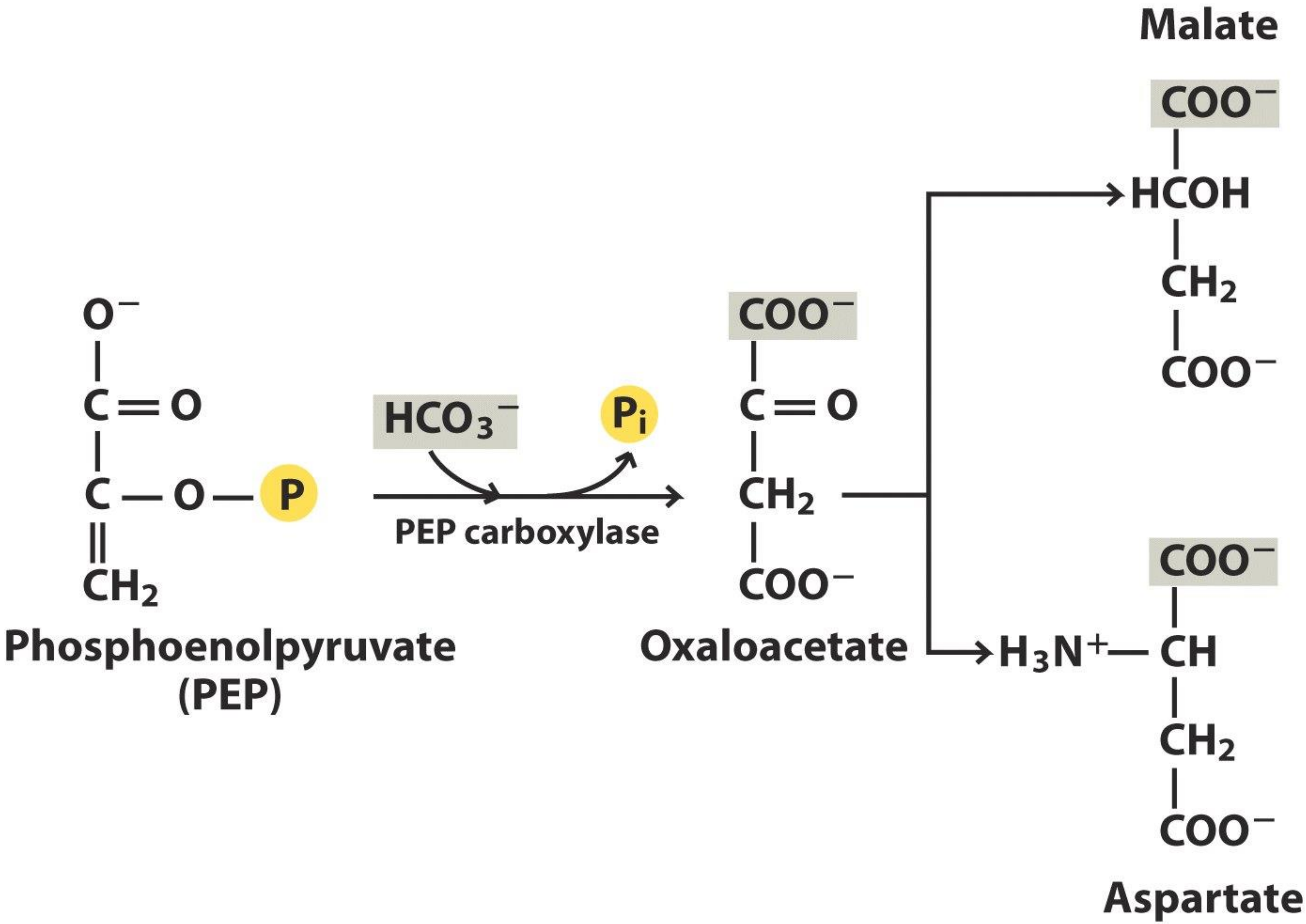

Figure 7-21
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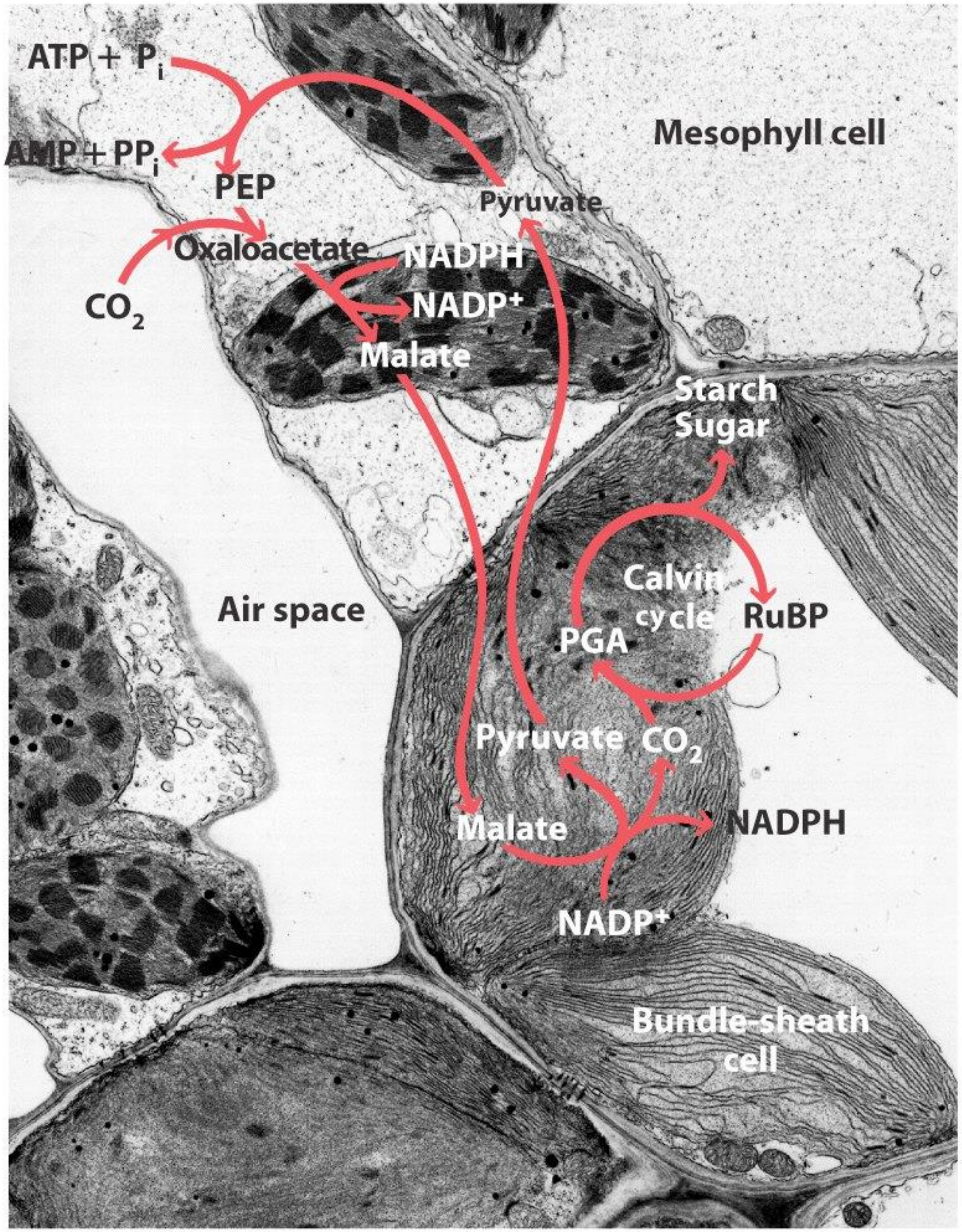

Figure 7-22
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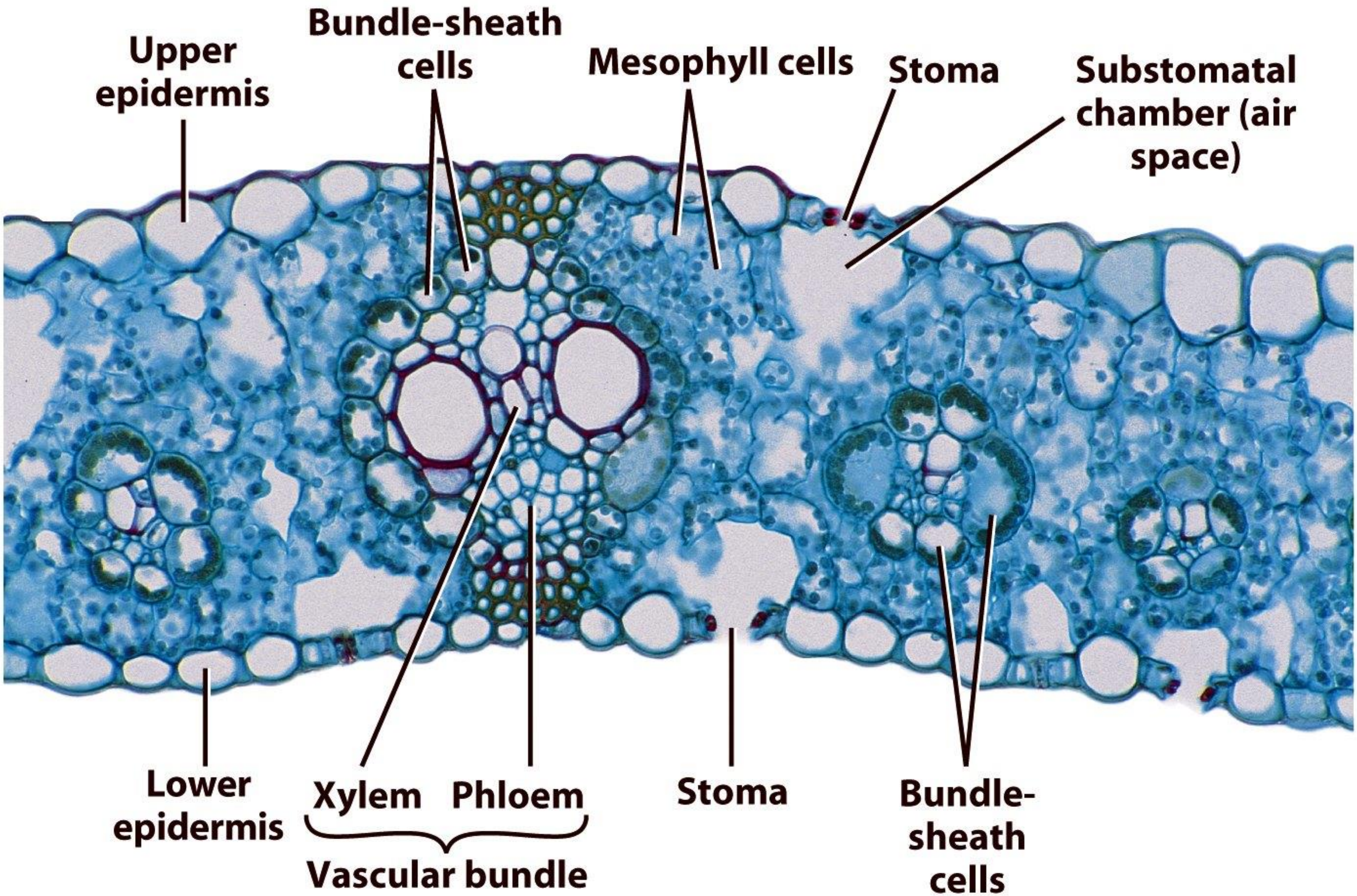

Figure 7-23
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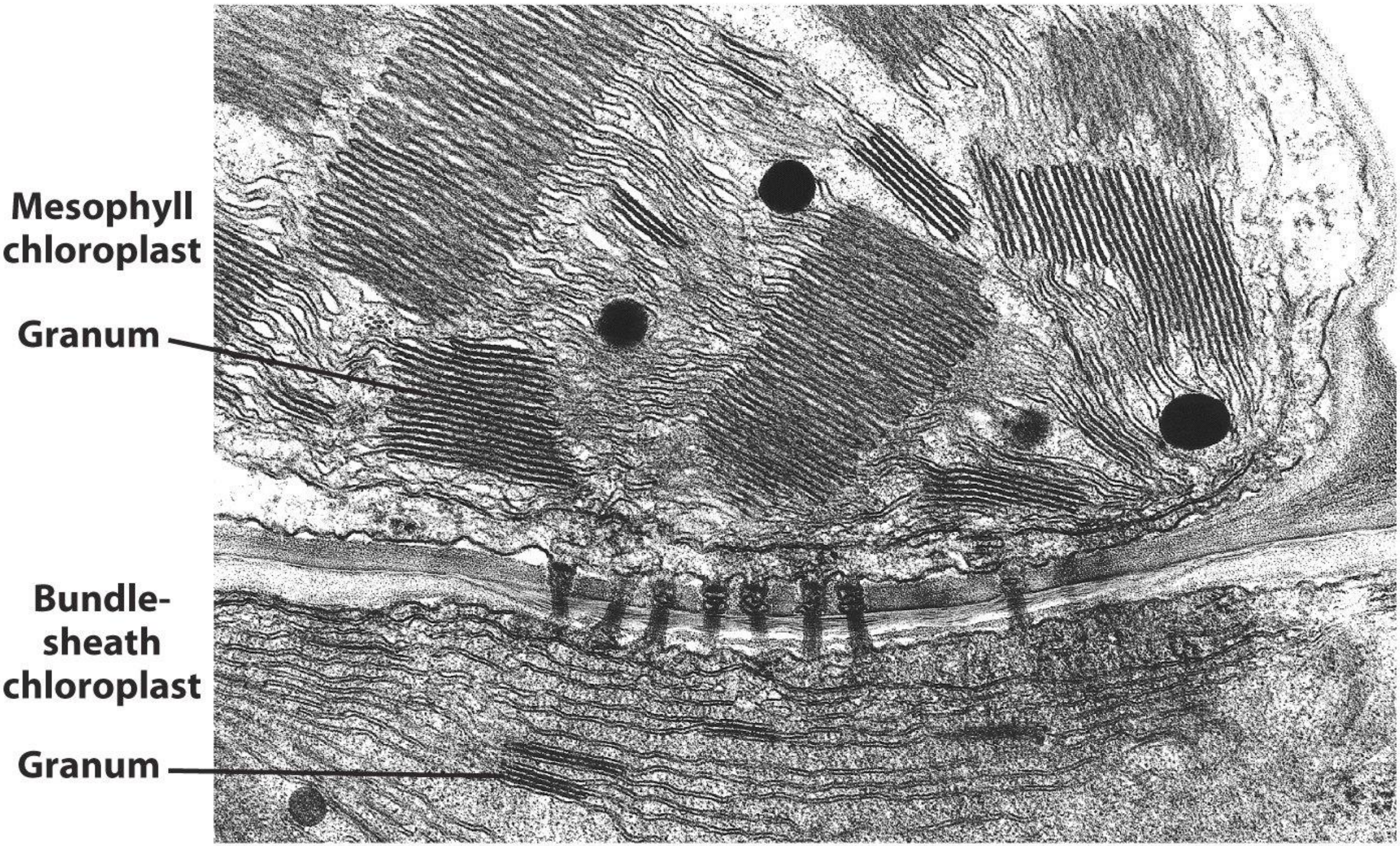

Figure 7-24
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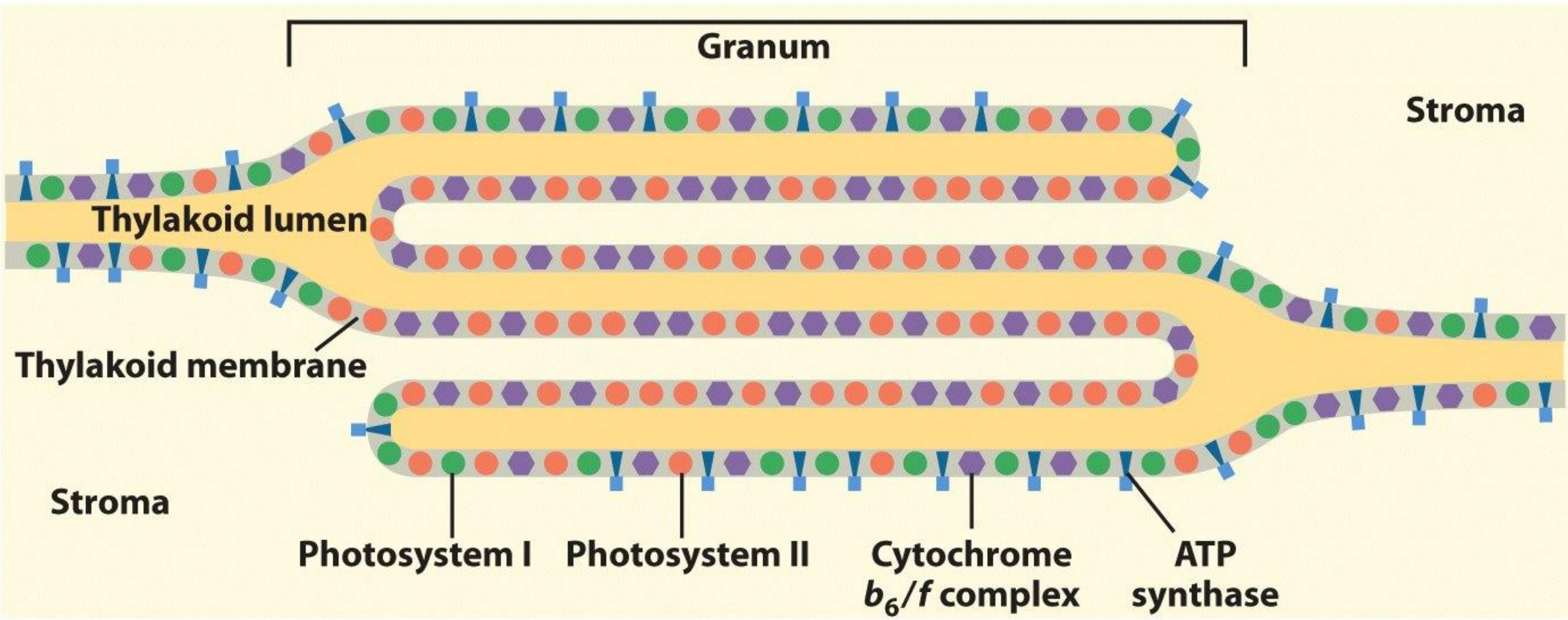


Figure 7-13
Biology of Plants, Seventh Edition

CAM Plants

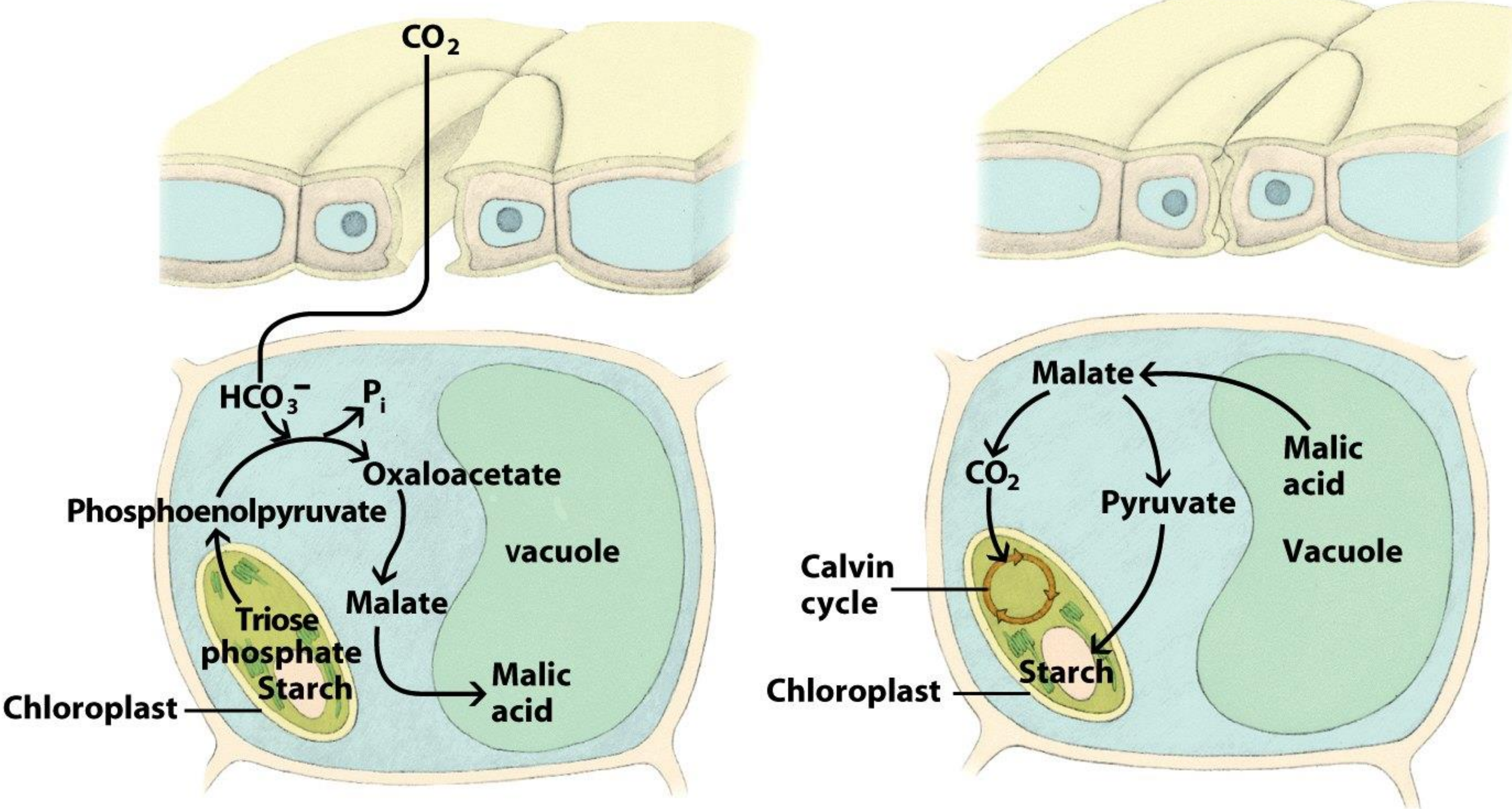
- CAM plants
  - Open their stomata at night, incorporating CO_2 into organic acids

- During the day, the stomata close
  - And the CO_2 is released from the organic acids for use in the Calvin cycle

Figure 10.21b

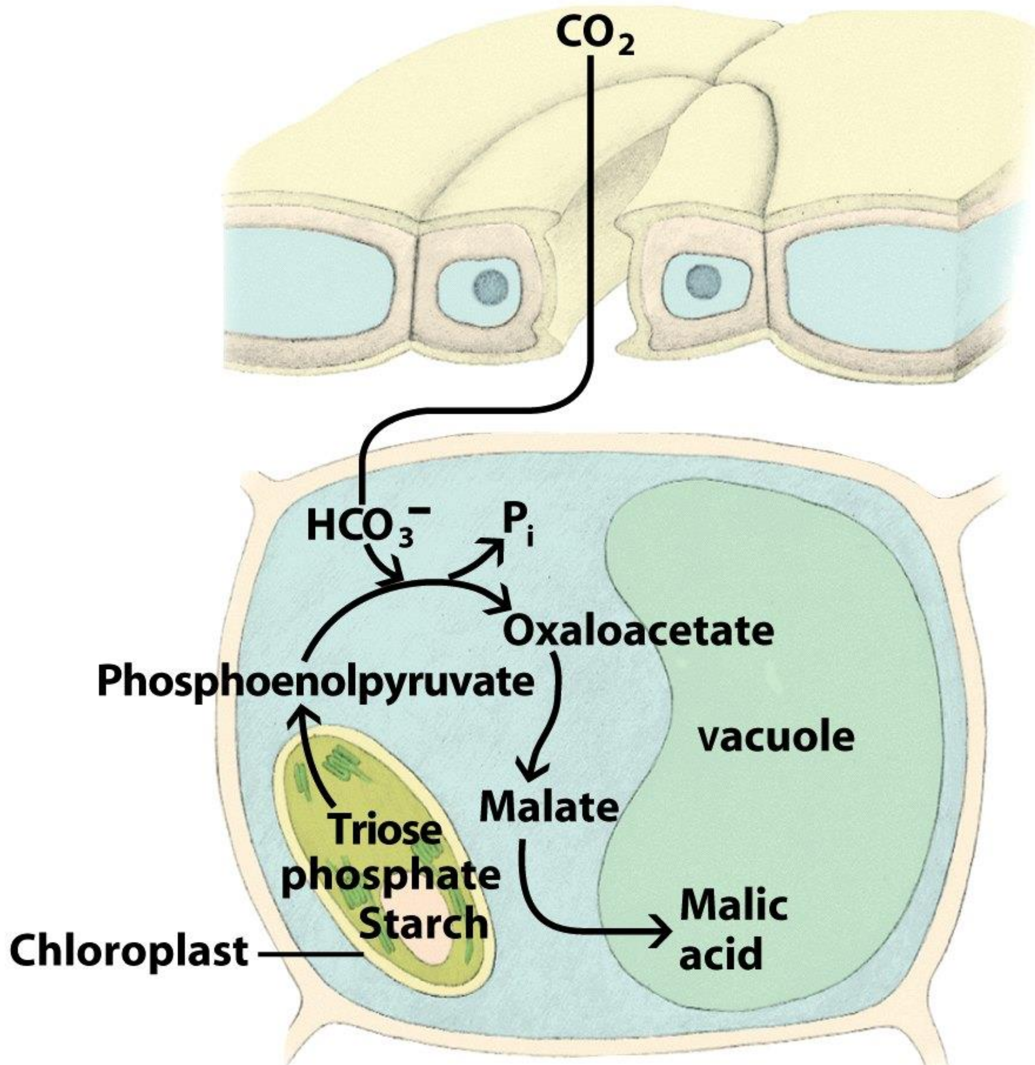
CAM

Pineapple



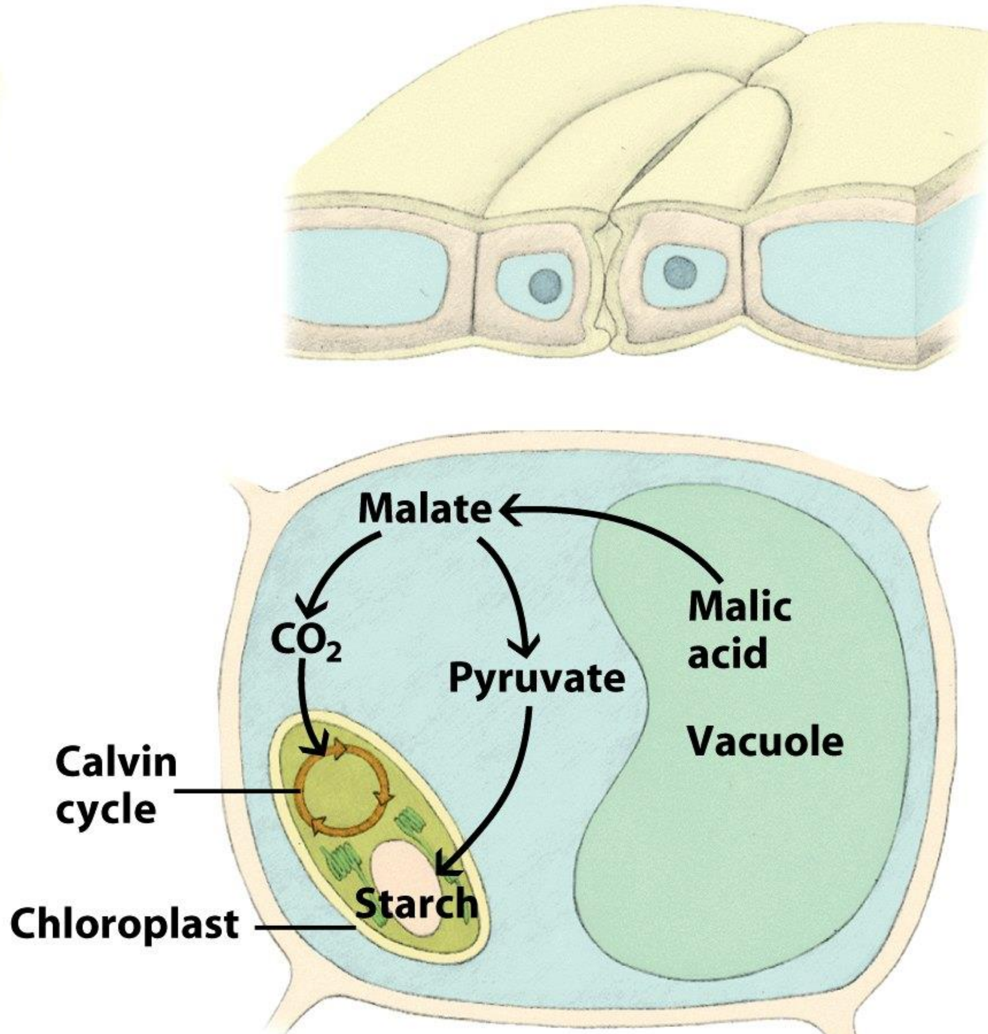
(a) Night: stomata open (b) Day: stomata closed

Figure 7-26
Biology of Plants, Seventh Edition



Night: stomata open

Figure 7-26a
Biology of Plants, Seventh Edition



Day: stomata closed

Figure 7-26b
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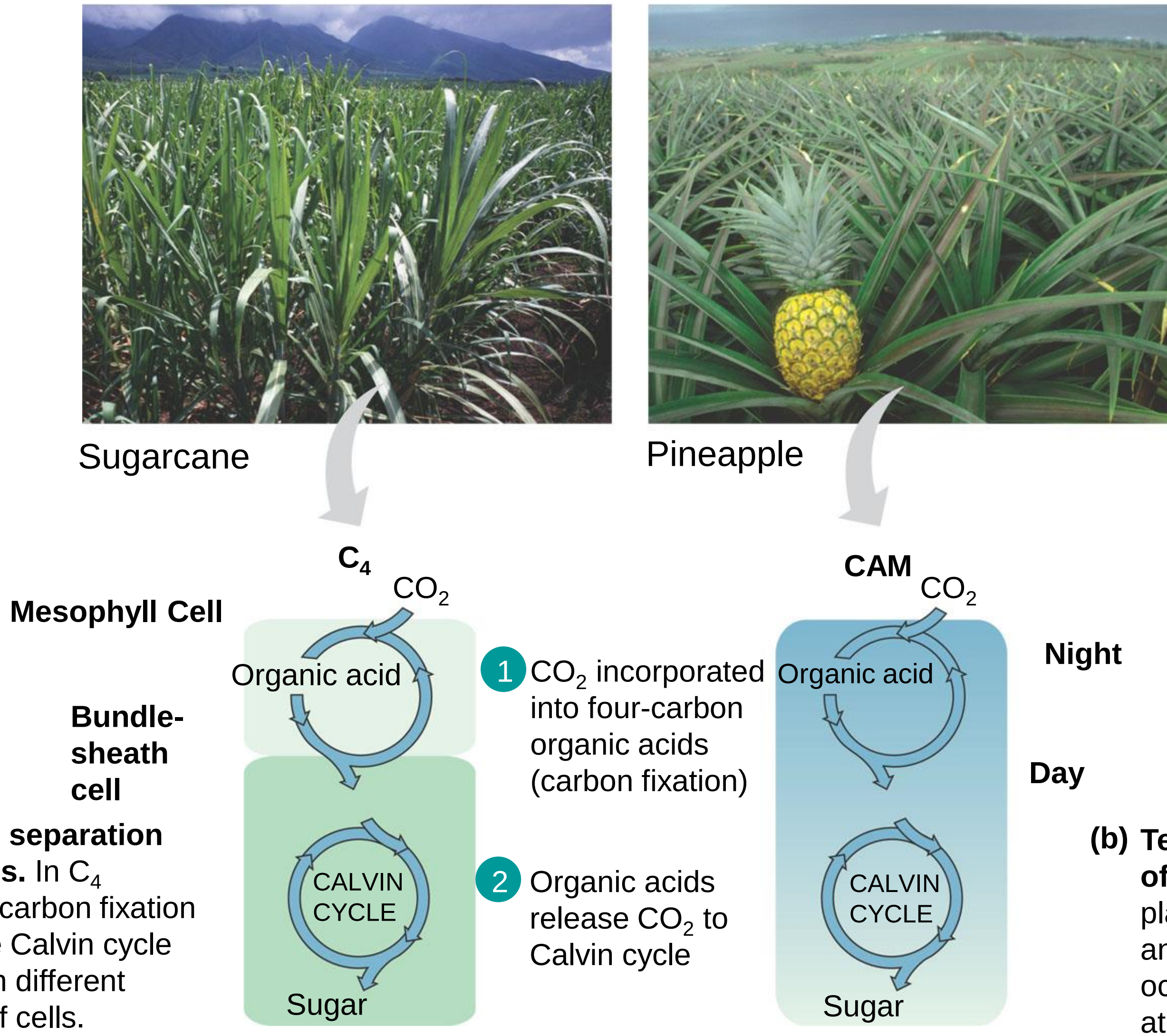
- The CAM pathway is similar to the C_4 pathway

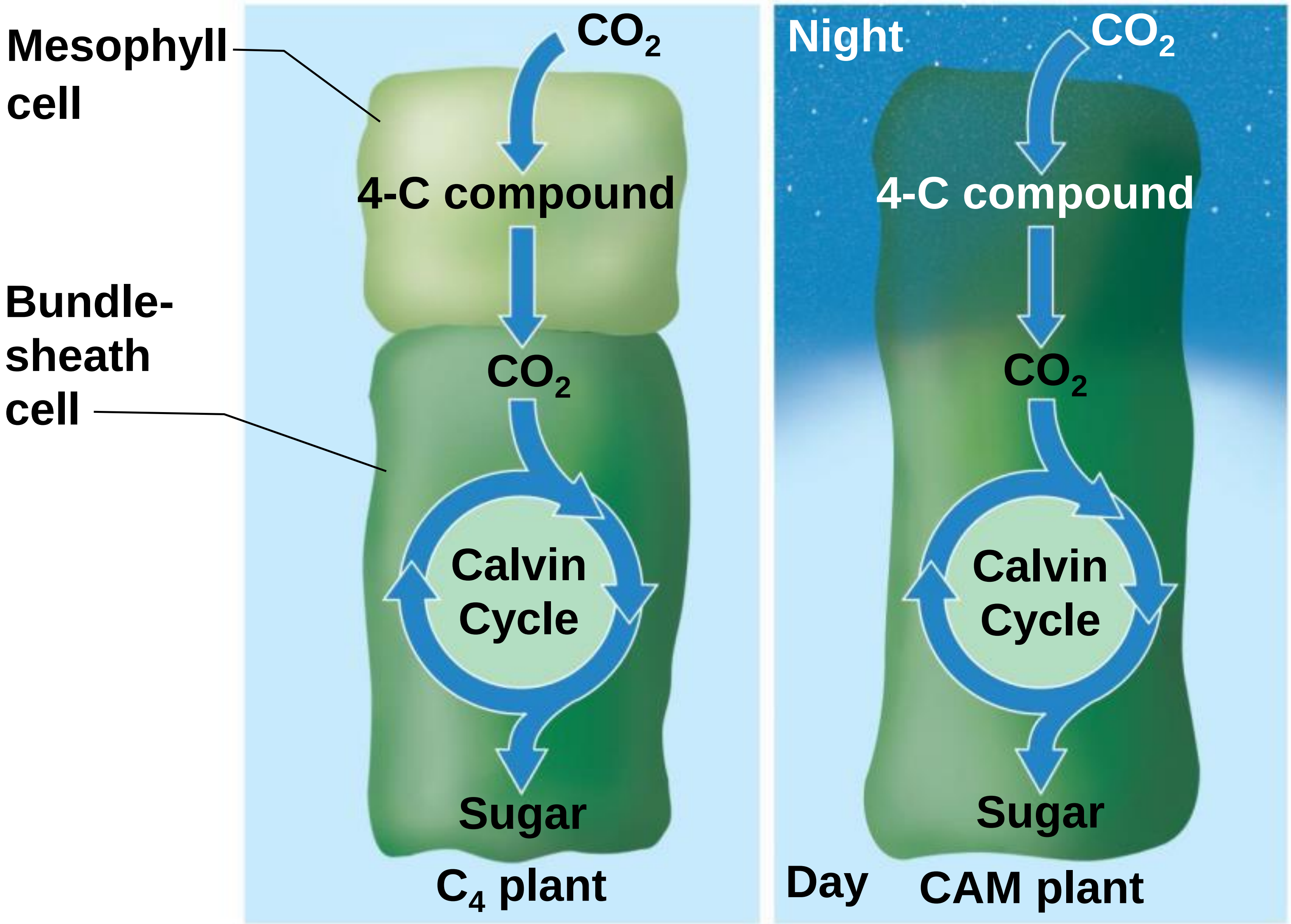


(a) Spatial separation of steps. In C_4 plants, carbon fixation and the Calvin cycle occur in different types of cells.

(b) Temporal separation of steps. In CAM plants, carbon fixation and the Calvin cycle occur in the same cells at different times.

Figure 10.20

Figure 7.11-1



Mesophyll cell
Bundle-sheath cell
CO_2
4-C compound
CO_2
Calvin Cycle
Sugar
C_4 plant
Night
CO_2
4-C compound
CO_2
Calvin Cycle
Sugar
Day
CAM plant