Chapter 10

Photosynthesis

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: The Process That Feeds the Biosphere

- **Photosynthesis** is the process that converts solar energy into chemical energy
- Directly or indirectly, photosynthesis nourishes almost the entire living world

- **Autotrophs** sustain themselves without eating anything derived from other organisms
- Autotrophs are the *producers* of the biosphere, producing organic molecules from CO_2 and other inorganic molecules
- Almost all plants are *photo*autotrophs, using the energy of sunlight to make organic molecules from H_2O and CO_2

Fig. 10-2

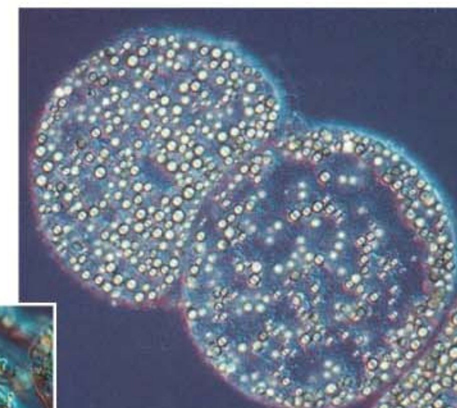
Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes

(a) Plants

(b) Multicellular alga

(c) Unicellular protist 10 µm

(d) Cyanobacteria 40 µm



(e) Purple sulfur bacteria 1.5 µm

- **Heterotrophs** obtain their organic material from other organisms
- Heterotrophs are the *consumers* of the biosphere
- Almost all heterotrophs, including humans, depend on photoautotrophs for food and O_2

Concept 10.1: Photosynthesis converts light energy to the chemical energy of food

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria
- The structural organization of these cells allows for the chemical reactions of photosynthesis

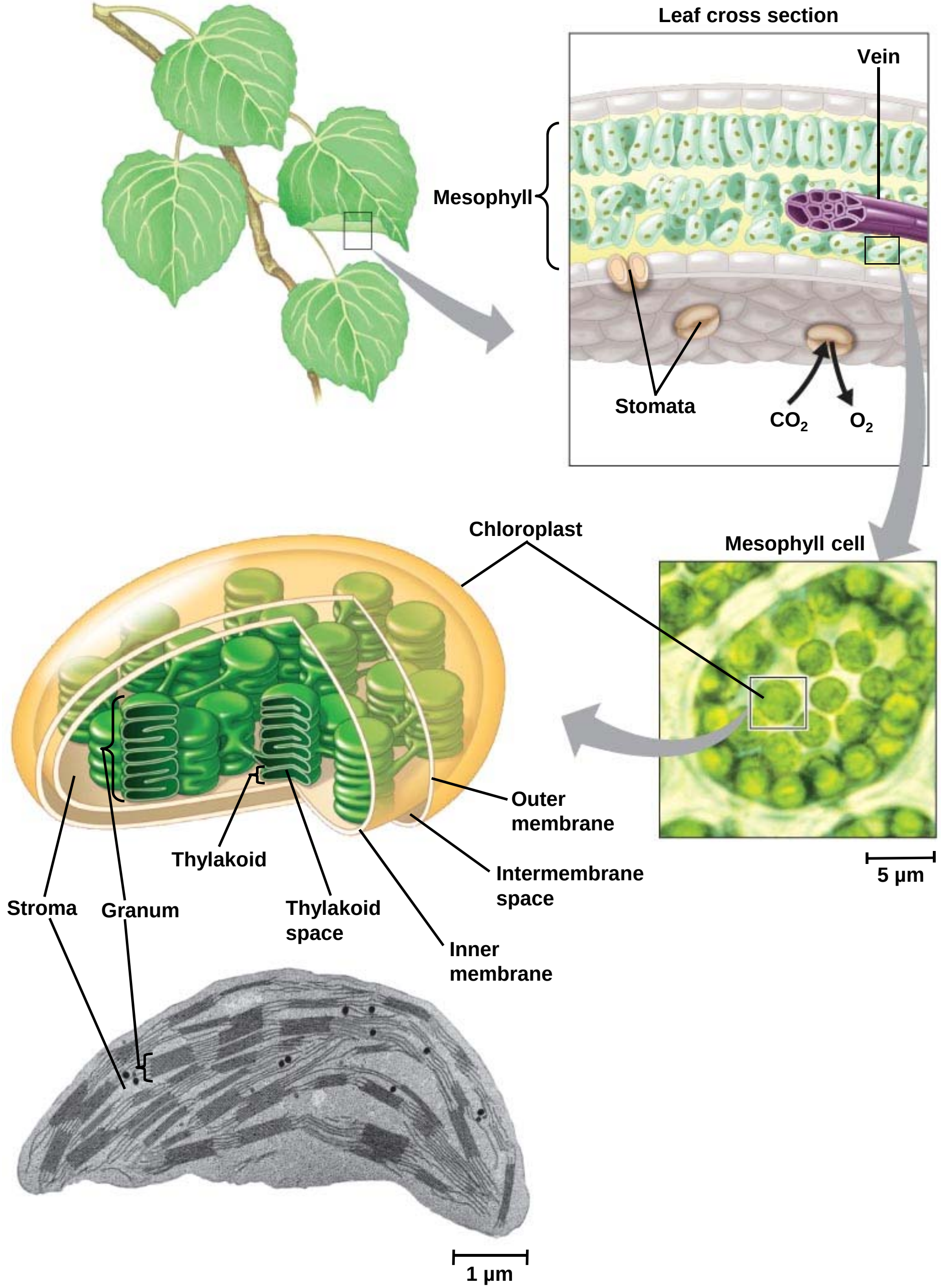
PLAY BioFlix: Photosynthesis

Chloroplasts: The Sites of Photosynthesis in Plants

- Leaves are the major locations of photosynthesis
- Their green color is from **chlorophyll**, the green pigment within chloroplasts
- Light energy absorbed by chlorophyll drives the synthesis of organic molecules in the chloroplast
- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**

- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- A typical mesophyll cell has 30–40 chloroplasts
- The chlorophyll is in the membranes of **thylakoids** (connected sacs in the chloroplast); thylakoids may be stacked in columns called *grana*
- Chloroplasts also contain **stroma**, a dense fluid

Fig. 10-3



Leaf cross section
Vein
Mesophyll
Stomata
CO_2
O_2
Chloroplast
Mesophyll cell
5 µm
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Stroma
Granum
Thylakoid space
1 µm

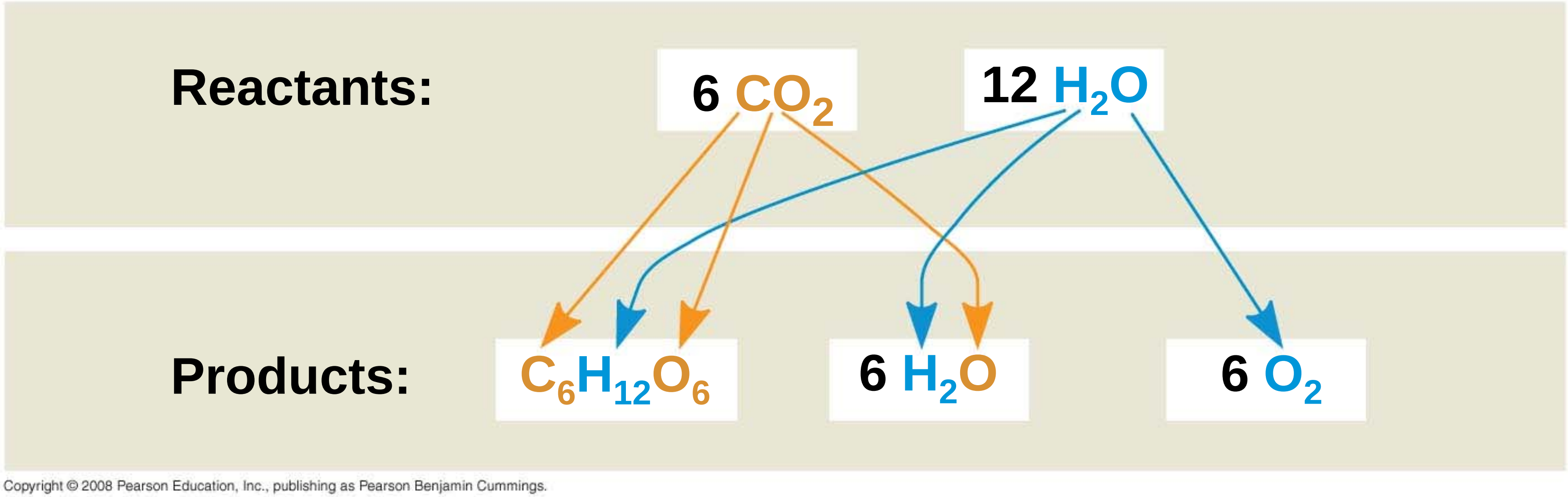
Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

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

The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules



Tracking atoms through photosynthesis

Photosynthesis as a Redox Process

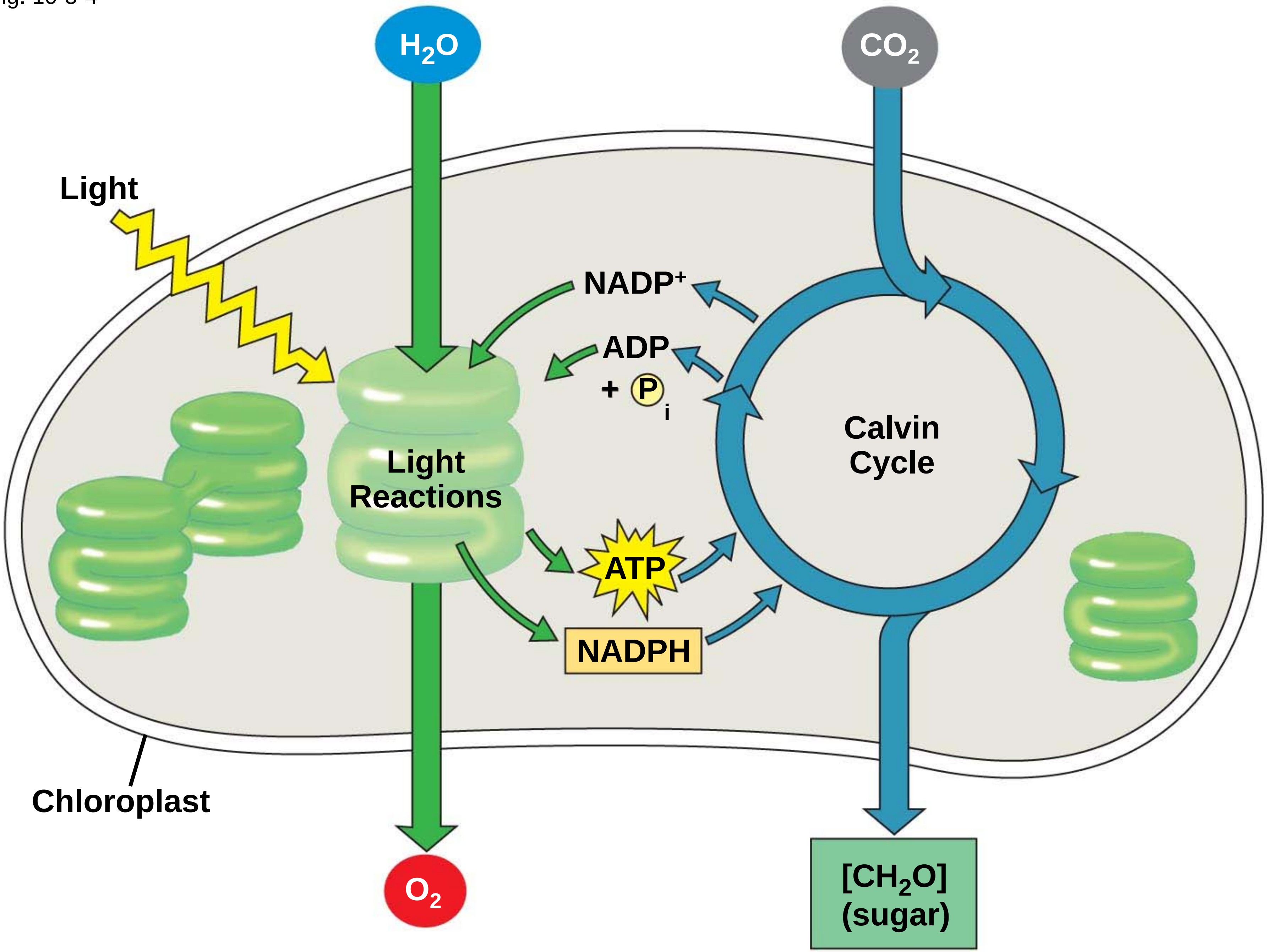
- Photosynthesis is a redox process in which H_2O is oxidized and CO_2 is reduced

The Two Stages of Photosynthesis: *A Preview*

- Photosynthesis consists of the **light reactions** (the *photo* part) and **Calvin cycle** (the *synthesis* part)
- The light reactions (in the thylakoids):
  - Split H_2O
  - Release O_2
  - Reduce **NADP$^+$** to NADPH
  - Generate ATP from ADP by **photophosphorylation**

- The Calvin cycle (in the stroma) forms sugar from CO_2, using ATP and NADPH
- The Calvin cycle begins with **carbon fixation**, incorporating CO_2 into organic molecules

Fig. 10-5-4


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

Concept 10.2: The light reactions convert solar energy to the chemical energy of ATP and NADPH

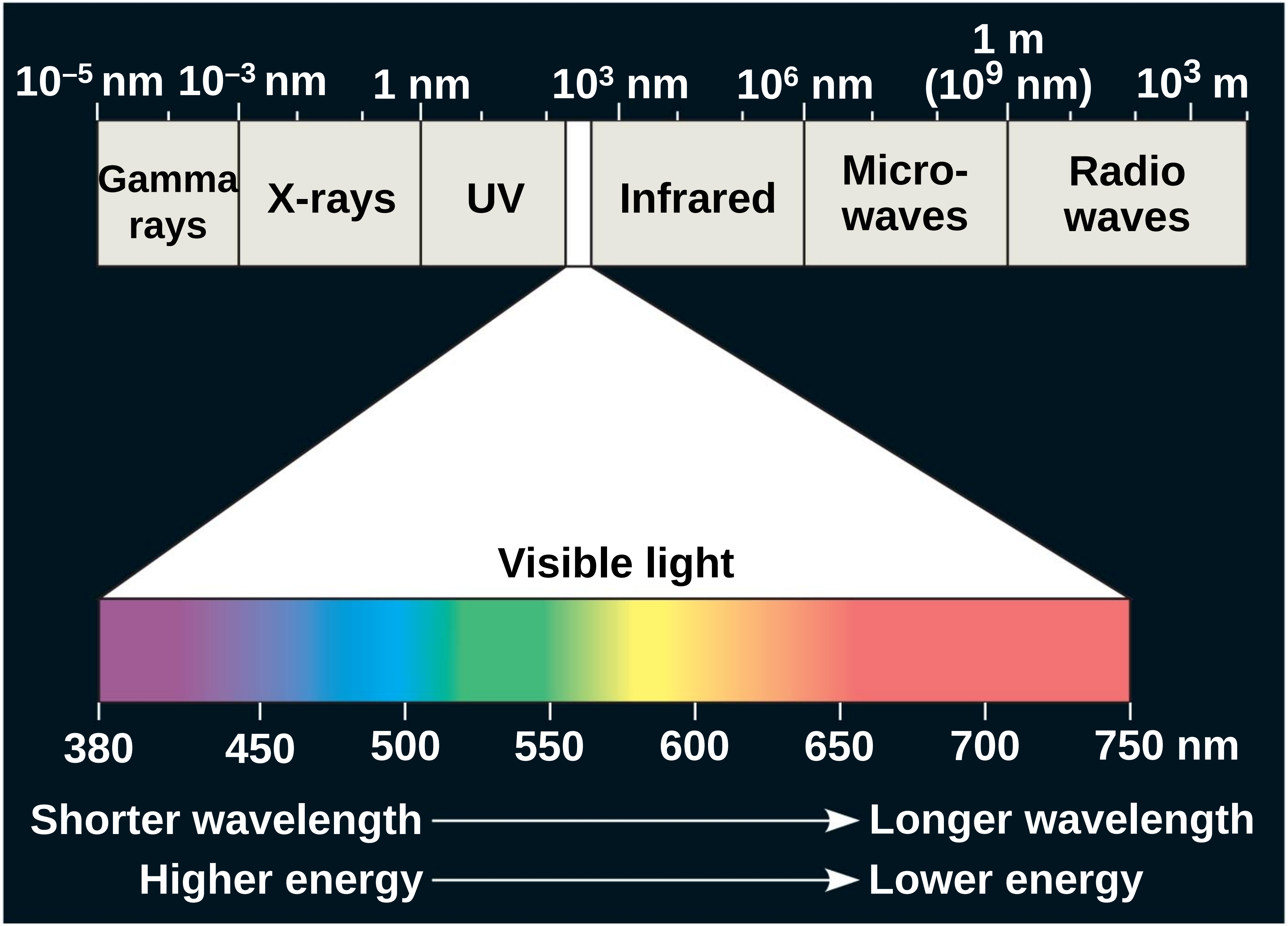
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is a form of electromagnetic energy, also called electromagnetic radiation
- Like other electromagnetic energy, light travels in rhythmic waves
- **Wavelength** is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

- The **electromagnetic spectrum** is the entire range of electromagnetic energy, or radiation
- **Visible light** consists of wavelengths (including those that drive photosynthesis) that produce colors we can see
- Light also behaves as though it consists of discrete particles, called **photons**

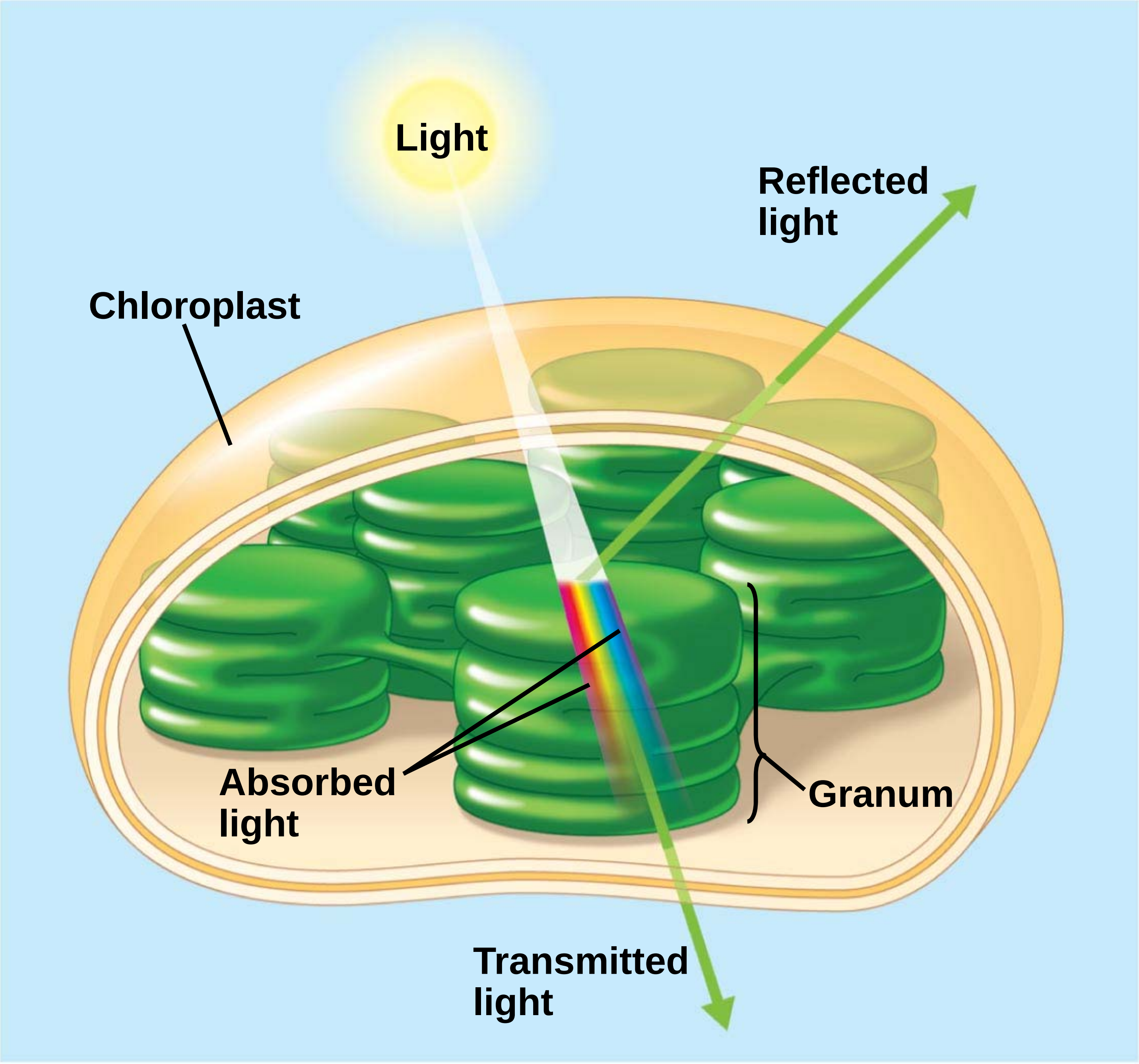
Fig. 10-6


10–5 nm
10–3 nm
1 nm
103 nm
106 nm
1 m
(109 nm)
103 m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

Photosynthetic Pigments: The Light Receptors

- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted
- Leaves appear green because chlorophyll reflects and transmits green light

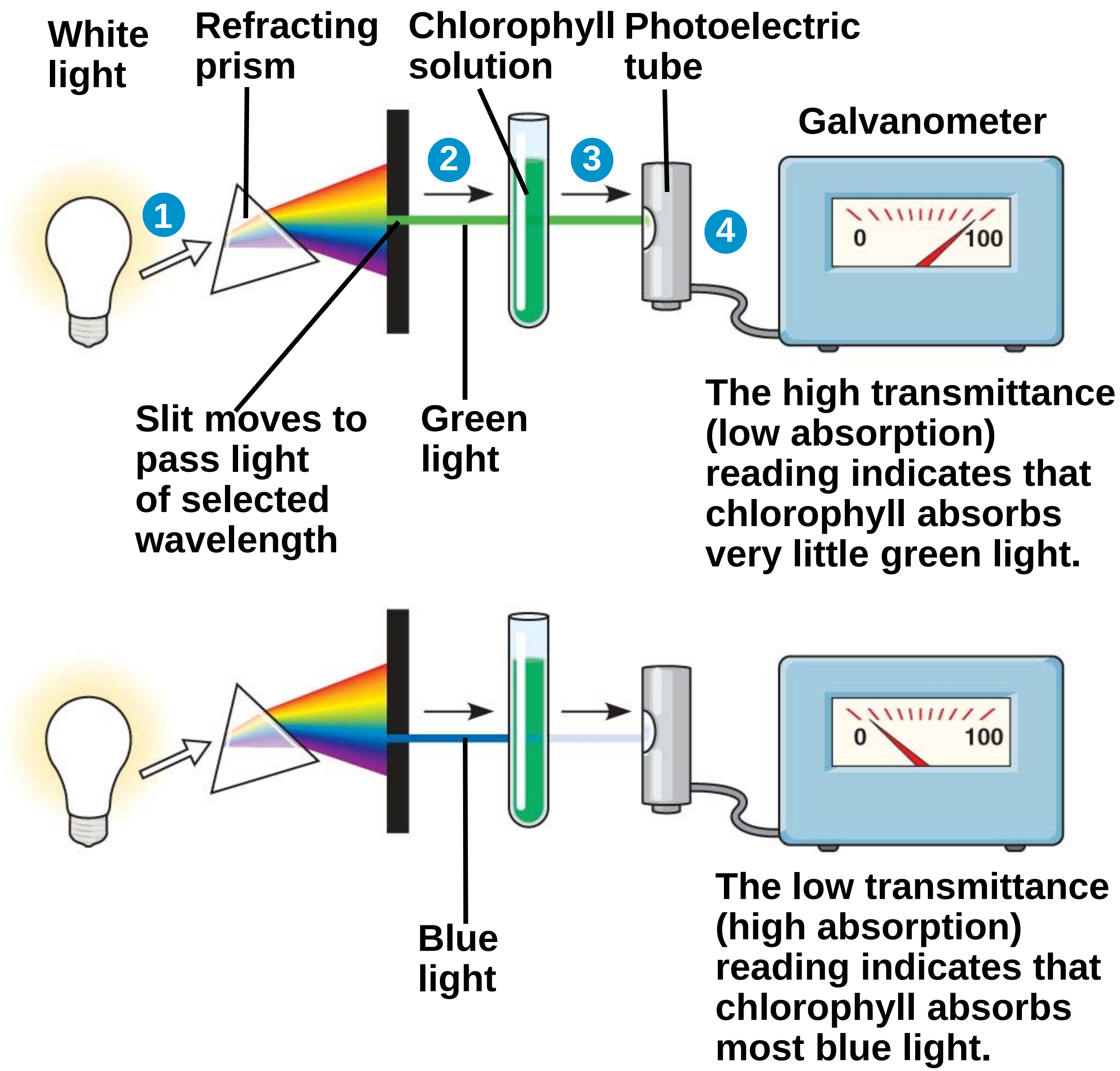
Fig. 10-7


Light
Reflected light
Chloroplast
Absorbed light
Granum
Transmitted light

- A **spectrophotometer** measures a pigment’s ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

Fig. 10-8

TECHNIQUE Determining an absorption spectrum



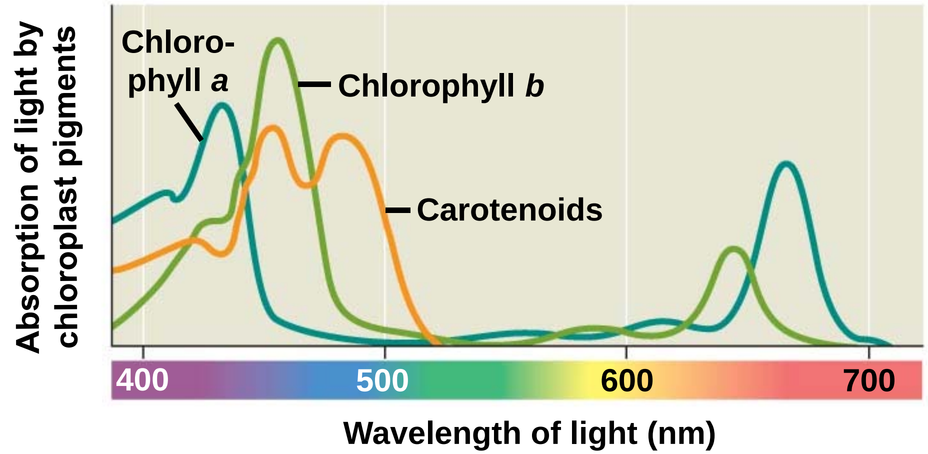
- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of radiation in driving a process

- The action spectrum of photosynthesis was first demonstrated in 1883 by Theodor W. Engelmann
- In his experiment, he exposed different segments of a filamentous alga to different wavelengths
- Areas receiving wavelengths favorable to photosynthesis produced excess O_2
- He used the growth of aerobic bacteria clustered along the alga as a measure of O_2 production

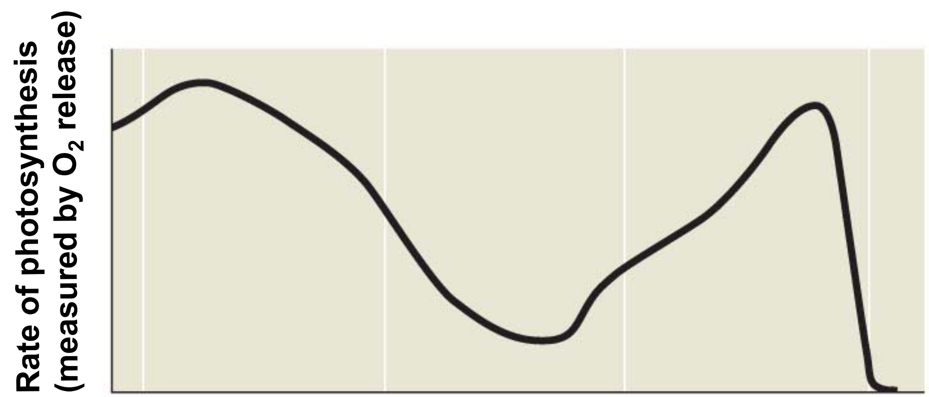
- Chlorophyll *a* is the main photosynthetic pigment
- Accessory pigments, such as **chlorophyll *b***, broaden the spectrum used for photosynthesis
- Accessory pigments called **carotenoids** absorb excessive light that would damage chlorophyll

Fig. 10-9

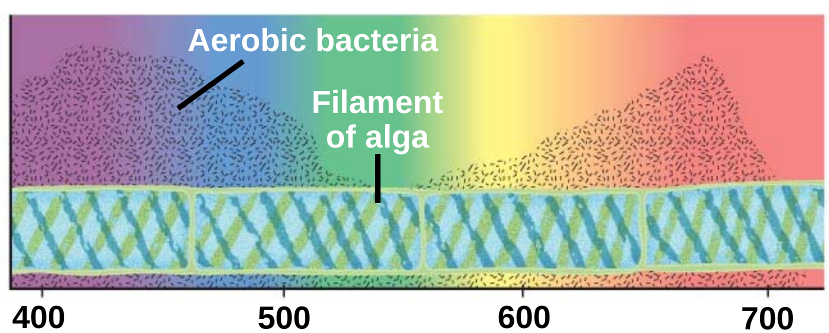
RESULTS



(a) Absorption spectra

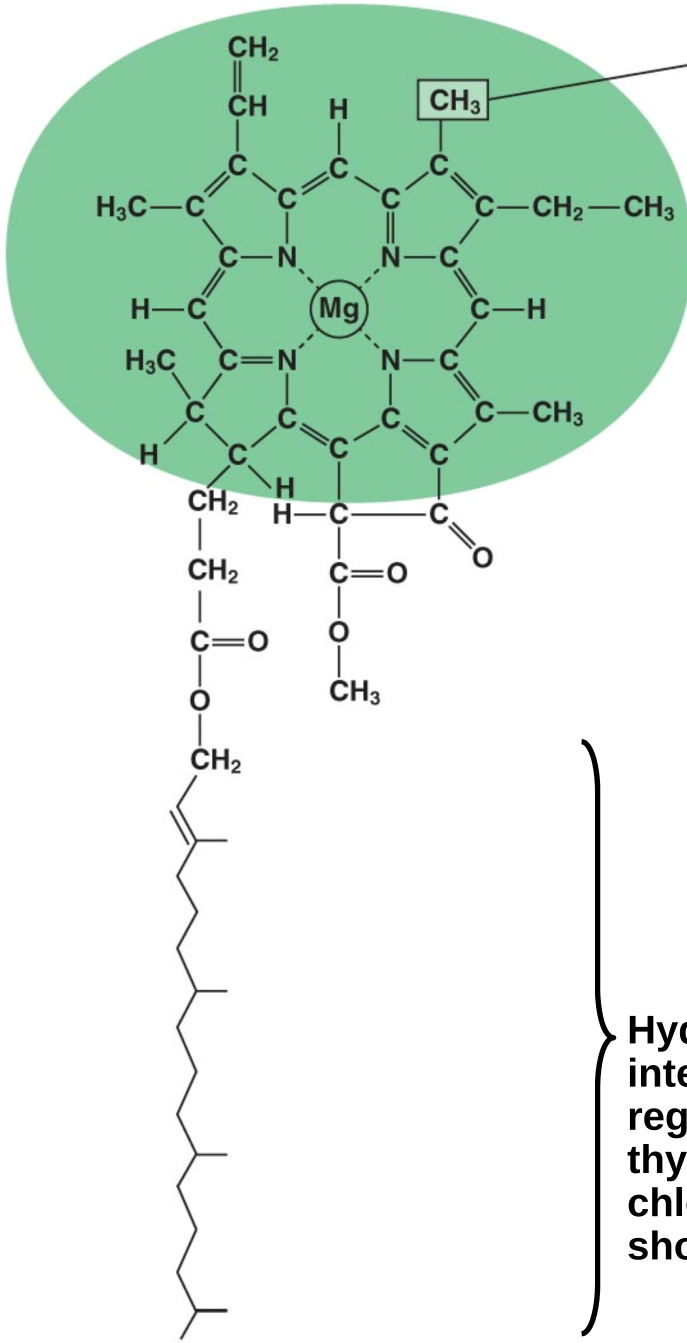


(b) Action spectrum



(c) Engelmann's experiment

Fig. 10-10



CH_3 in chlorophyll *a*
CHO in chlorophyll *b*

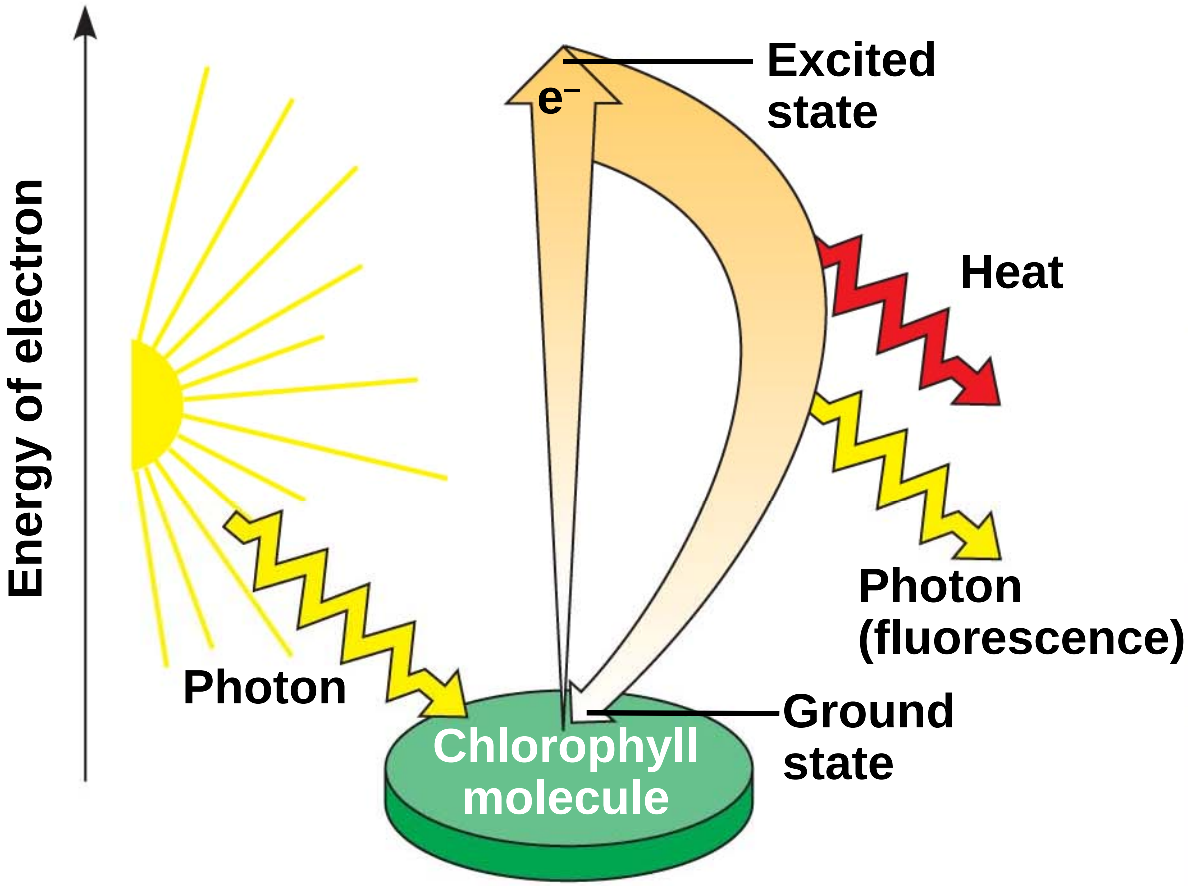
Porphyrin ring: light-absorbing "head" of molecule; note magnesium atom at center

Hydrocarbon tail: interacts with hydrophobic regions of proteins inside thylakoid membranes of chloroplasts; H atoms not shown

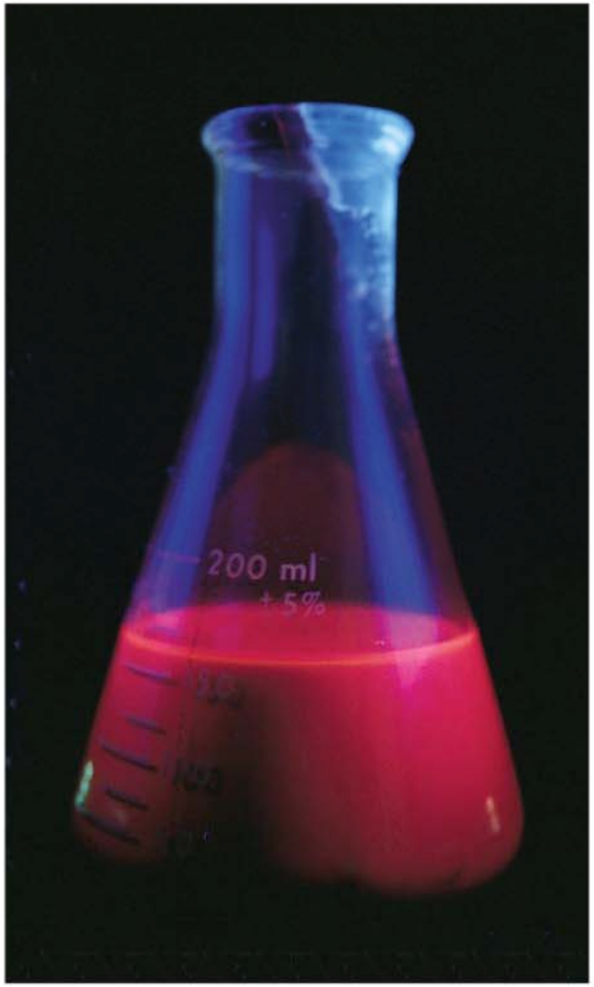
Excitation of Chlorophyll by Light

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

Fig. 10-11



(a) Excitation of isolated chlorophyll molecule



(b) Fluorescence

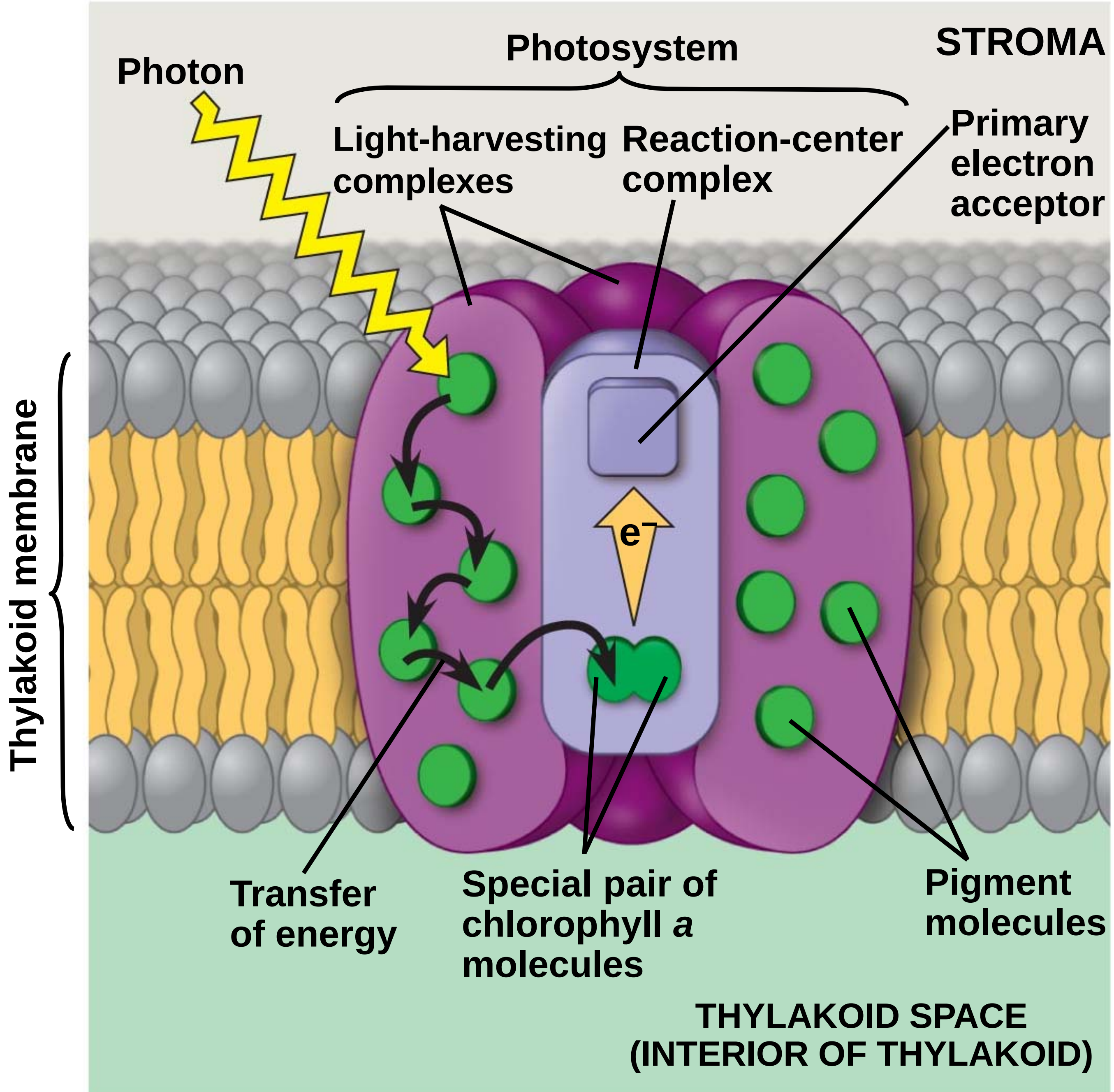
A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

- A **photosystem** consists of a **reaction-center complex** (a type of protein complex) surrounded by light-harvesting complexes
- The **light-harvesting complexes** (pigment molecules bound to proteins) funnel the energy of photons to the reaction center

- A **primary electron acceptor** in the reaction center accepts an excited electron from chlorophyll *a*

- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions

Fig. 10-12


Photosystem
STROMA
Photon
Light-harvesting complexes
Reaction-center complex
Primary electron acceptor
Thylakoid membrane
e⁻
Transfer of energy
Special pair of chlorophyll *a* molecules
Pigment molecules
THYLAKOID SPACE (INTERIOR OF THYLAKOID)

- There are two types of photosystems in the thylakoid membrane
- **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of 680 nm
- The reaction-center chlorophyll *a* of PS II is called P680

- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

Linear Electron Flow

- During the light reactions, there are two possible routes for electron flow: cyclic and linear

- **Linear electron flow**, the primary pathway, involves both photosystems and produces ATP and NADPH using light energy

Fig. 10-13-5

Linear electron flow during the light reactions generates ATP and NADPH

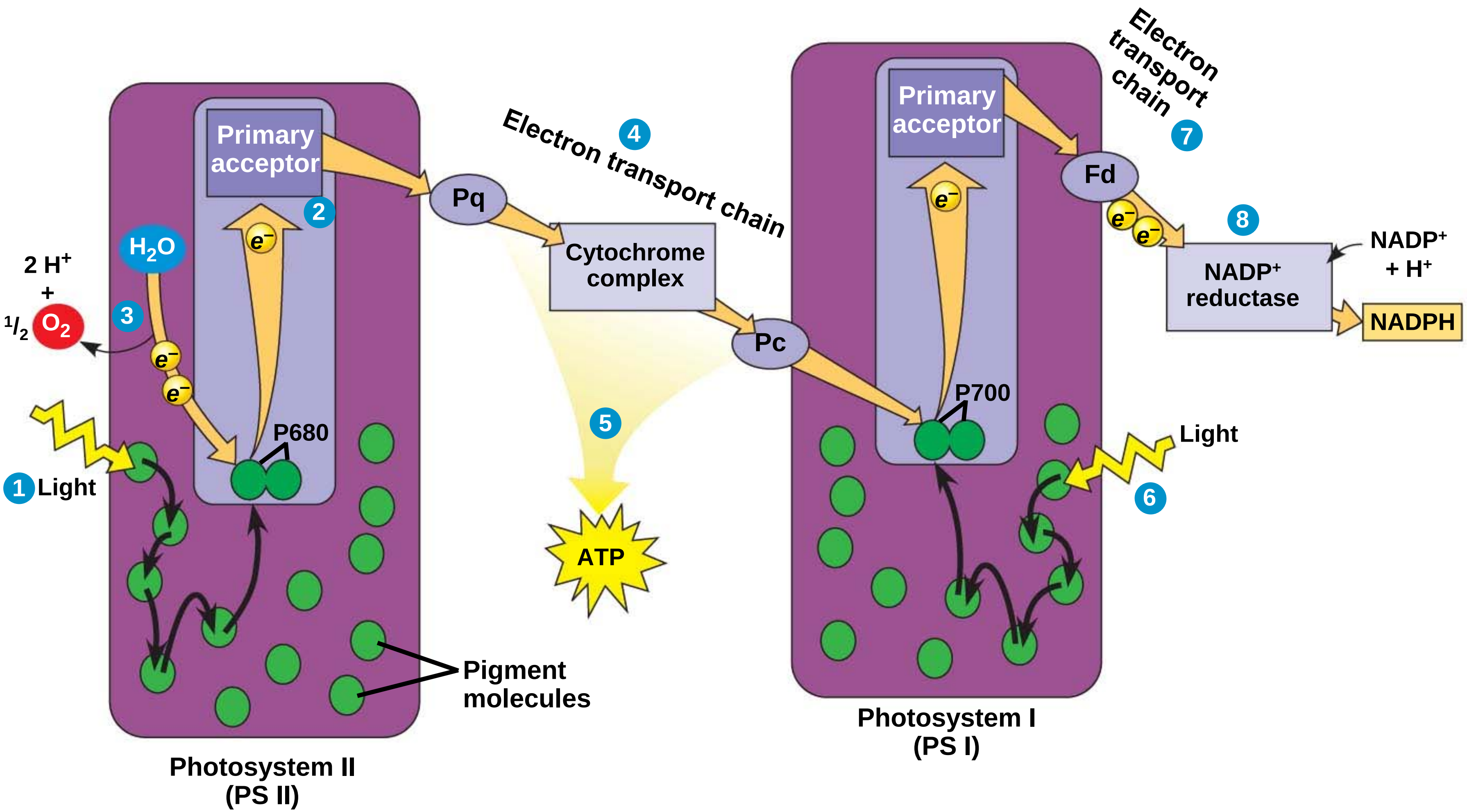
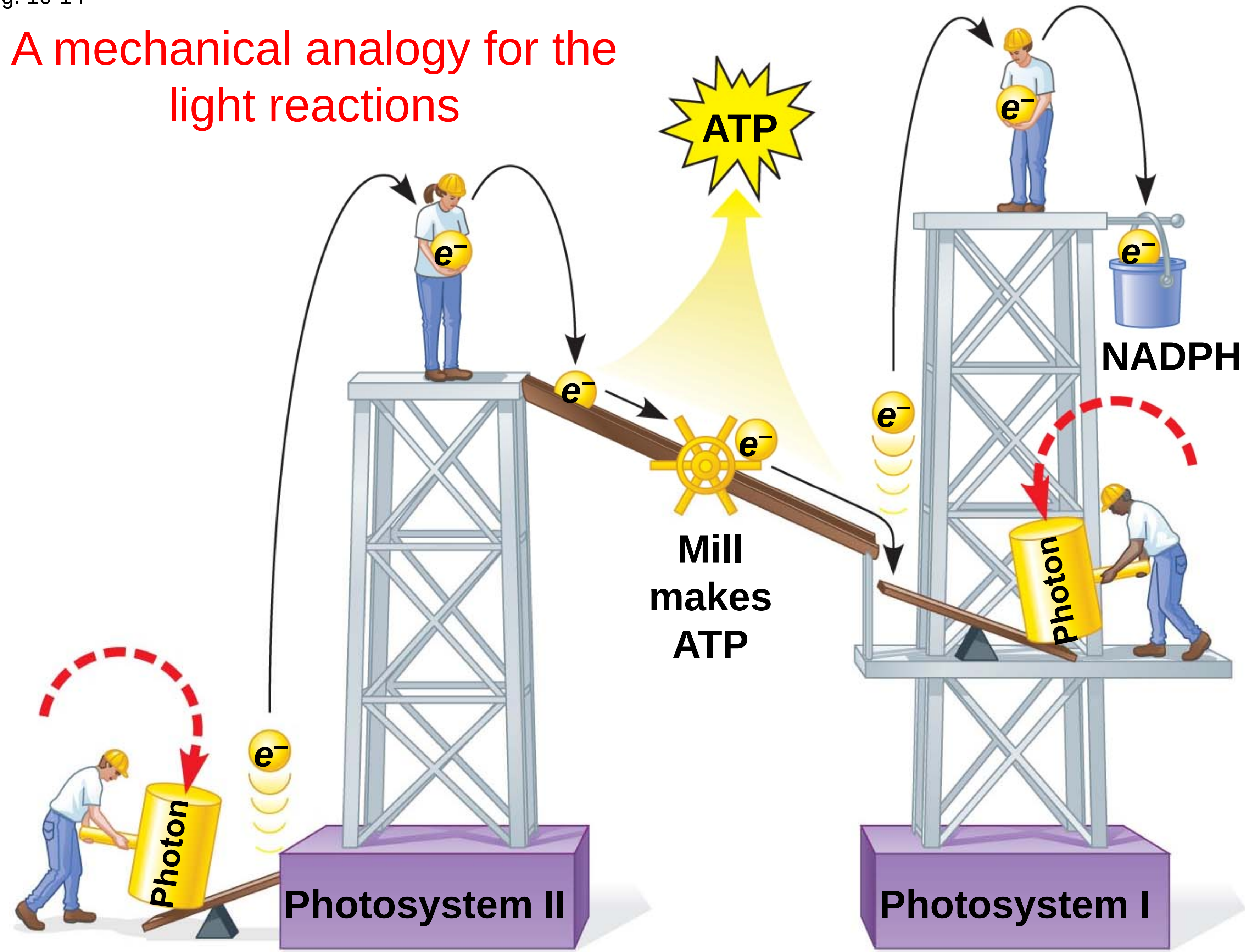


Fig. 10-14

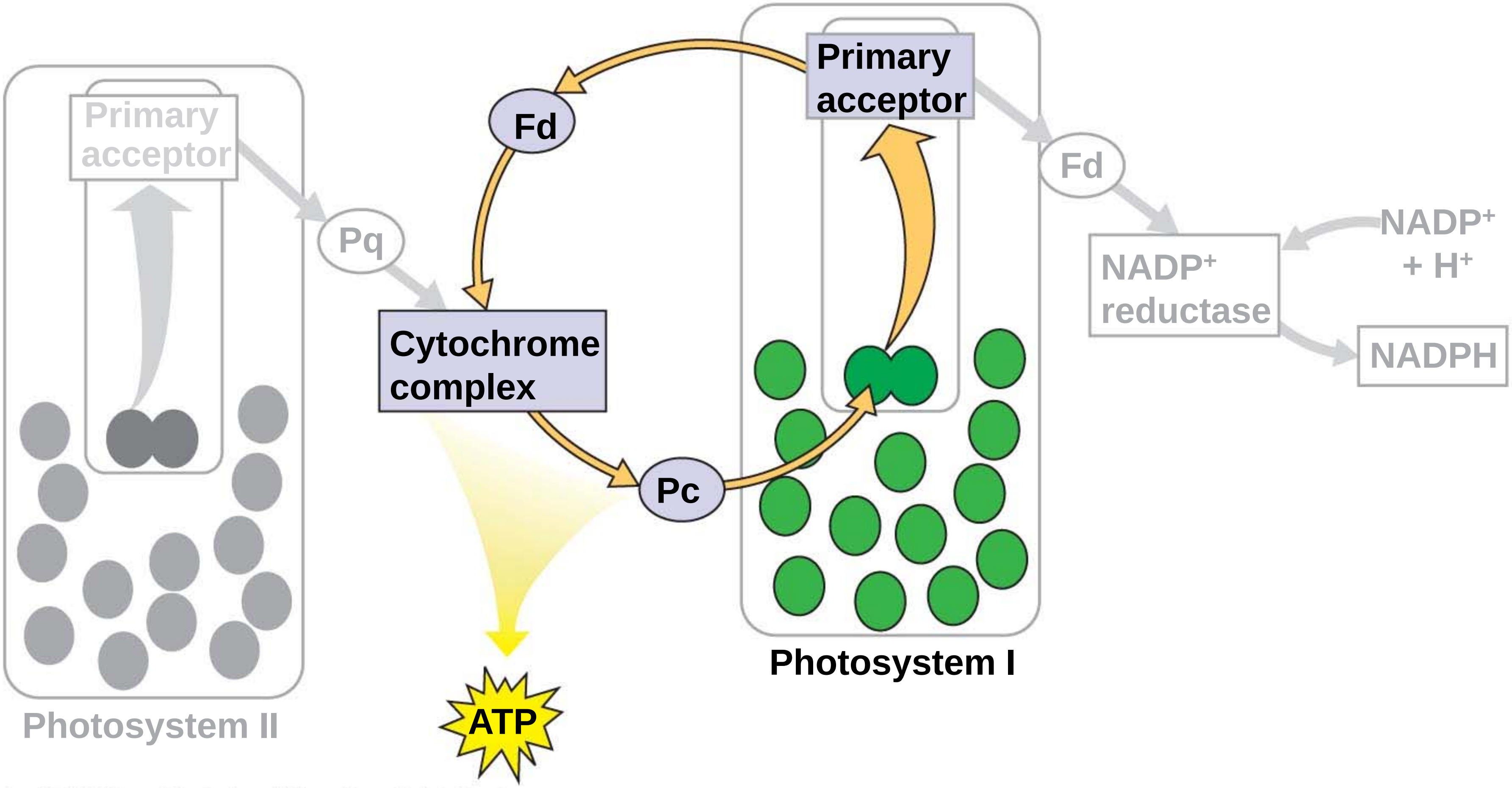
A mechanical analogy for the light reactions



Cyclic Electron Flow

- **Cyclic electron flow** uses only photosystem I and produces ATP, but not NADPH
- Cyclic electron flow generates surplus ATP, satisfying the higher demand in the Calvin cycle

Fig. 10-15


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

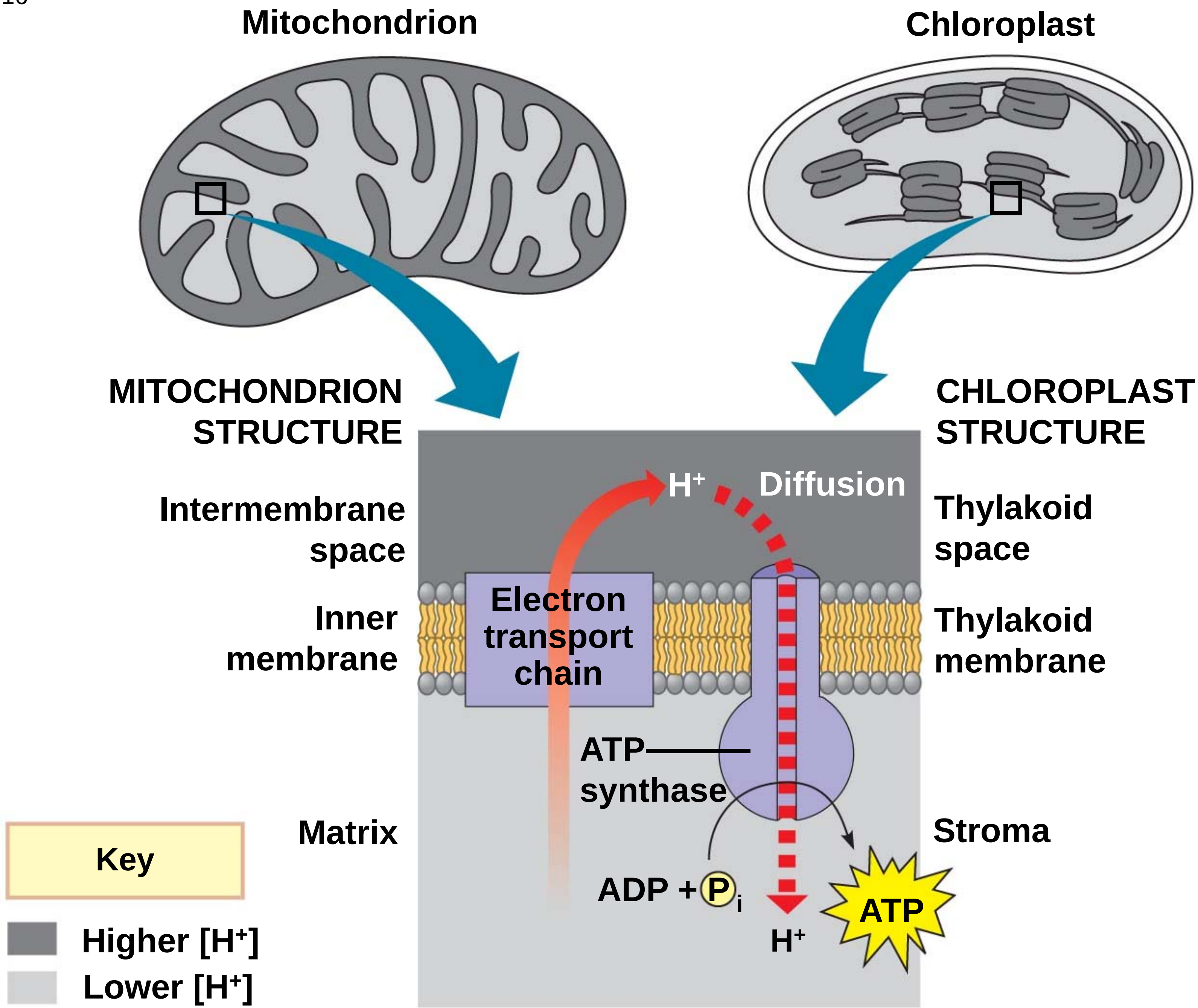
- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

A Comparison of Chemiosmosis in Chloroplasts and Mitochondria

- Chloroplasts and mitochondria generate ATP by chemiosmosis, but use different sources of energy
- Mitochondria transfer chemical energy from food to ATP; chloroplasts transform light energy into the chemical energy of ATP
- Spatial organization of chemiosmosis differs between chloroplasts and mitochondria but also shows similarities

- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma

Fig. 10-16

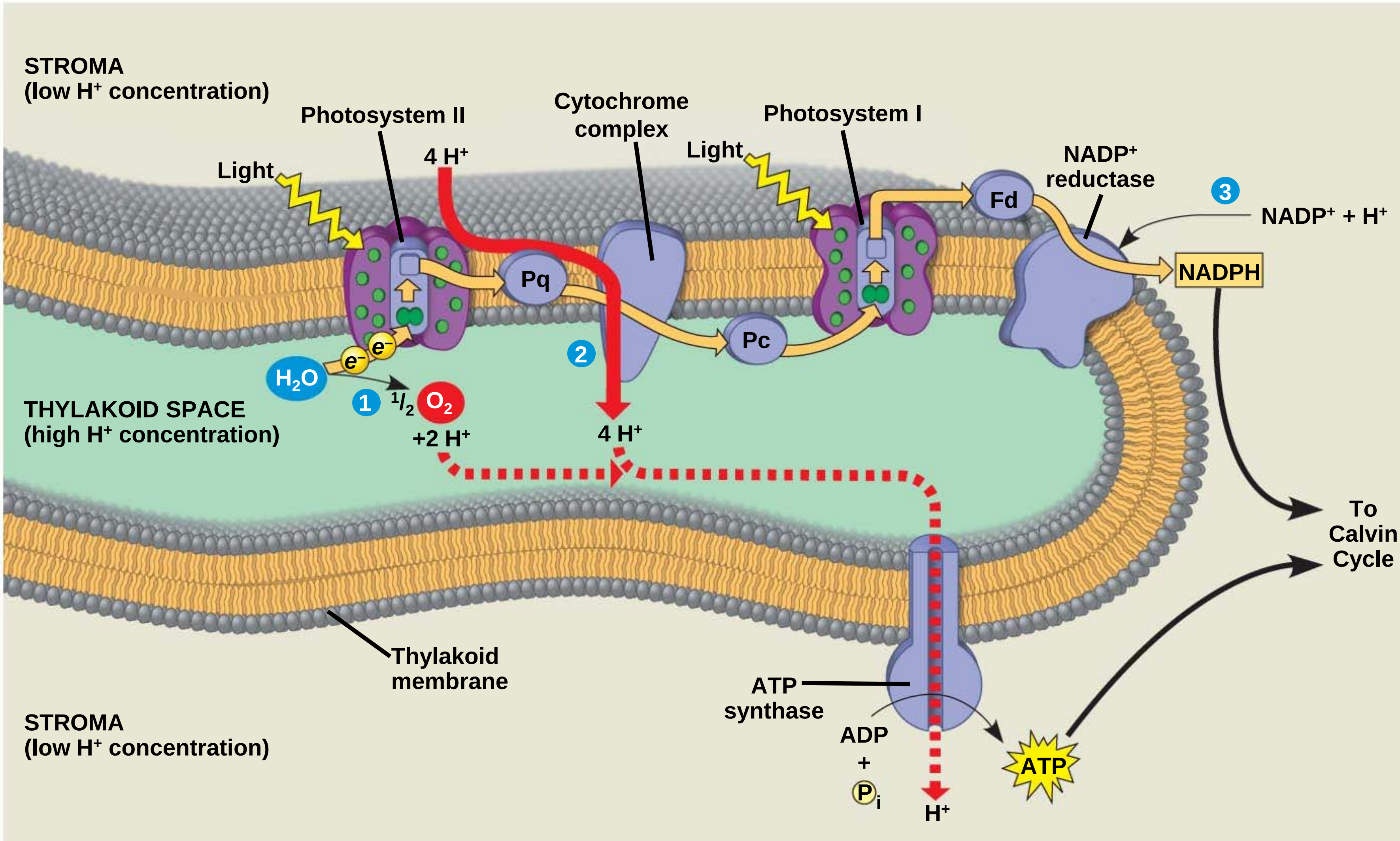

Mitochondrion
Chloroplast
MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Intermembrane space
Inner membrane
Matrix
Thylakoid space
Thylakoid membrane
Stroma
H+
Diffusion
Electron transport chain
ATP synthase
ADP + P i
ATP
H+
Key
Higher [H+]
Lower [H+]

- ATP and NADPH are produced on the side facing the stroma, where the Calvin cycle takes place

- In summary, light reactions generate ATP and increase the potential energy of electrons by moving them from H_2O to NADPH

Fig. 10-17

The light reactions and chemiosmosis: the organization of the thylakoid membrane



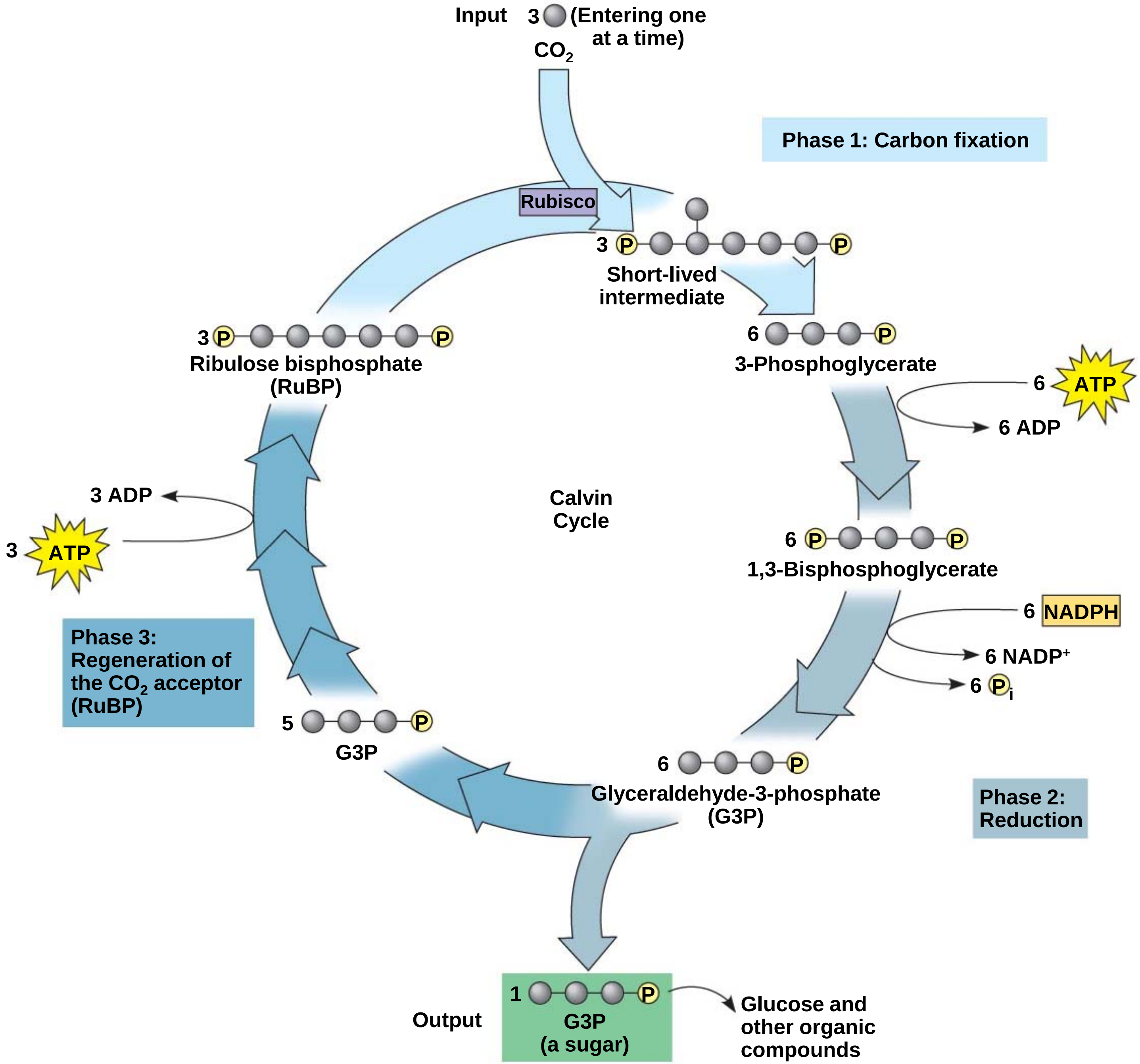
Concept 10.3: The Calvin cycle uses ATP and NADPH to convert CO_2 to sugar

- The Calvin cycle, like the citric acid cycle, regenerates its starting material after molecules enter and leave the cycle

- The cycle builds sugar from smaller molecules by using ATP and the reducing power of electrons carried by NADPH

- Carbon enters the cycle as CO_2 and leaves as a sugar named **glyceraldehyde-3-phospate (G3P)**
- For net synthesis of 1 G3P, the cycle must take place three times, fixing 3 molecules of CO_2
- The Calvin cycle has three phases:
  - **Carbon fixation** (catalyzed by **rubisco**)
  - **Reduction**
  - **Regeneration of the CO_2 acceptor (RuBP)**

Fig. 10-18-3



Input
3 (Entering one at a time)
CO_2
Phase 1: Carbon fixation
Rubisco
3 P P
Short-lived intermediate
6 P
3-Phosphoglycerate
6 ATP
6 ADP
6 P P
1,3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 P_i
6 P
Glyceraldehyde-3-phosphate (G3P)
Phase 2: Reduction
Calvin Cycle
3 P P
Ribulose bisphosphate (RuBP)
3 ADP
3 ATP
Phase 3: Regeneration of the CO_2 acceptor (RuBP)
5 P
G3P
Output
1 P
G3P (a sugar)
Glucose and other organic compounds

Concept 10.4: Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- Dehydration is a problem for plants, sometimes requiring trade-offs with other metabolic processes, especially photosynthesis
- On hot, dry days, plants close stomata, which conserves H_2O but also limits photosynthesis
- The closing of stomata reduces access to CO_2 and causes O_2 to build up
- These conditions favor a seemingly wasteful process called photorespiration

Photorespiration: An Evolutionary Relic?

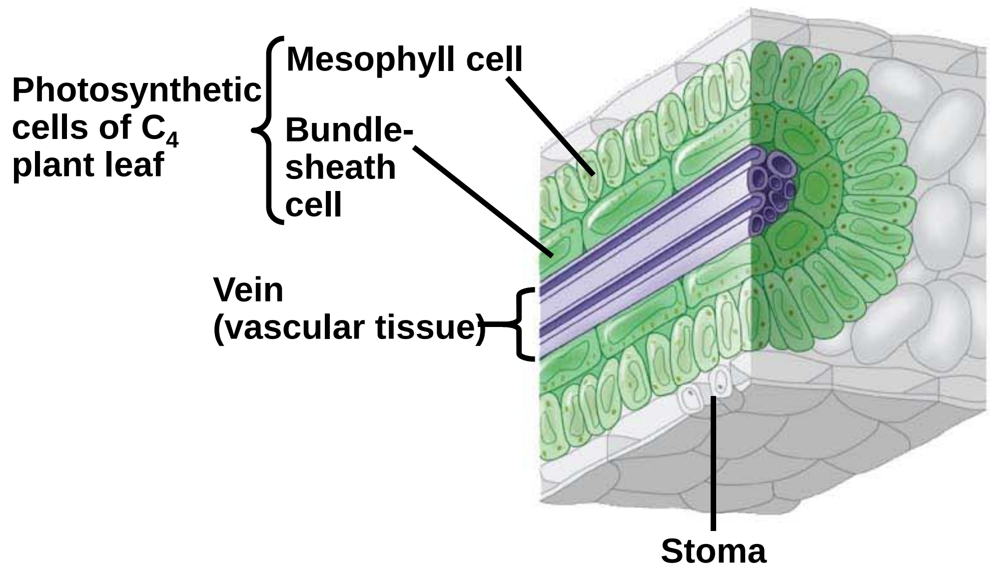
- In most plants (**C_3 plants**), initial fixation of CO_2, via rubisco, forms a three-carbon compound
- In **photorespiration**, rubisco adds O_2 instead of CO_2 in the Calvin cycle
- Photorespiration consumes O_2 and organic fuel and releases CO_2 without producing ATP or sugar

- Photorespiration may be an evolutionary relic because rubisco first evolved at a time when the atmosphere had far less O_2 and more CO_2
- Photorespiration limits damaging products of light reactions that build up in the absence of the Calvin cycle
- In many plants, photorespiration is a problem because on a hot, dry day it can drain as much as 50% of the carbon fixed by the Calvin cycle

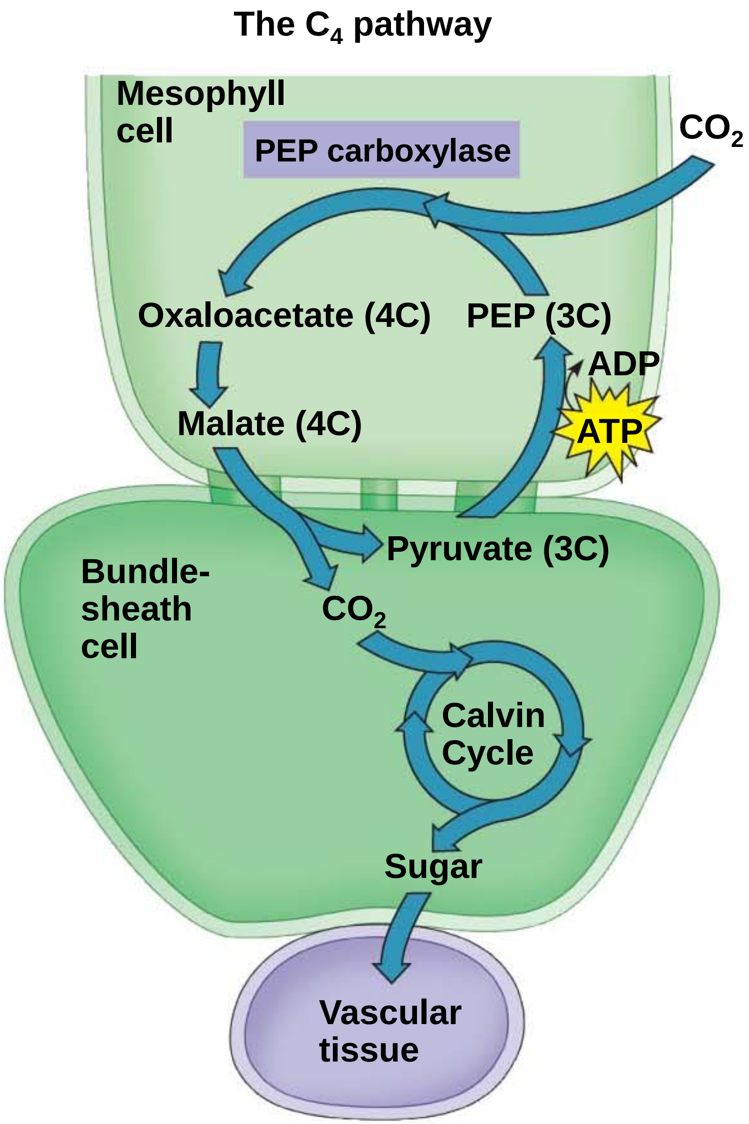
C_4 Plants

- **C_4 plants** minimize the cost of photorespiration by incorporating CO_2 into four-carbon compounds in **mesophyll cells**
- This step requires the enzyme **PEP carboxylase**
- PEP carboxylase has a higher affinity for CO_2 than rubisco does; it can fix CO_2 even when CO_2 concentrations are low
- These four-carbon compounds are exported to **bundle-sheath cells**, where they release CO_2 that is then used in the Calvin cycle

Fig. 10-19



C_4 leaf anatomy
Photosynthetic cells of C_4 plant leaf
Mesophyll cell
Bundle-sheath cell
Vein (vascular tissue)
Stoma

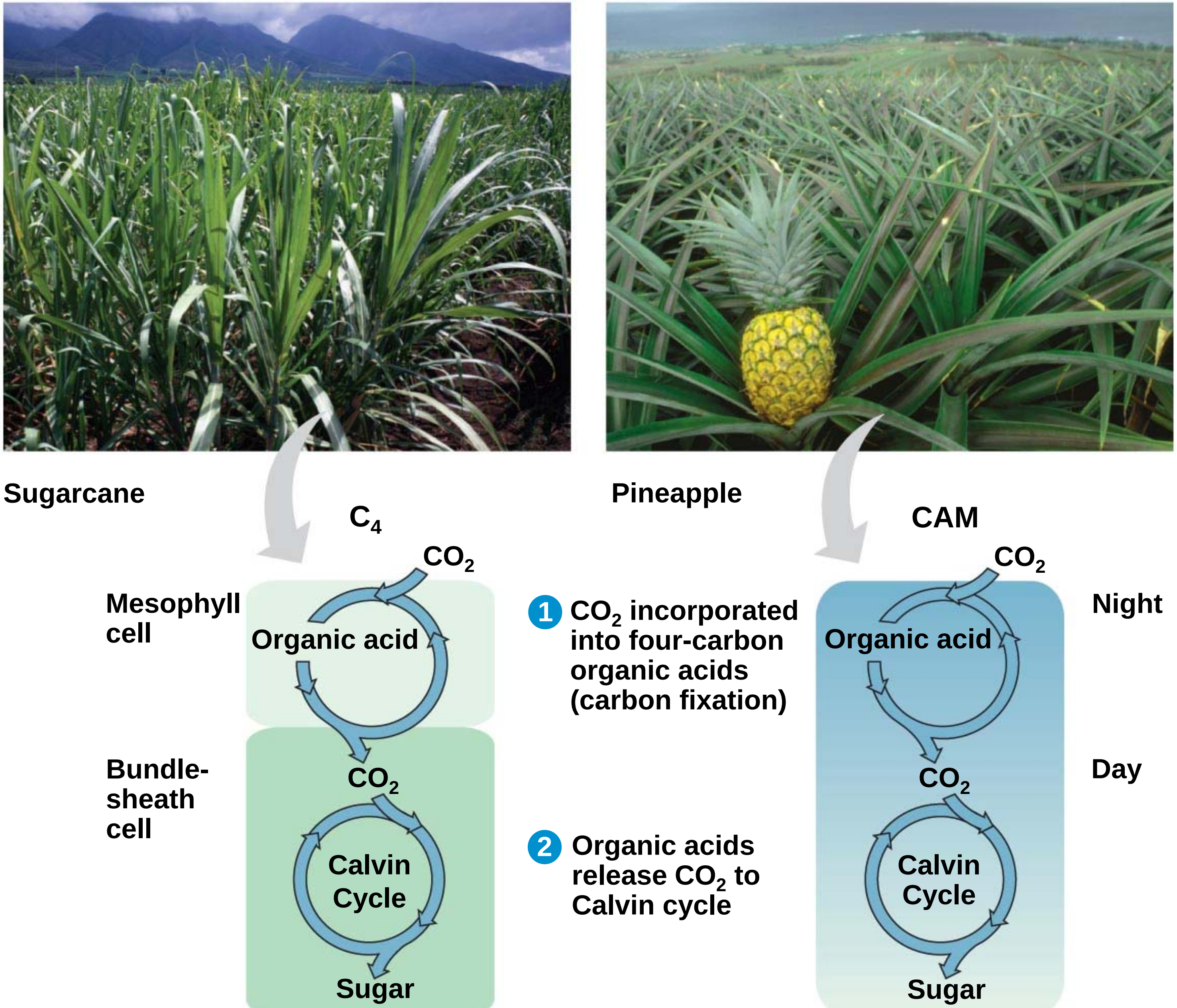


The C_4 pathway
Mesophyll cell
PEP carboxylase
CO_2
Oxaloacetate (4C)
PEP (3C)
ADP
Malate (4C)
ATP
Pyruvate (3C)
Bundle-sheath cell
CO_2
Calvin Cycle
Sugar
Vascular tissue

CAM Plants

- Some plants, including succulents, use **crassulacean acid metabolism (CAM)** to fix carbon
- **CAM plants** open their stomata at night, incorporating CO_2 into organic acids
- Stomata close during the day, and CO_2 is released from organic acids and used in the Calvin cycle

Fig. 10-20



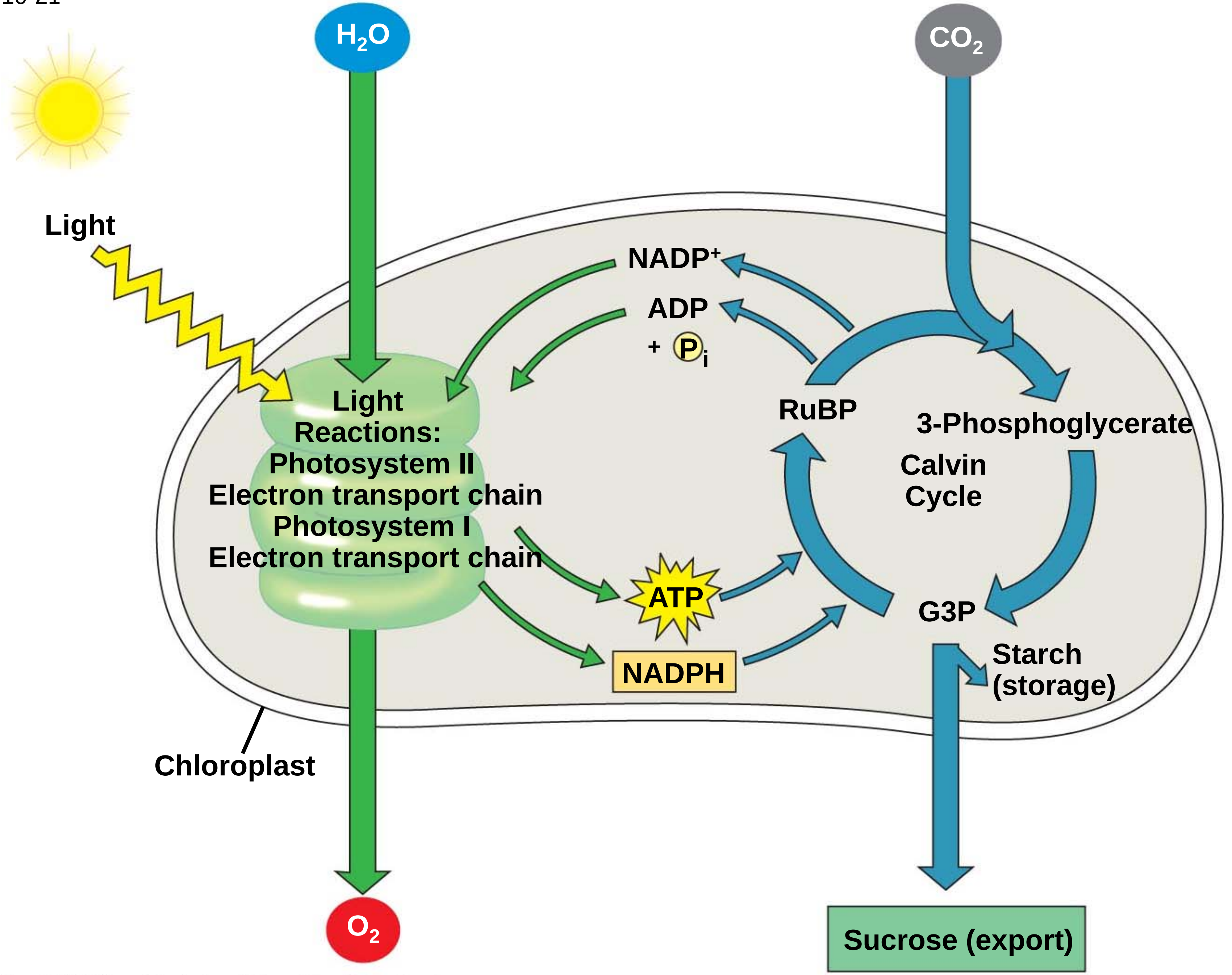
(a) Spatial separation of steps

(b) Temporal separation of steps

The Importance of Photosynthesis: *A Review*

- The energy entering chloroplasts as sunlight gets stored as chemical energy in organic compounds
- Sugar made in the chloroplasts supplies chemical energy and carbon skeletons to synthesize the organic molecules of cells
- Plants store excess sugar as starch in structures such as roots, tubers, seeds, and fruits
- In addition to food production, photosynthesis produces the O_2 in our atmosphere

Fig. 10-21



H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
Light
Reactions:
Photosystem II
Electron transport chain
Photosystem I
Electron transport chain
RuBP
3-Phosphoglycerate
Calvin
Cycle
ATP
NADPH
G3P
Starch
(storage)
Chloroplast
O_2
Sucrose (export)

You should now be able to:

1. Describe the structure of a chloroplast
2. Describe the relationship between an action spectrum and an absorption spectrum
3. Trace the movement of electrons in linear electron flow
4. Trace the movement of electrons in cyclic electron flow

5. Describe the similarities and differences between oxidative phosphorylation in mitochondria and photophosphorylation in chloroplasts
6. Describe the role of ATP and NADPH in the Calvin cycle
7. Describe the major consequences of photorespiration
8. Describe two important photosynthetic adaptations that minimize photorespiration