LECTURE PRESENTATIONS
For CAMPBELL BIOLOGY, NINTH EDITION
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Chapter 10

Photosynthesis

Lectures by
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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

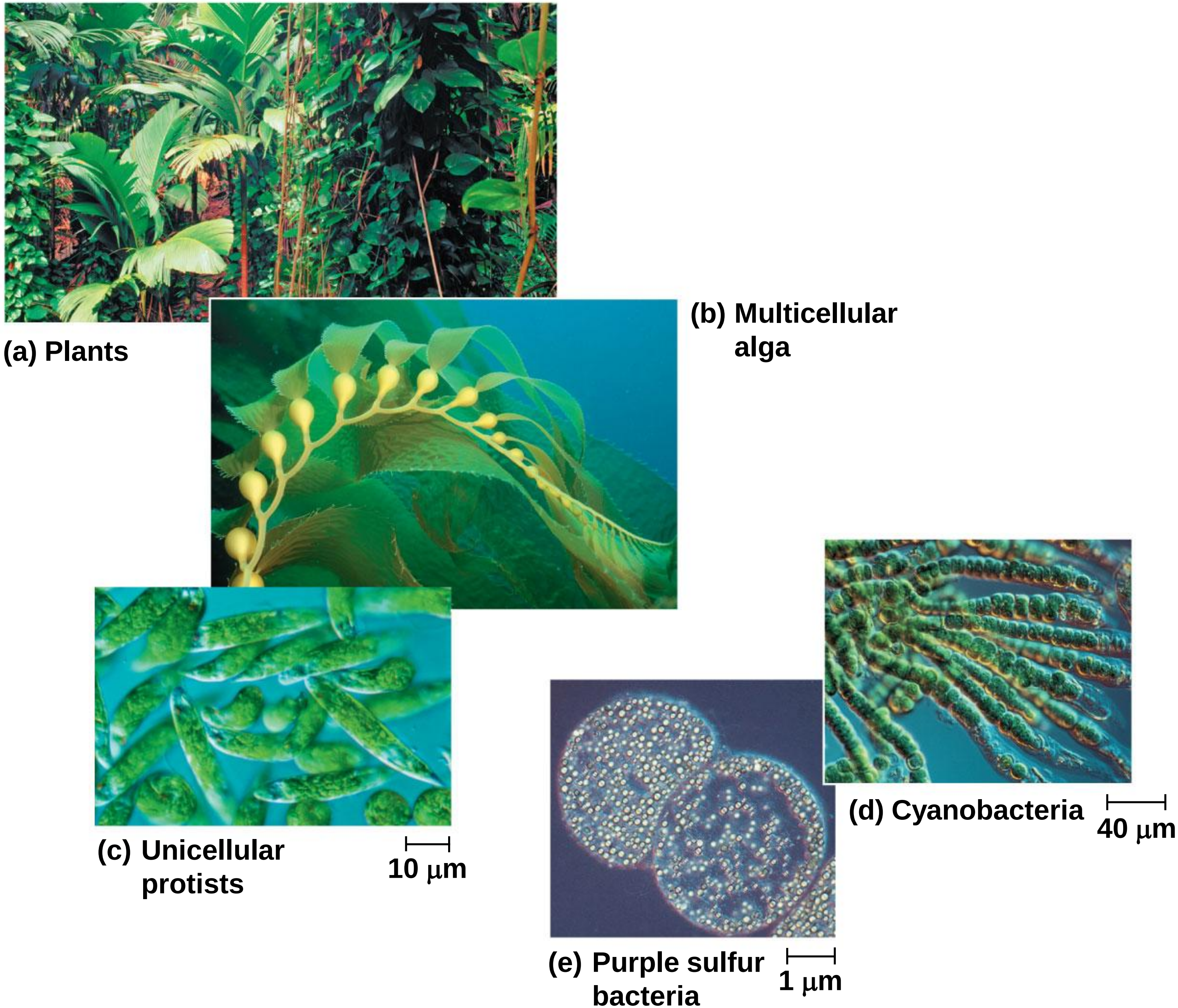
- **Autotrophs** sustain themselves without eating anything derived from other organisms
- Autotrophs are the producers of the biosphere, producing organic molecules from CO_2 and other inorganic molecules
- Almost all plants are photoautotrophs, using the energy of sunlight to make organic molecules

Figure 10.1

- Photosynthesis occurs in plants, algae, certain other protists, and some prokaryotes
- These organisms feed not only themselves but also most of the living world

PLAY BioFlix: Photosynthesis

Figure 10.2



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

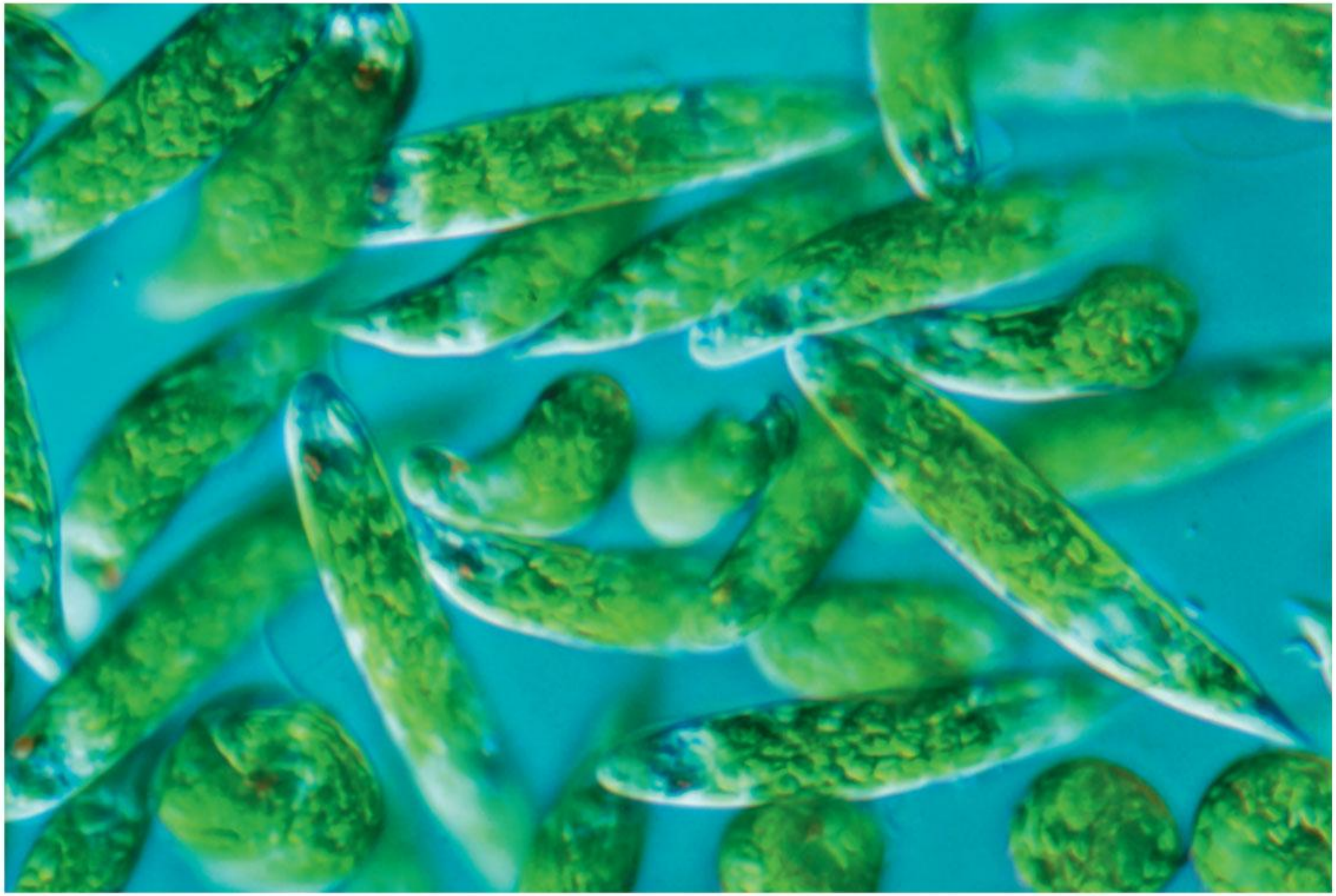
Figure 10.2a

(a) Plants

Figure 10.2b

(b) Multicellular alga

Figure 10.2c



(c) Unicellular protists

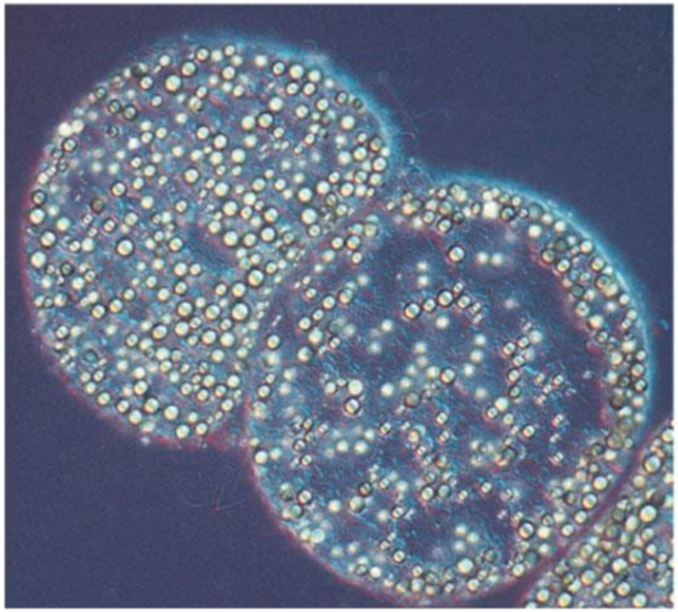
10 µm

Figure 10.2d

(d) Cyanobacteria

40 µm

Figure 10.2e



1 μm

(e) Purple sulfur bacteria

- **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

- 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

Figure 10.3

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

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
- Chloroplasts are found mainly in cells of the **mesophyll**, the interior tissue of the leaf
- Each mesophyll cell contains 30–40 chloroplasts

- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**
- 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 interior fluid

Figure 10.4

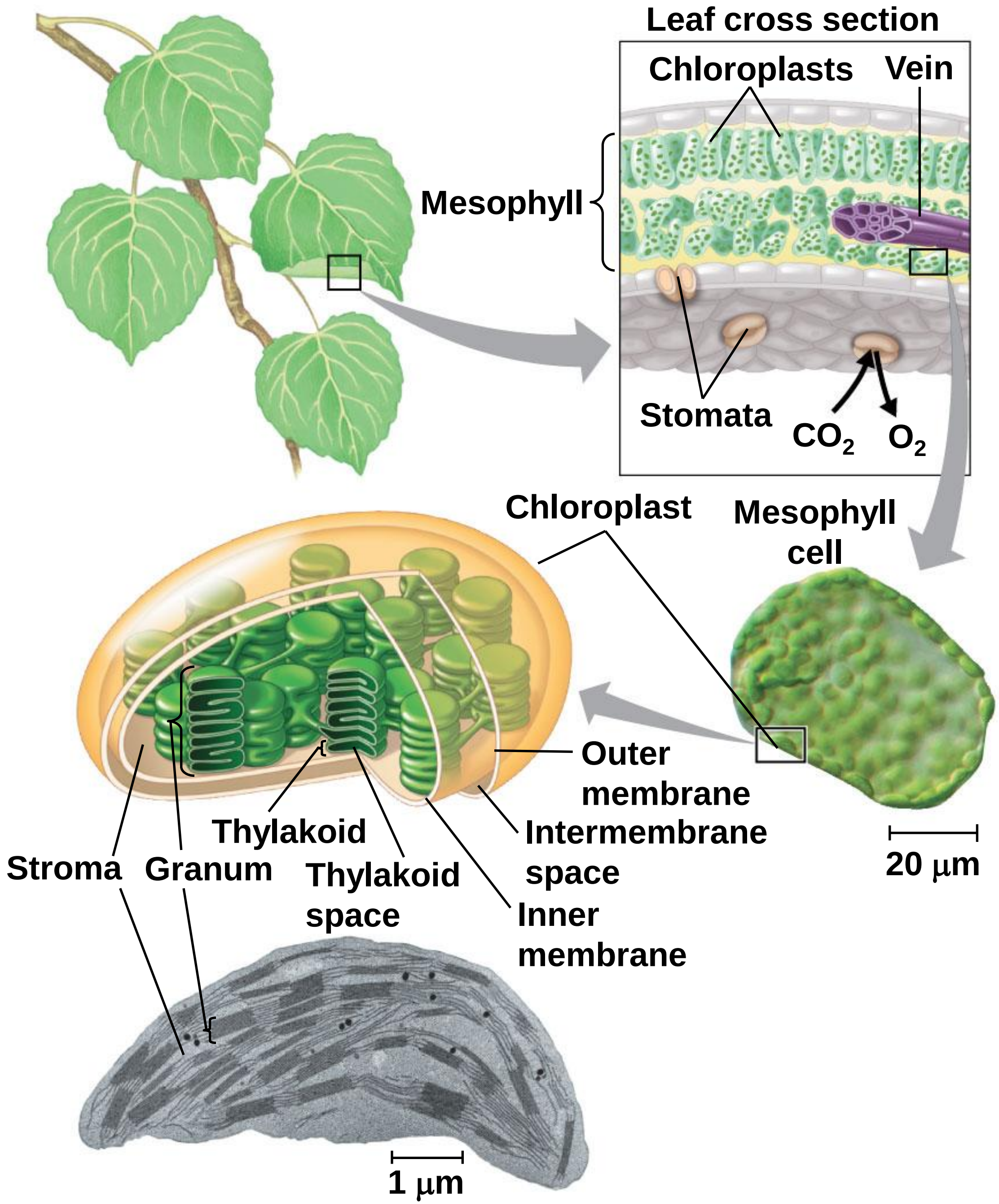

Leaf cross section
Chloroplasts
Vein
Mesophyll
Stomata
CO_2
O_2
Chloroplast
Mesophyll
cell
Outer
membrane
Intermembrane
space
Inner
membrane
Thylakoid
Thylakoid
space
Stroma
Granum
20 μm
1 μm

Figure 10.4a

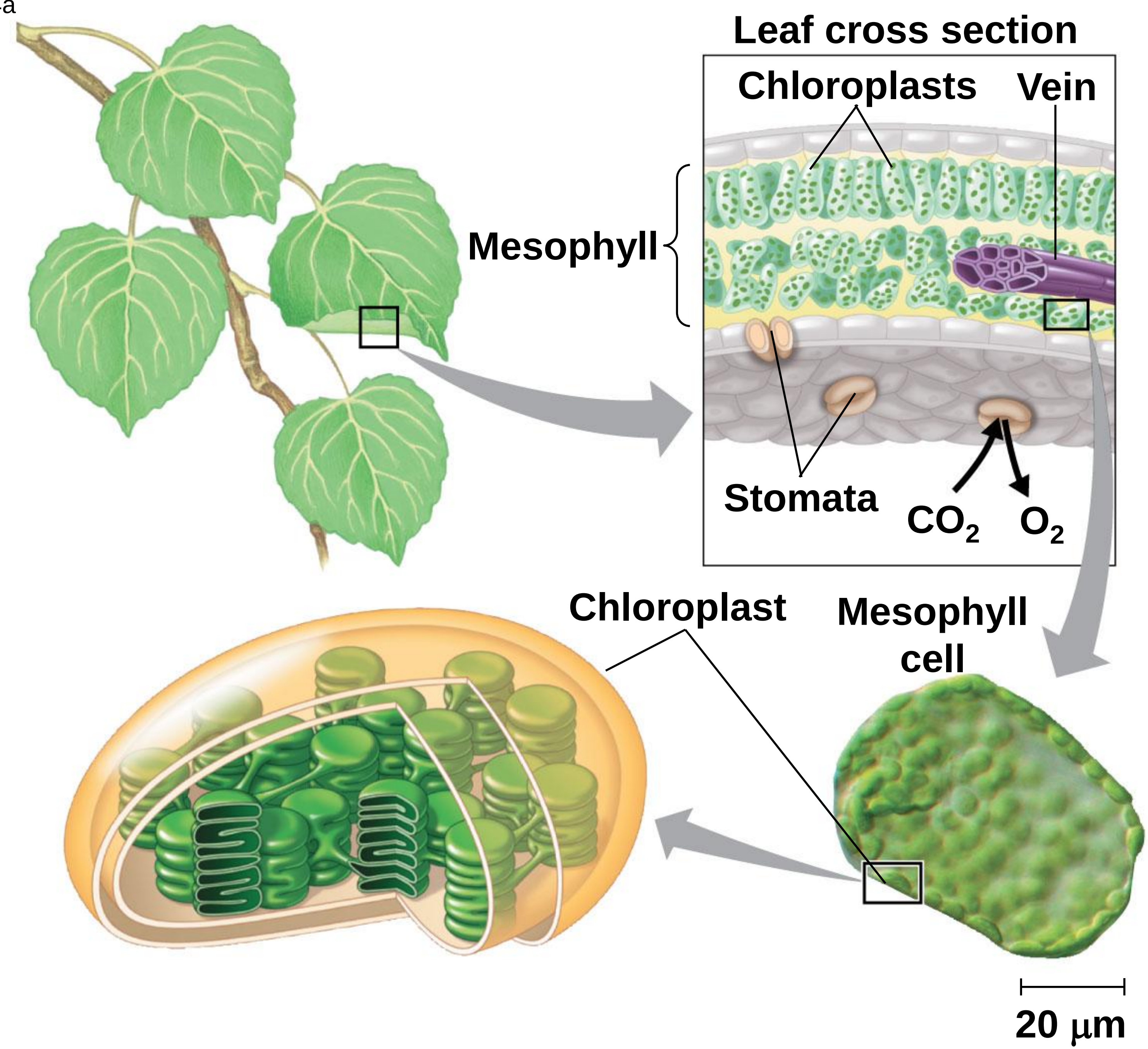
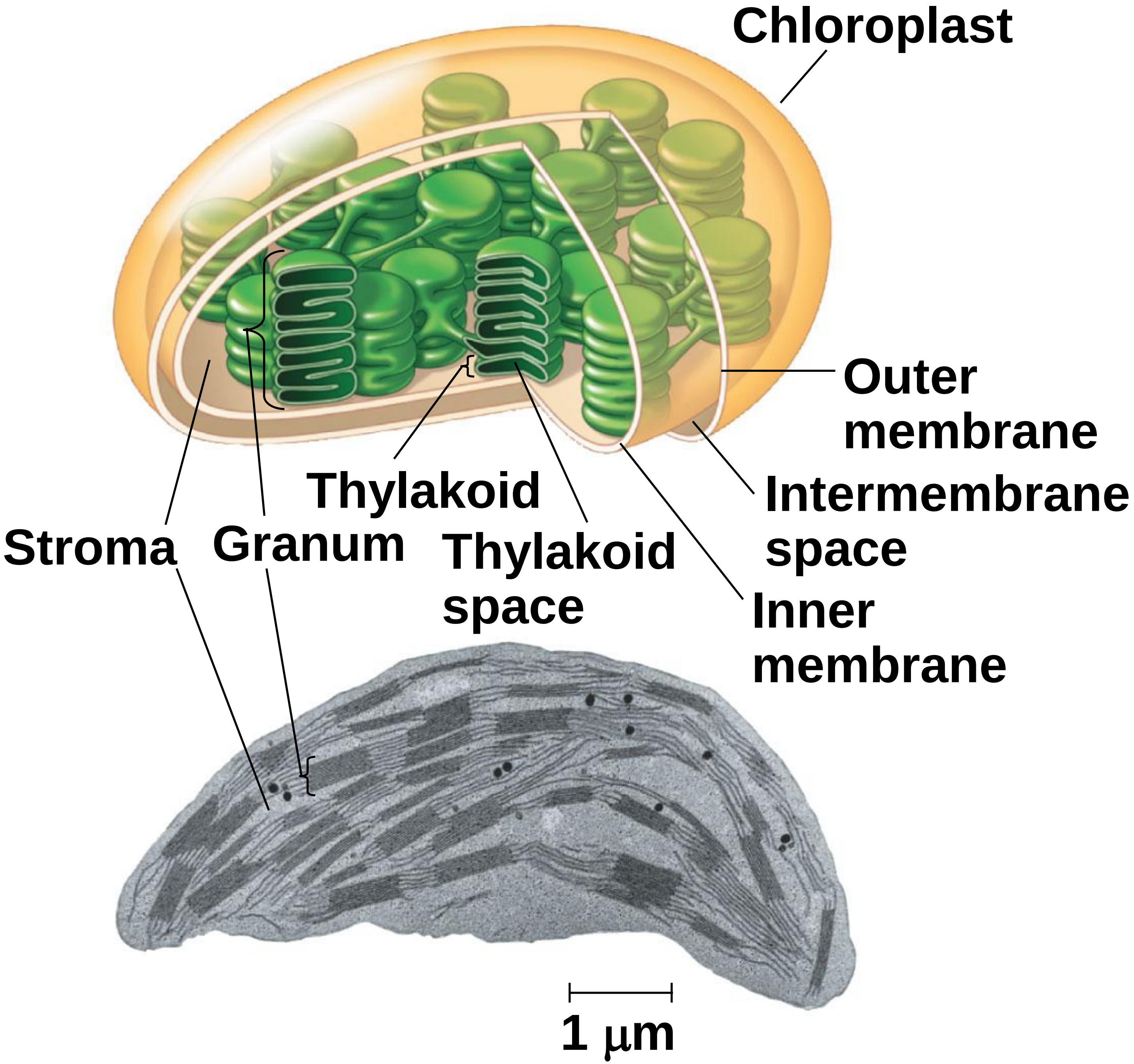

Leaf cross section
Chloroplasts
Vein
Mesophyll
Stomata
CO_2
O_2
Chloroplast
Mesophyll cell
20 µm

Figure 10.4b



Chloroplast
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Thylakoid space
Stroma
Granum
1 µm

Figure 10.4c

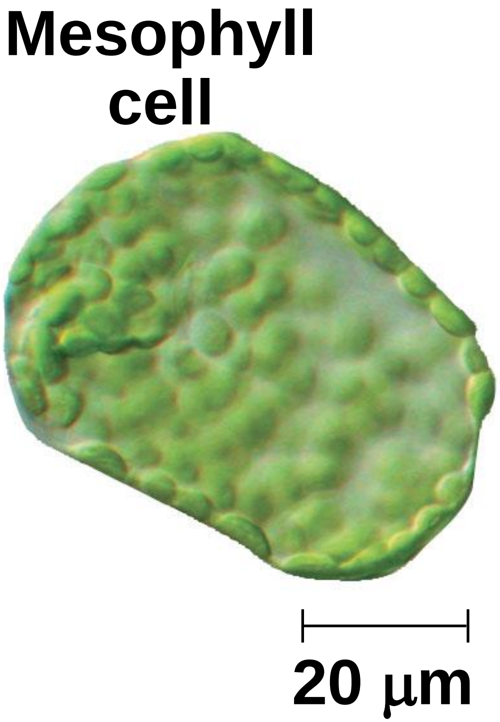
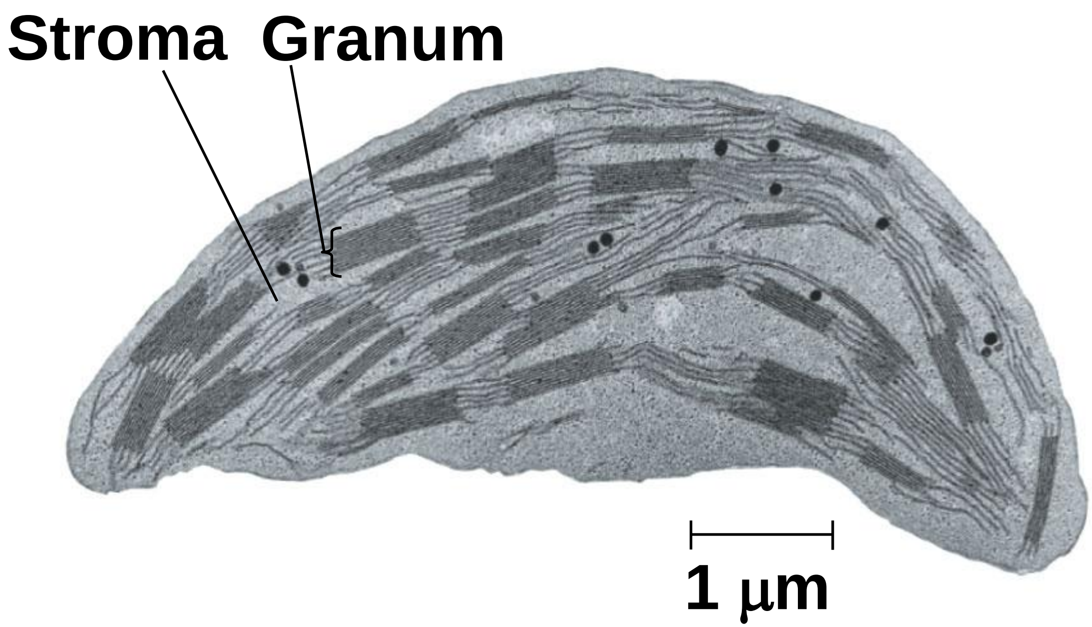


Figure 10.4d



Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

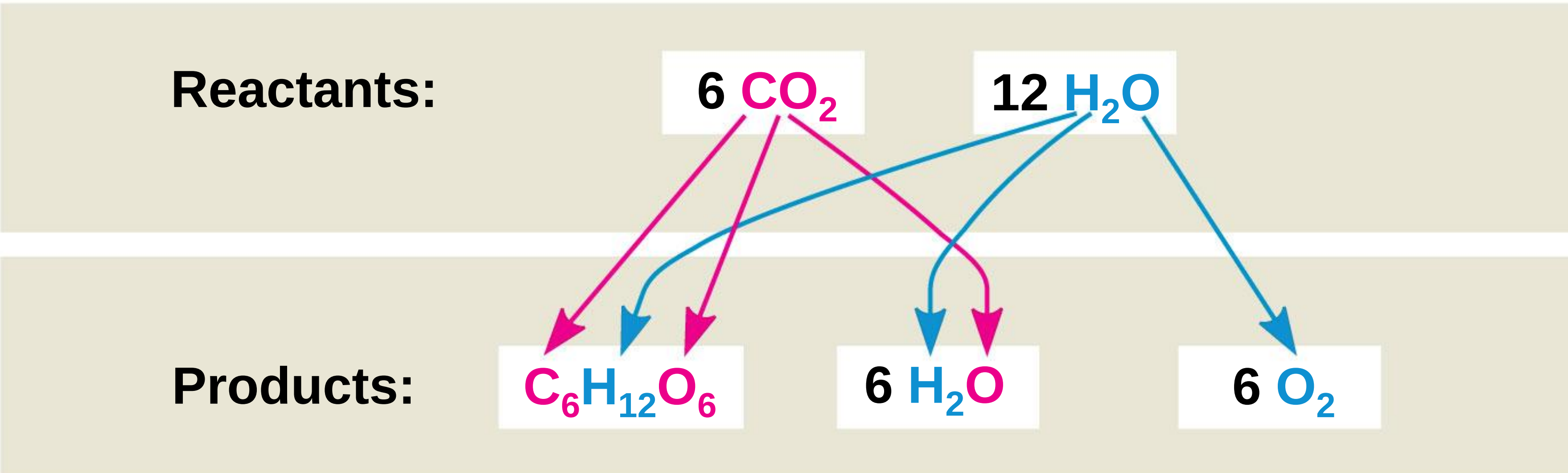
- Photosynthesis is a complex series of reactions that can be summarized as the following equation:

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

The Splitting of Water

- Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules and releasing oxygen as a by-product

Figure 10.5



Photosynthesis as a Redox Process

- Photosynthesis reverses the direction of electron flow compared to respiration
- Photosynthesis is a redox process in which H_2O is oxidized and CO_2 is reduced
- Photosynthesis is an endergonic process; the energy boost is provided by light

Figure 10.UN01

becomes reduced

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

becomes oxidized

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

Figure 10.6-1

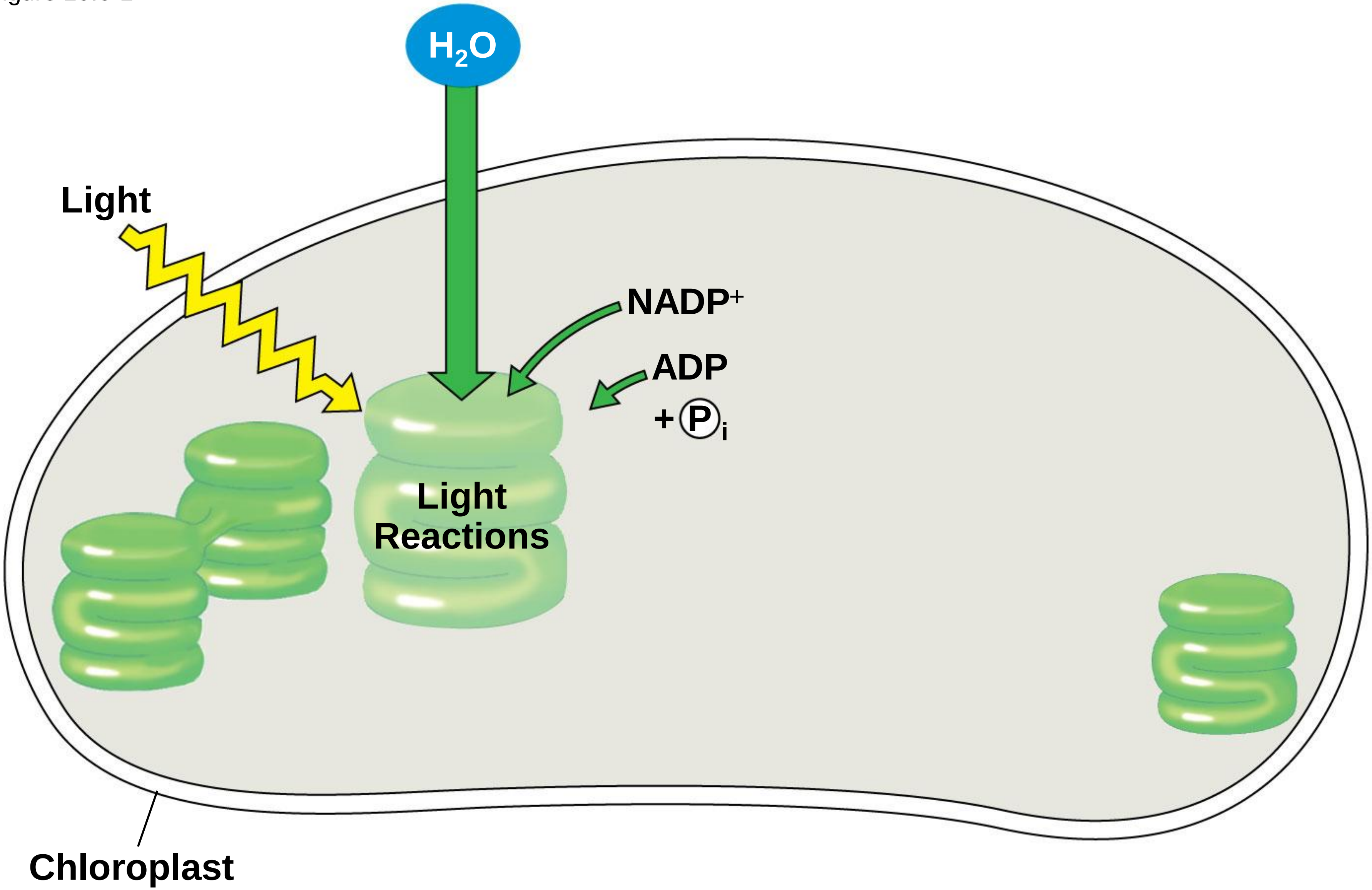
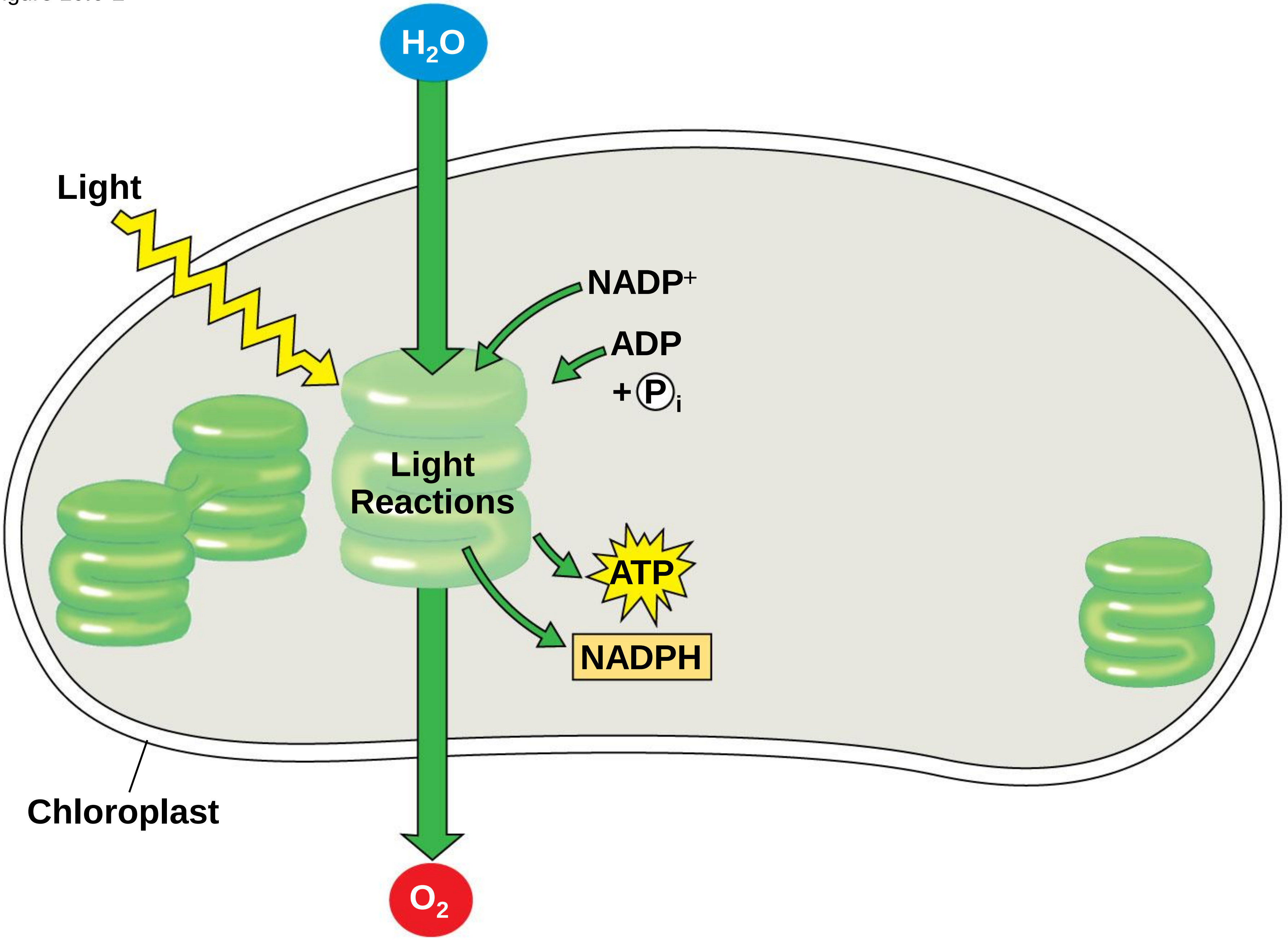
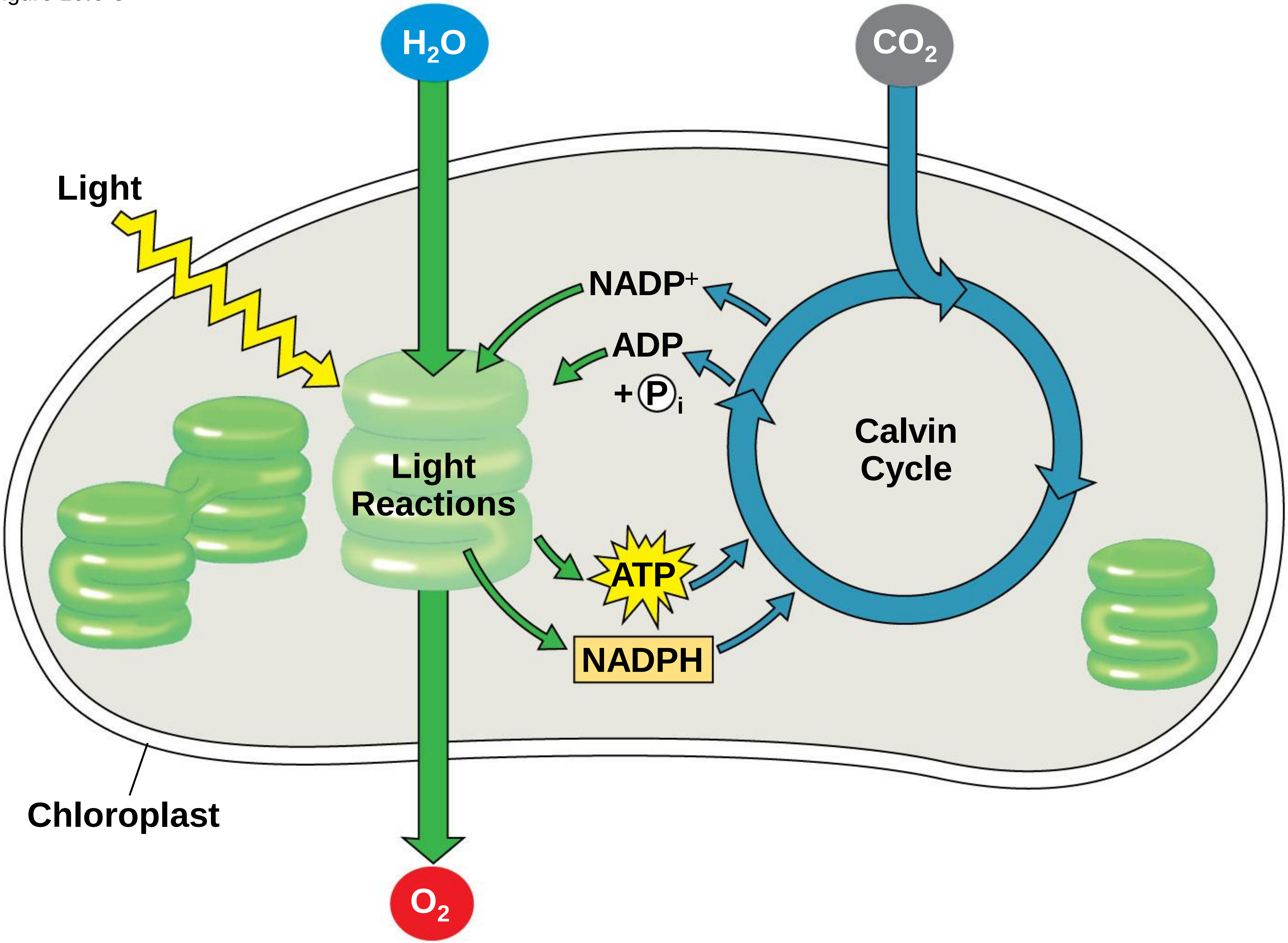


Figure 10.6-2



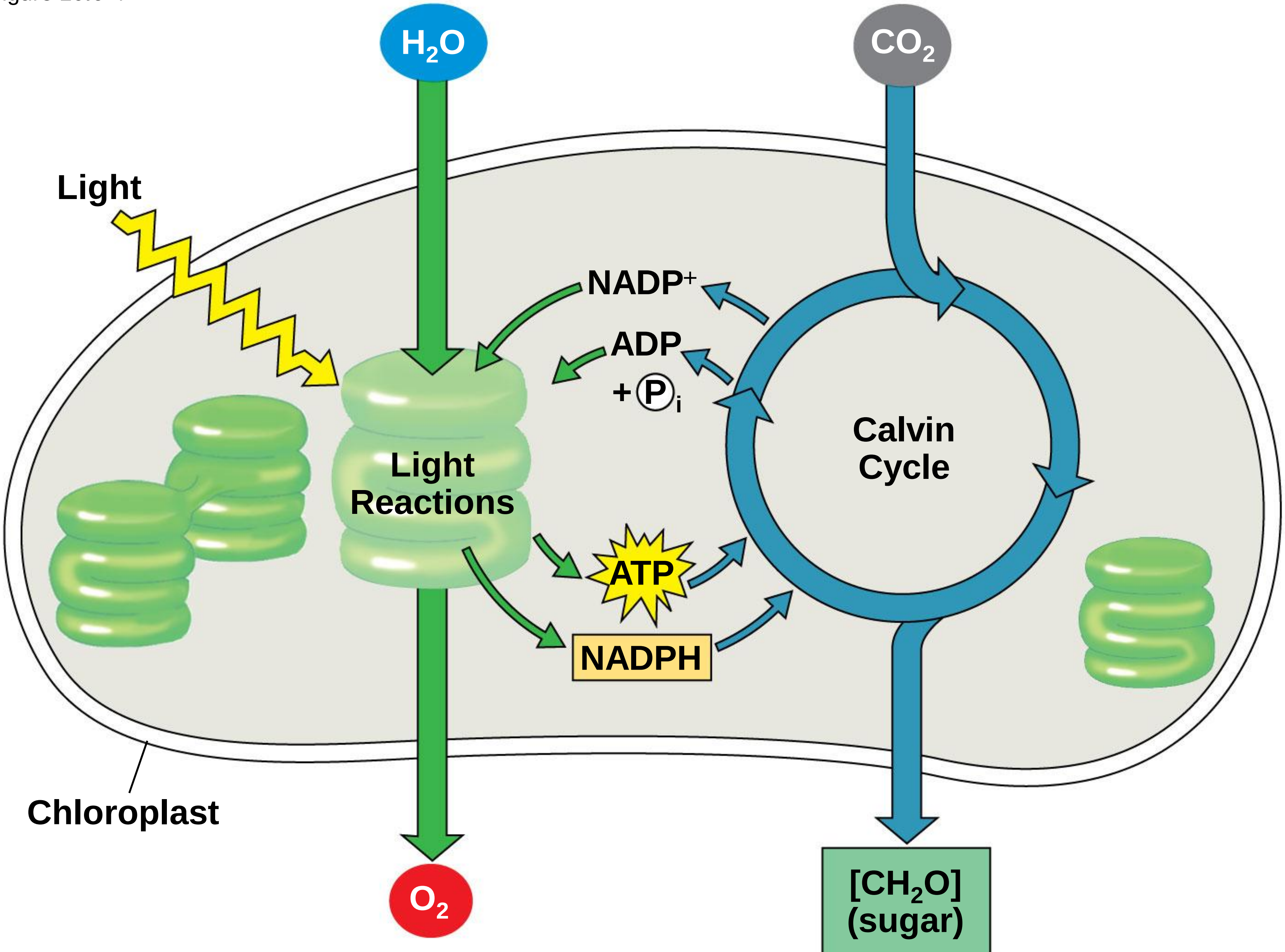
H_2O
Light
$NADP^+$
ADP
+ P$_i$
Light
Reactions
ATP
NADPH
Chloroplast
O_2

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
+ Ⓟ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

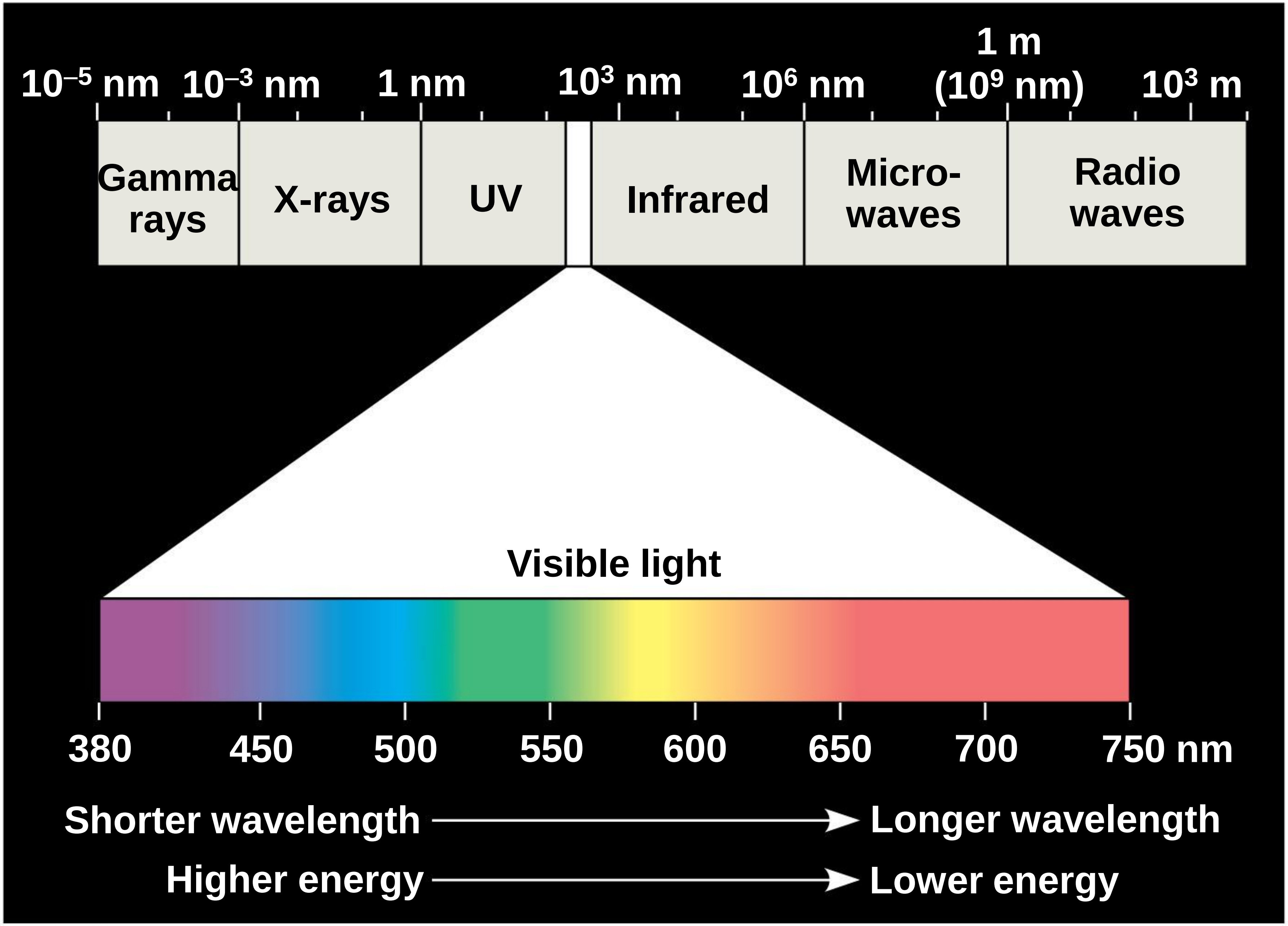
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

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**

Figure 10.7



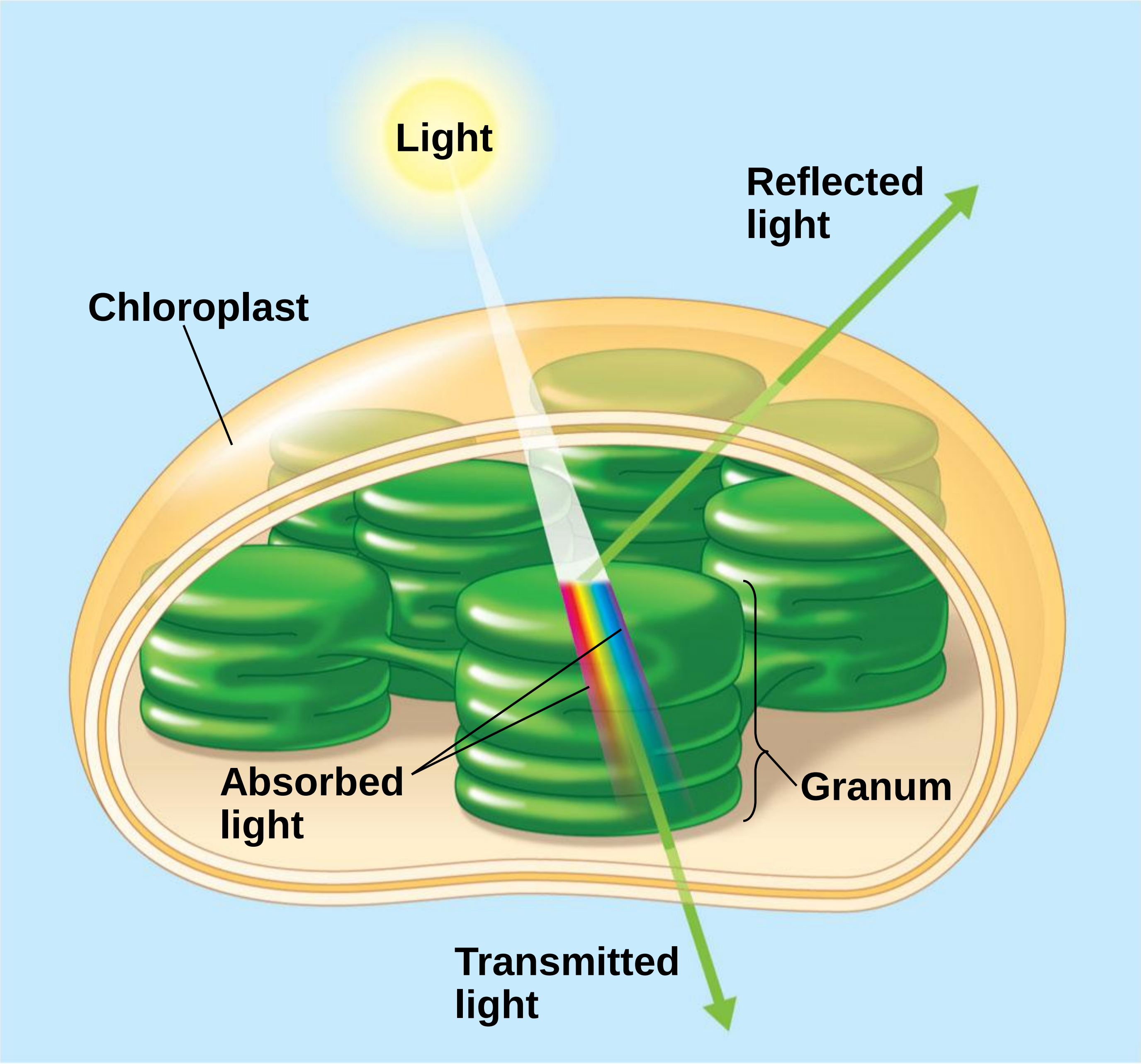
1 m
10–5 nm
10–3 nm
1 nm
10³ nm
10⁶ nm
(10⁹ nm)
10³ m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

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

PLAY Animation: Light and Pigments

Figure 10.8

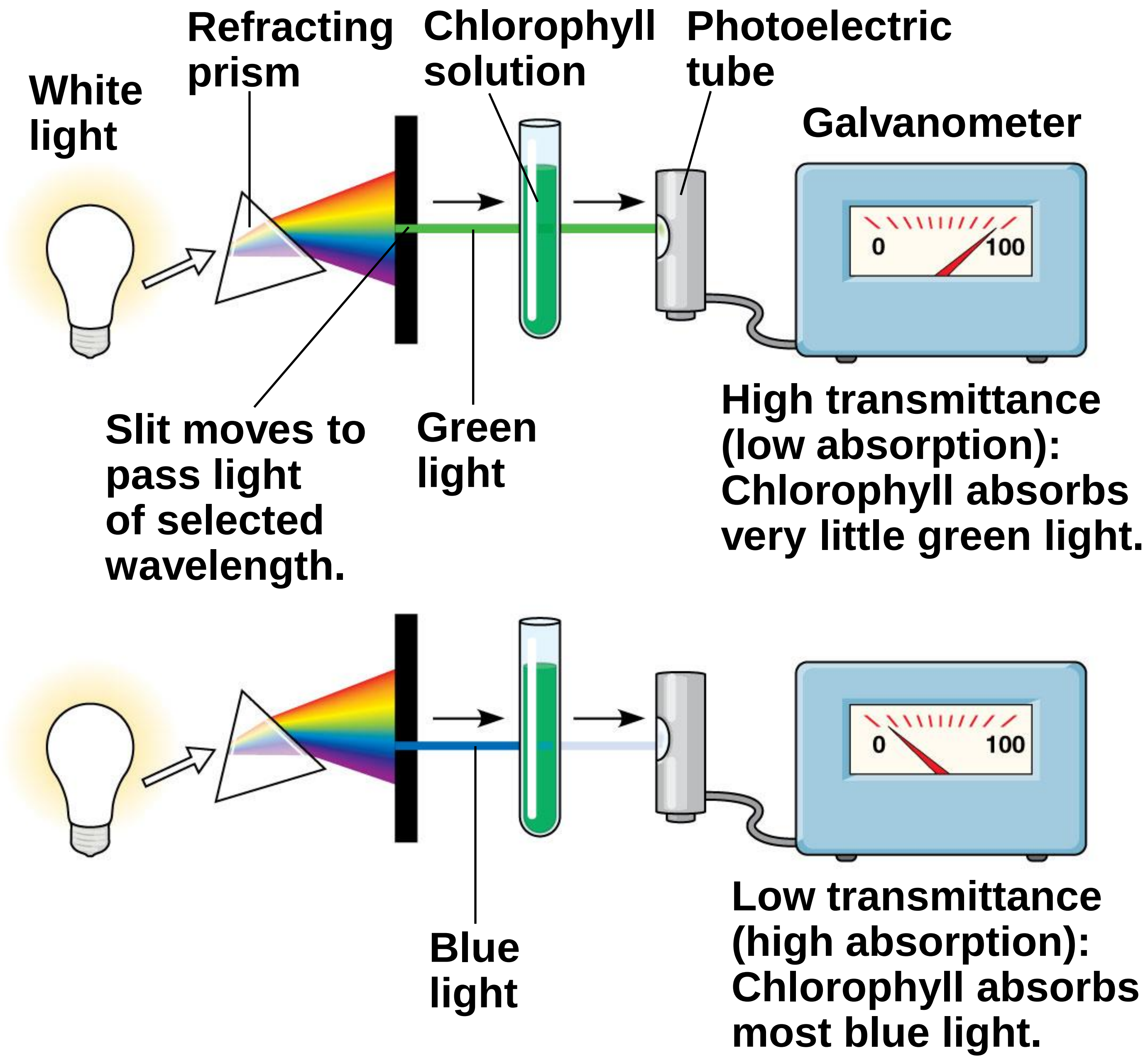


Light
Reflected light
Chloroplast
Absorbed light
Granum
Transmitted light

- 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

Figure 10.9

TECHNIQUE

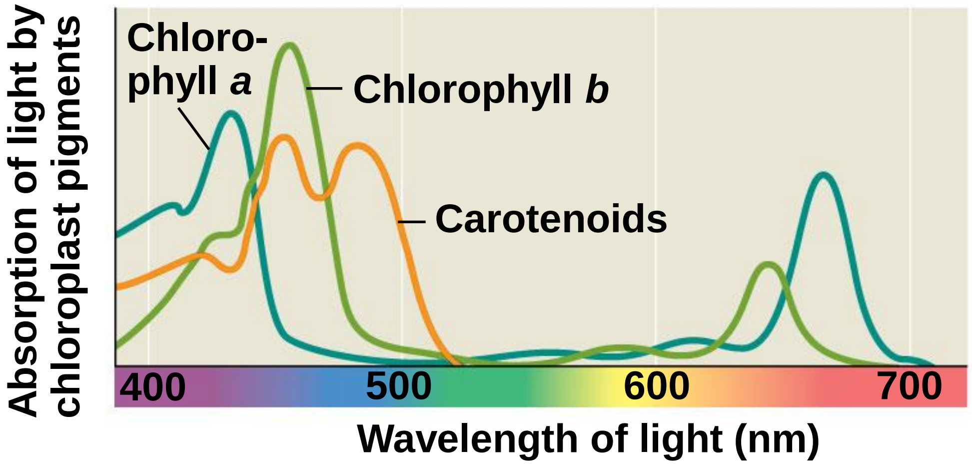


- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of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

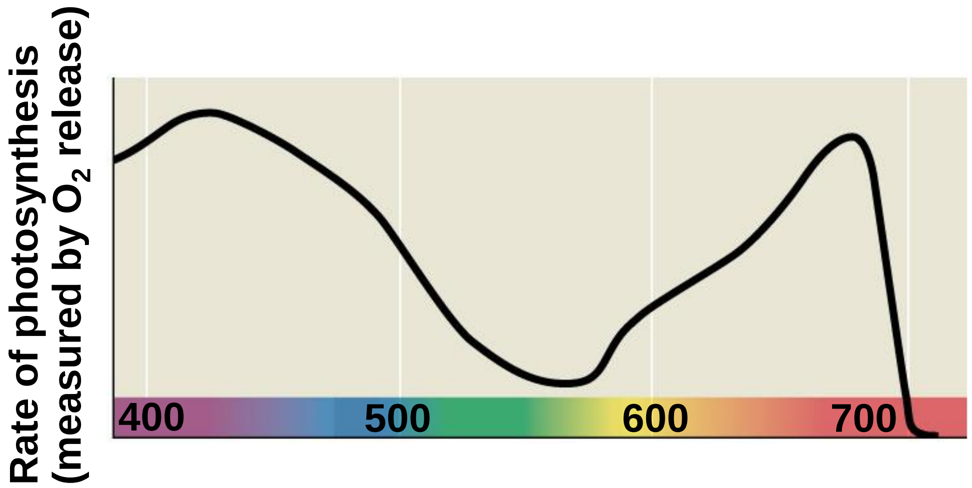
Figure 10.10

RESULTS

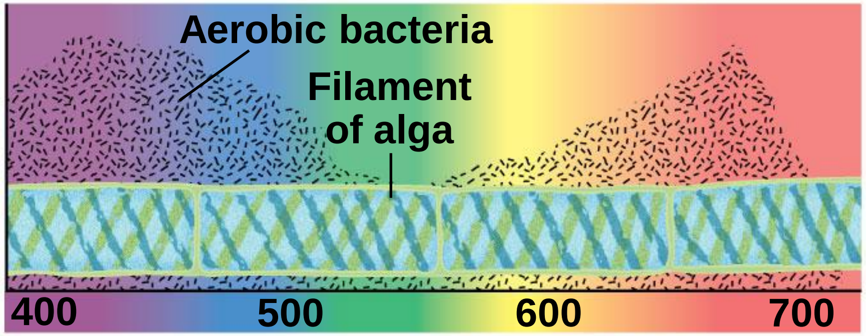
(a) Absorption spectra



(b) Action spectrum



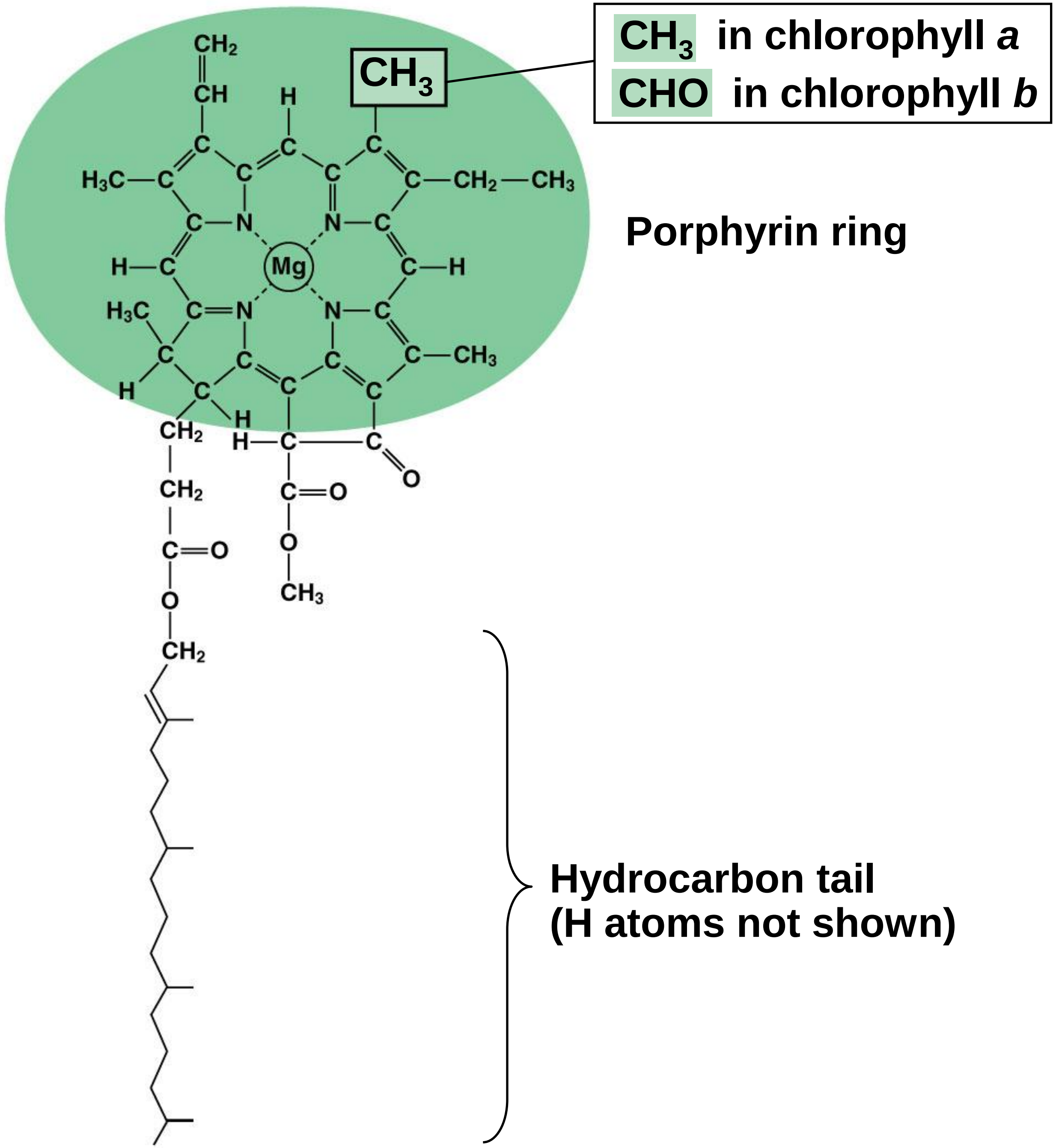
(c) Engelmann's experiment



- 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

Figure 10.11

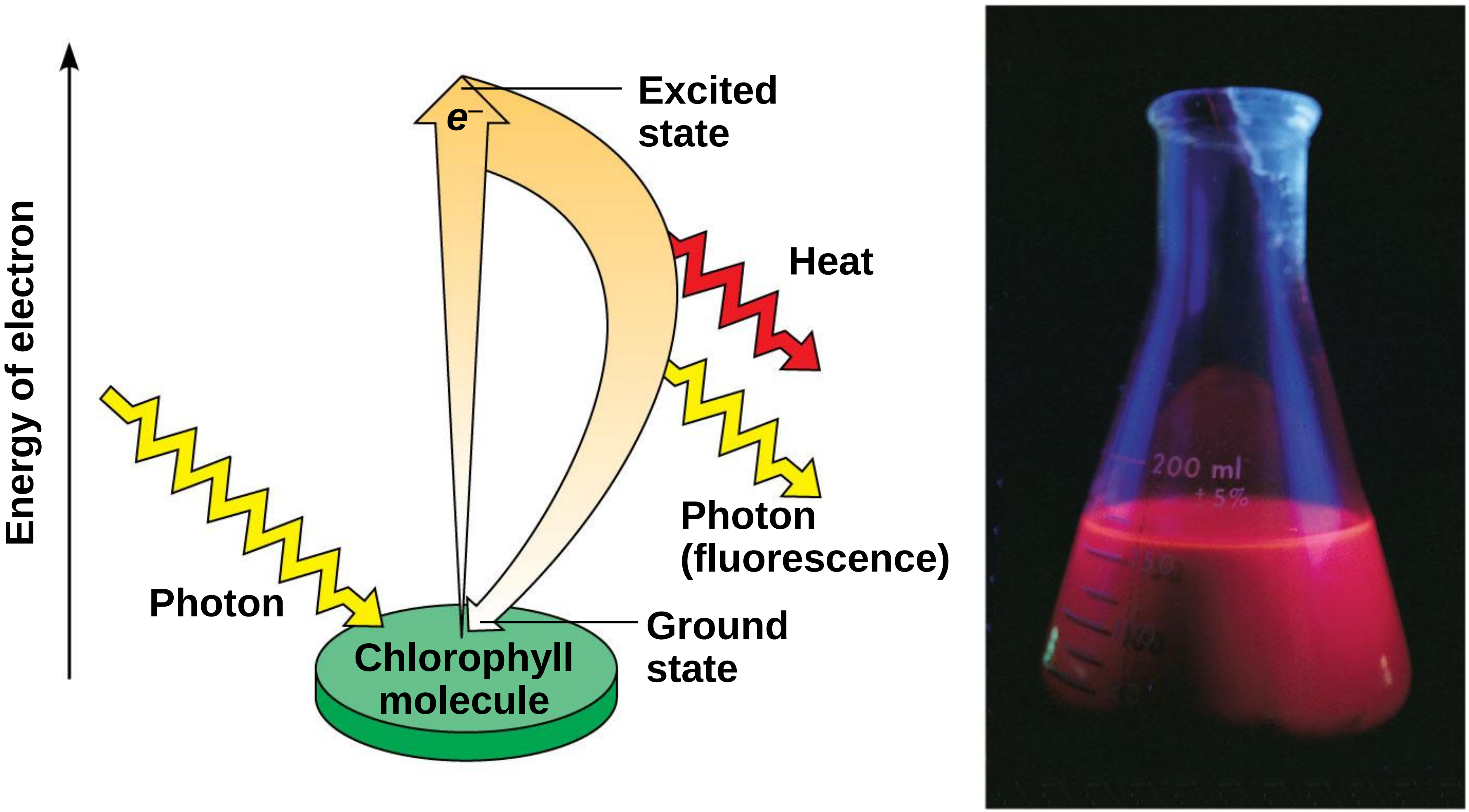


CH3 in chlorophyll a
CHO in chlorophyll b
Porphyrin ring
Hydrocarbon tail
(H atoms not shown)

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

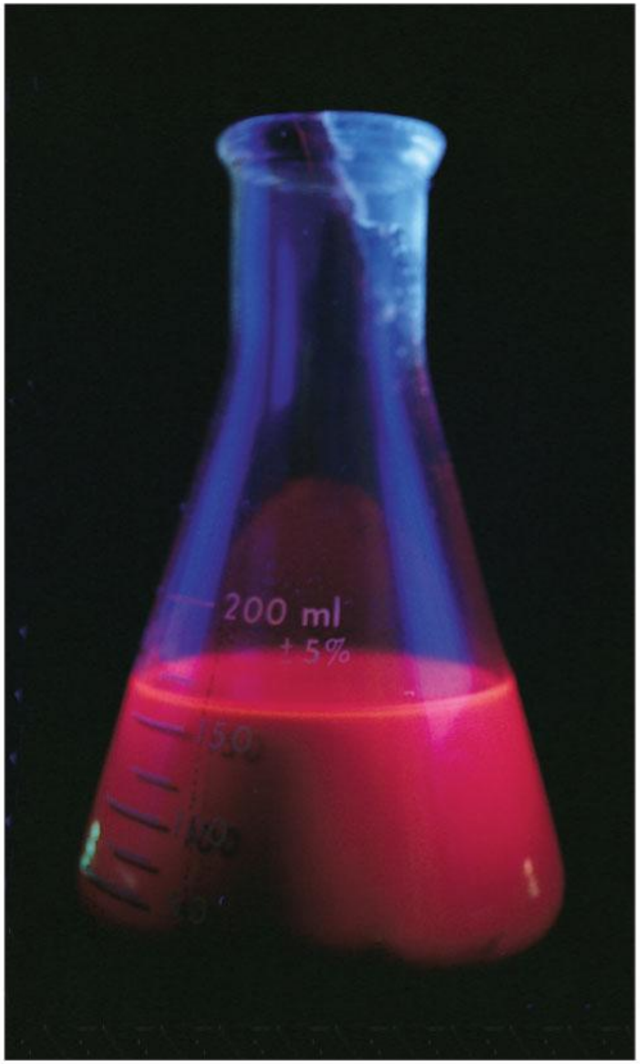
Figure 10.12



(a) Excitation of isolated chlorophyll molecule

(b) Fluorescence

Figure 10.12a

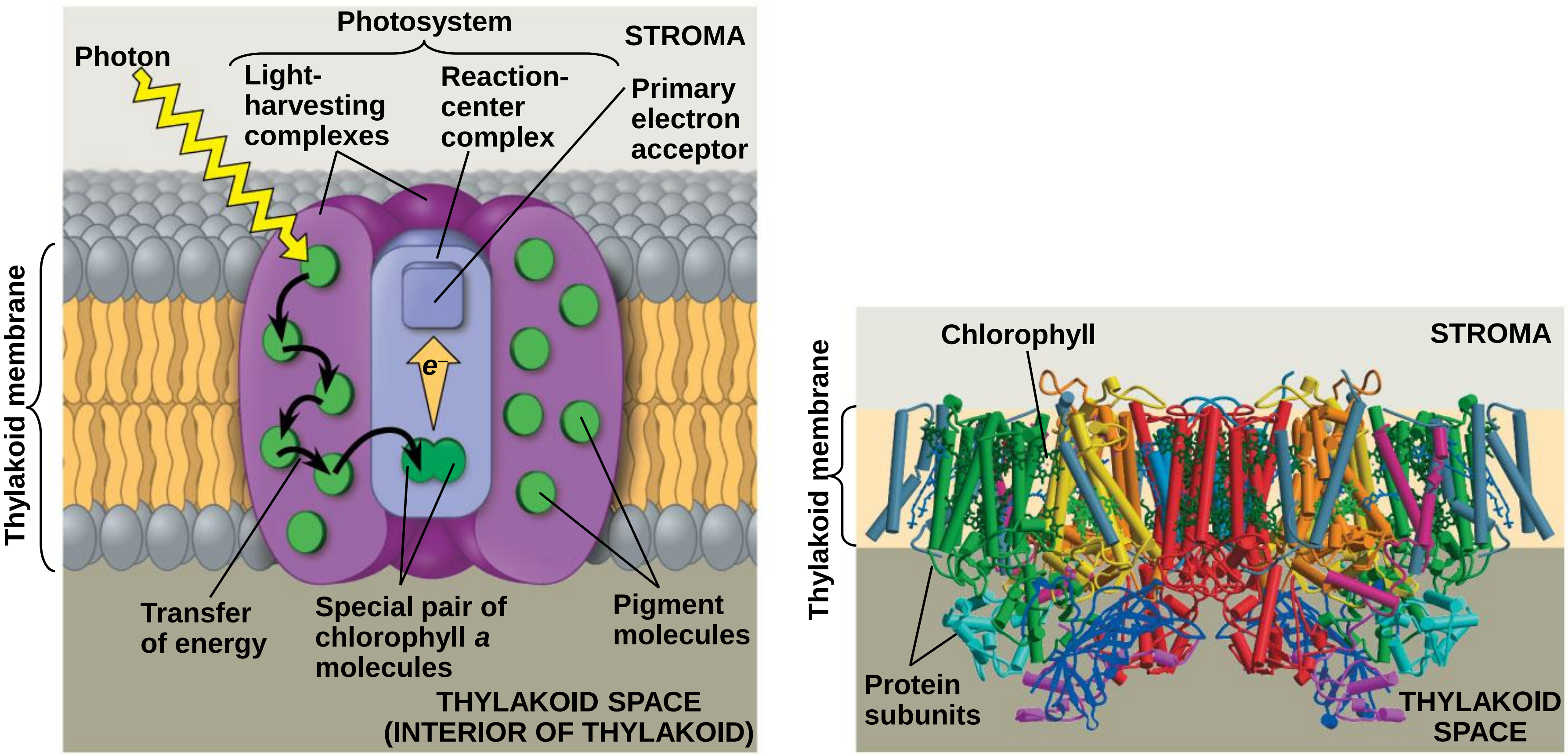


(b) Fluorescence

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) transfer the energy of photons to the reaction center

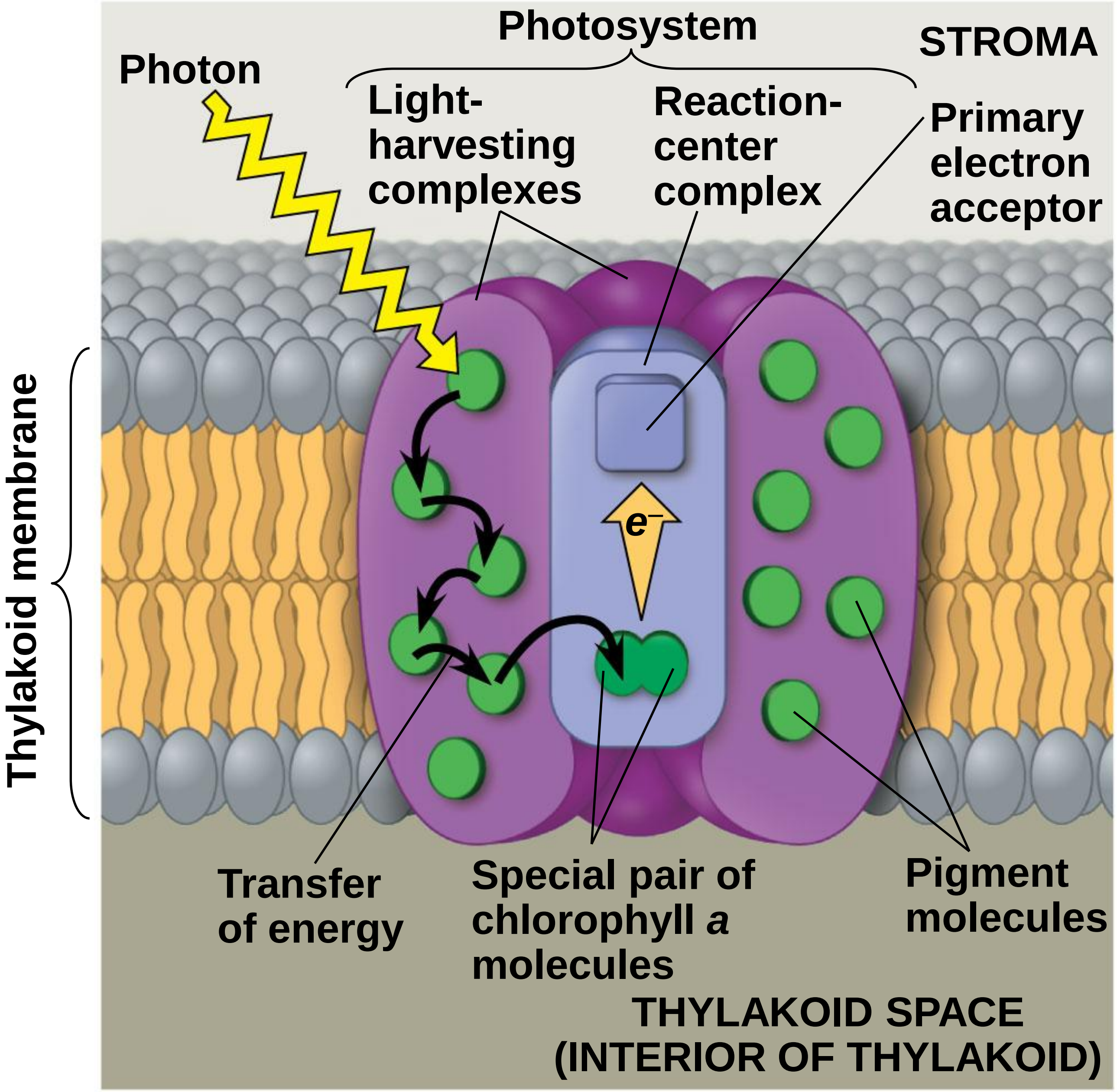
Figure 10.13



(a) How a photosystem harvests light

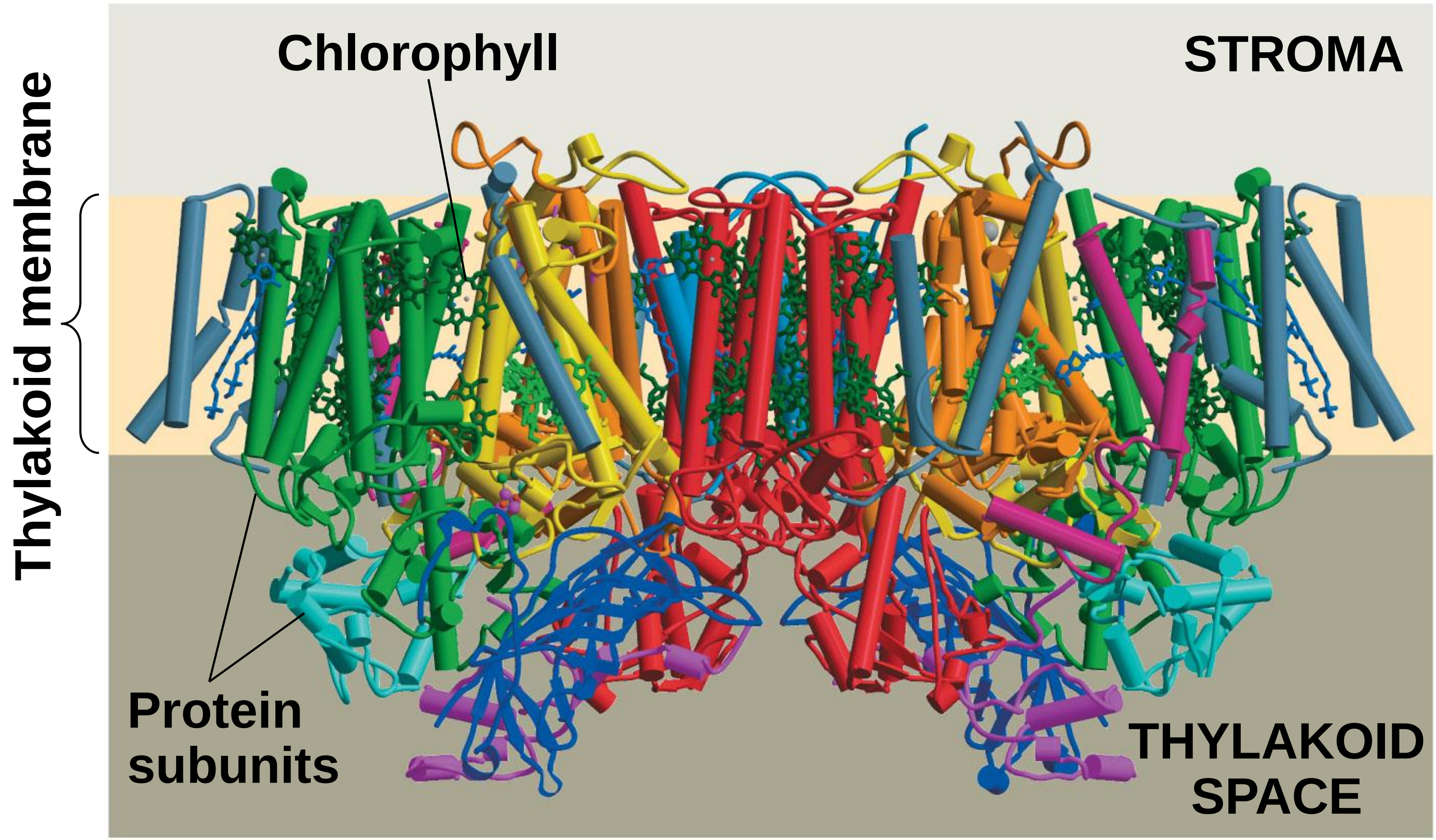
(b) Structure of photosystem II

Figure 10.13a



(a) How a photosystem harvests light

Figure 10.13b



(b) Structure of photosystem II

- A **primary electron acceptor** in the reaction center accepts excited electrons and is reduced as a result
- Solar-powered transfer of an electron from a chlorophyll *a* molecule to the primary electron acceptor is the first step of the light reactions

- 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

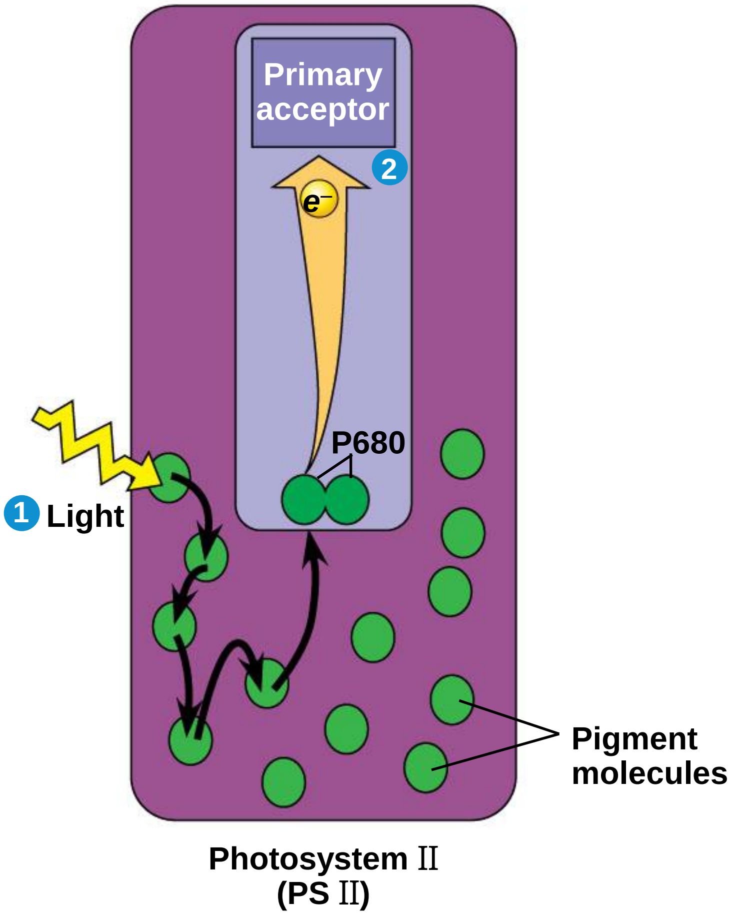
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

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

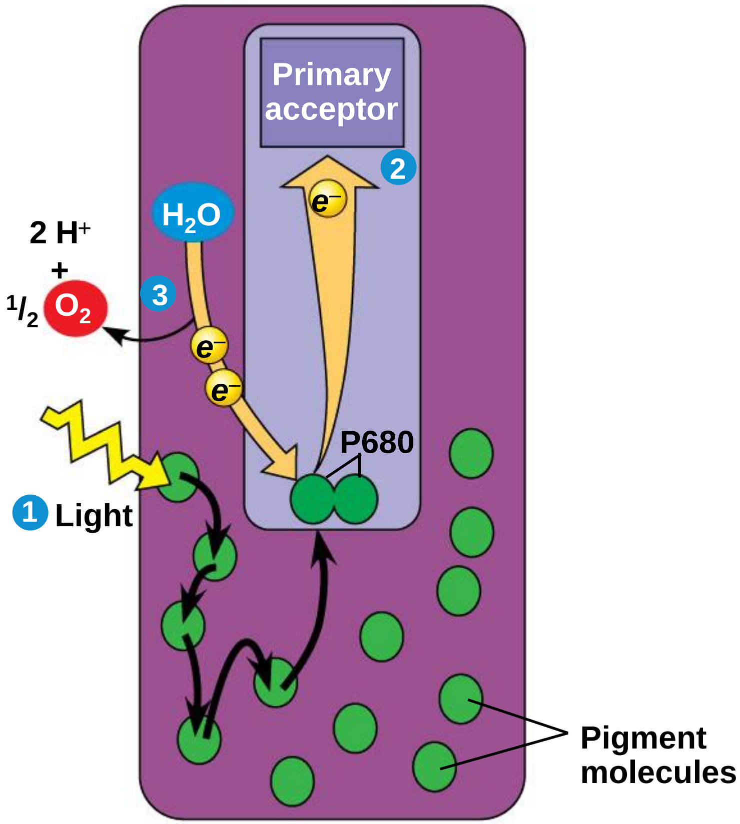
- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680
- An excited electron from P680 is transferred to the primary electron acceptor (we now call it $P680^+$)

Figure 10.14-1



- $P680^+$ is a very strong oxidizing agent
- H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680
- O_2 is released as a by-product of this reaction

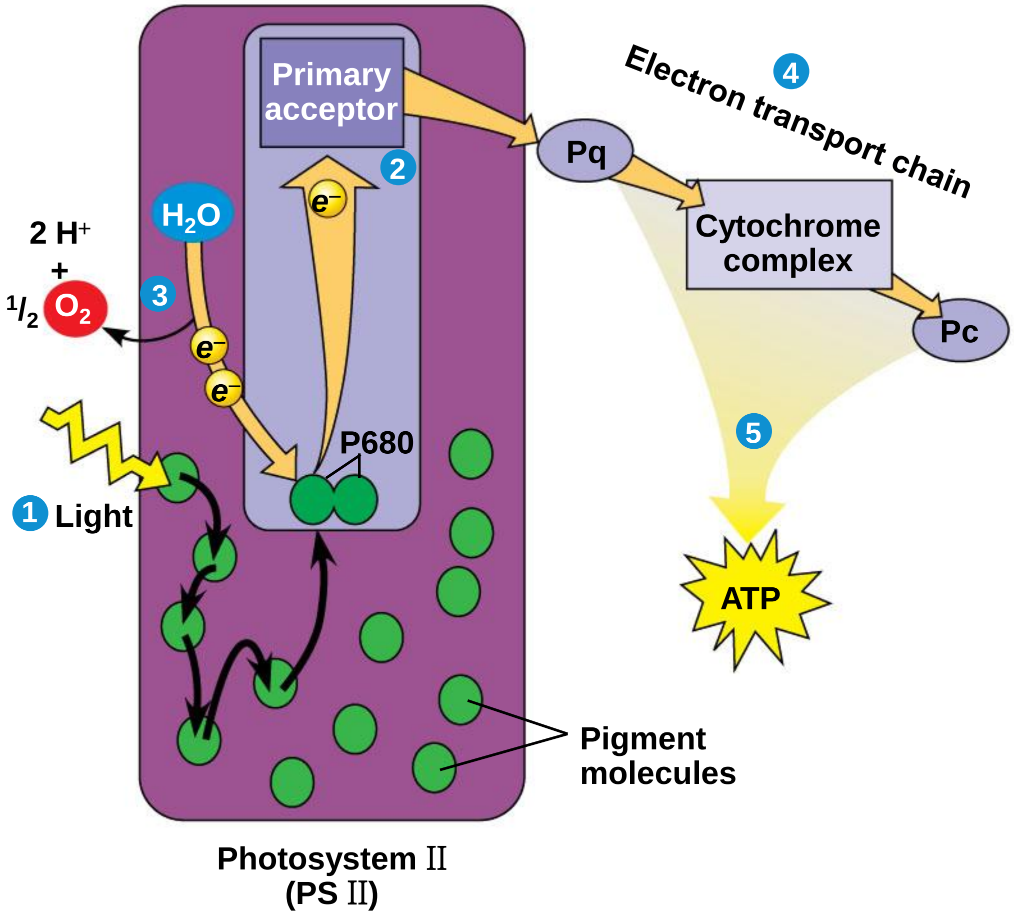
Figure 10.14-2



Photosystem II
(PS II)

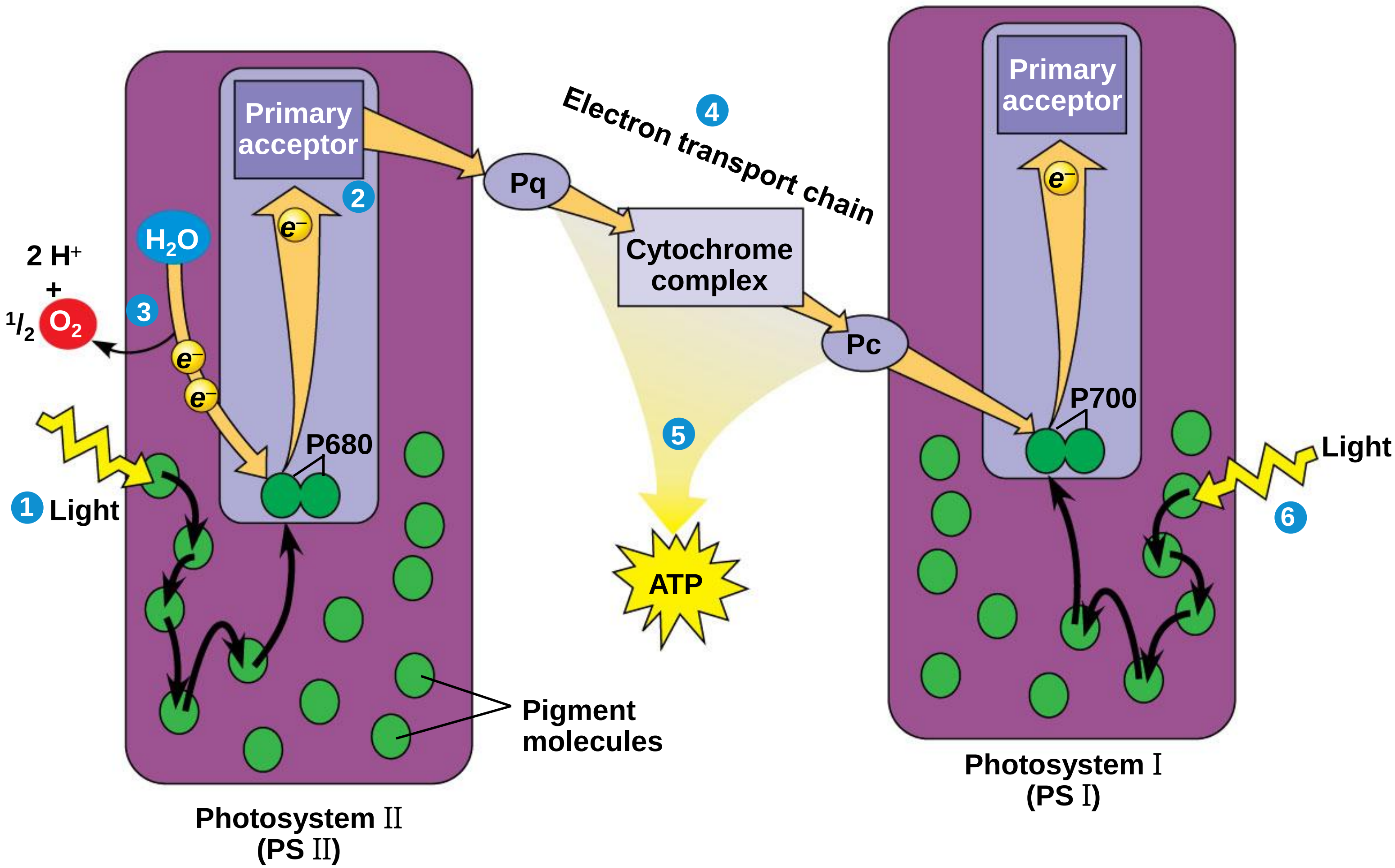
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of H^+ (protons) across the membrane drives ATP synthesis

Figure 10.14-3



- In PS I (like PS II), transferred light energy excites P700, which loses an electron to an electron acceptor
- $P700^+$ (P700 that is missing an electron) accepts an electron passed down from PS II via the electron transport chain

Figure 10.14-4



- Each electron "falls" down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
- The electrons are then transferred to $NADP^+$ and reduce it to NADPH
- The electrons of NADPH are available for the reactions of the Calvin cycle
- This process also removes an H^+ from the stroma

Figure 10.14-5

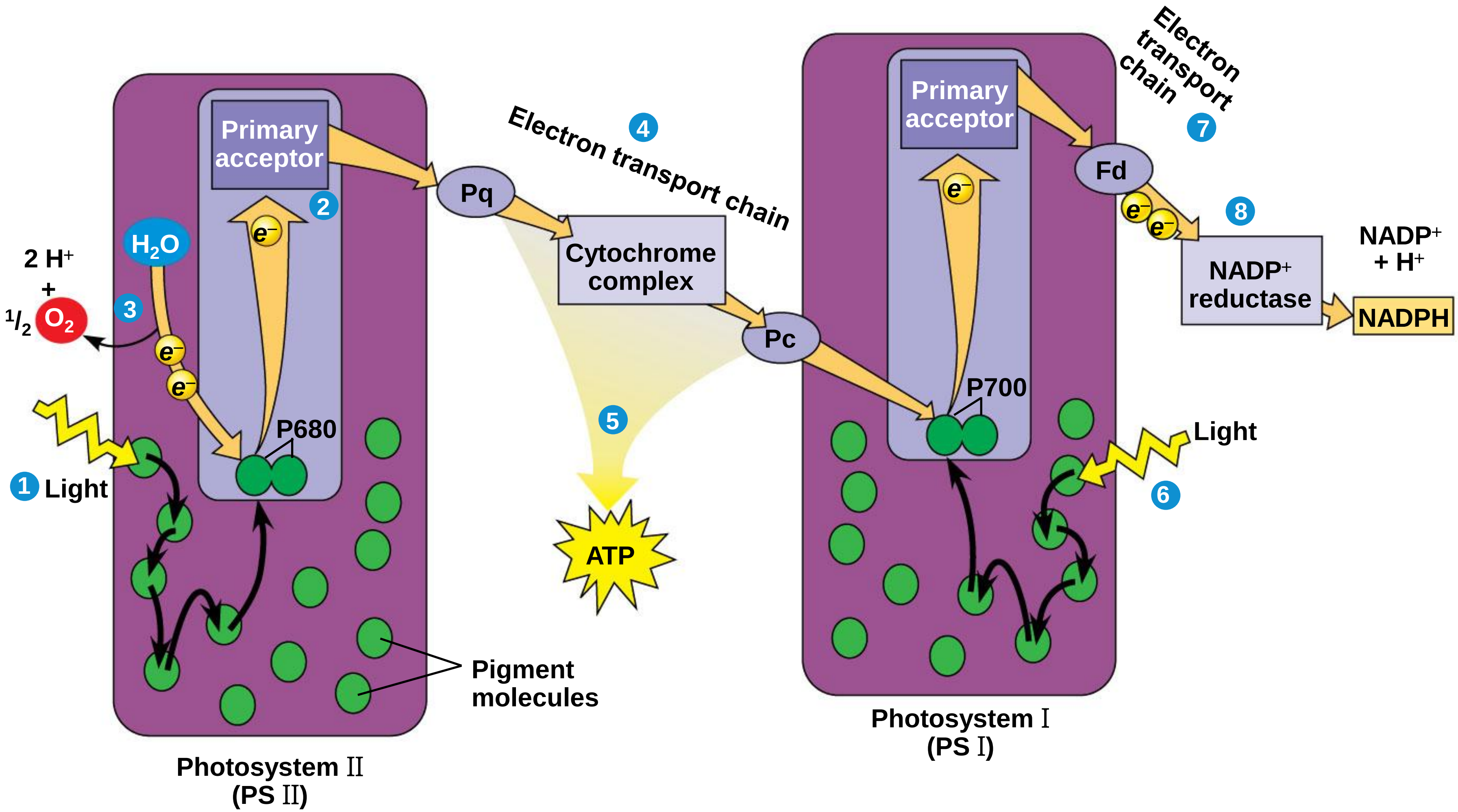
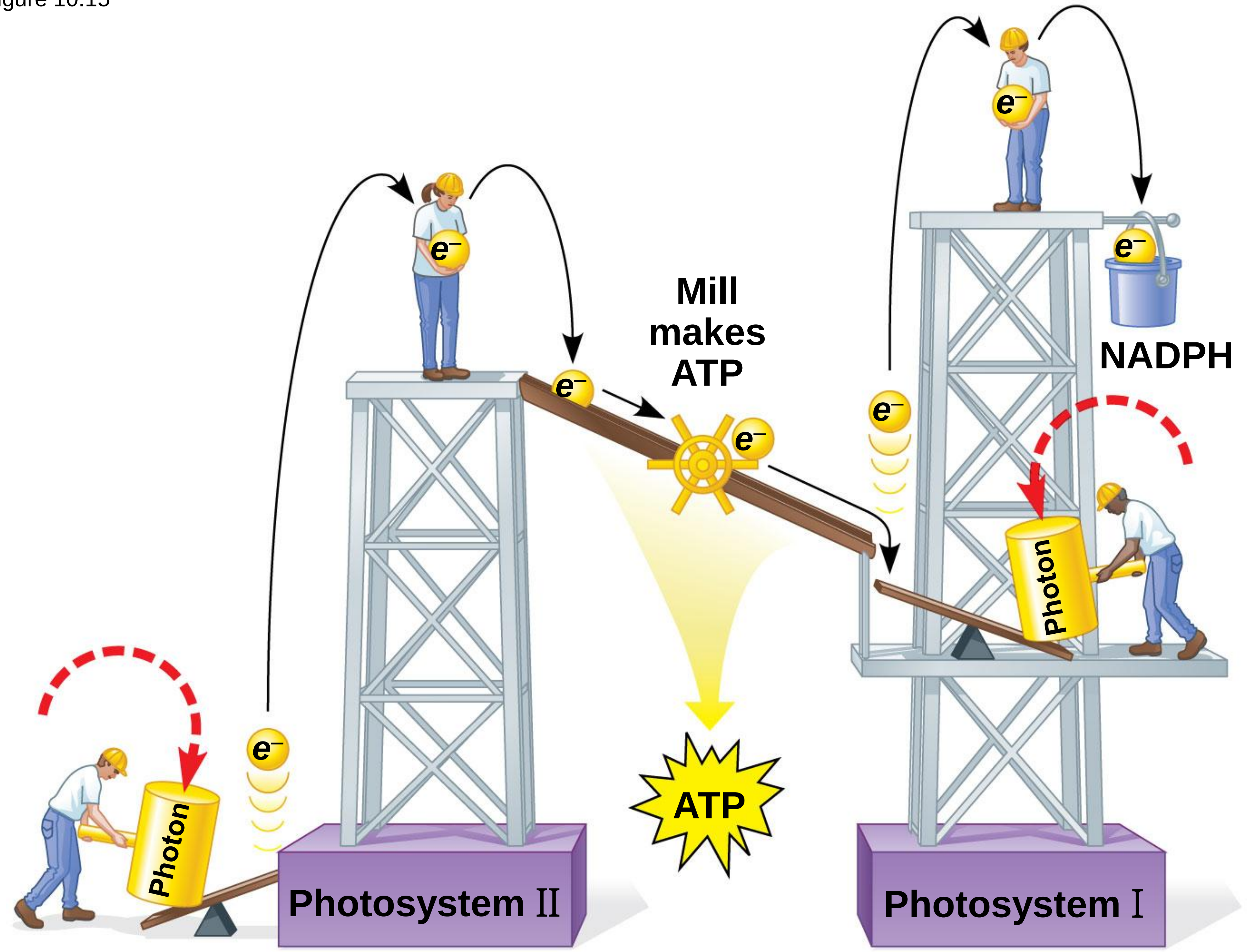


Figure 10.15

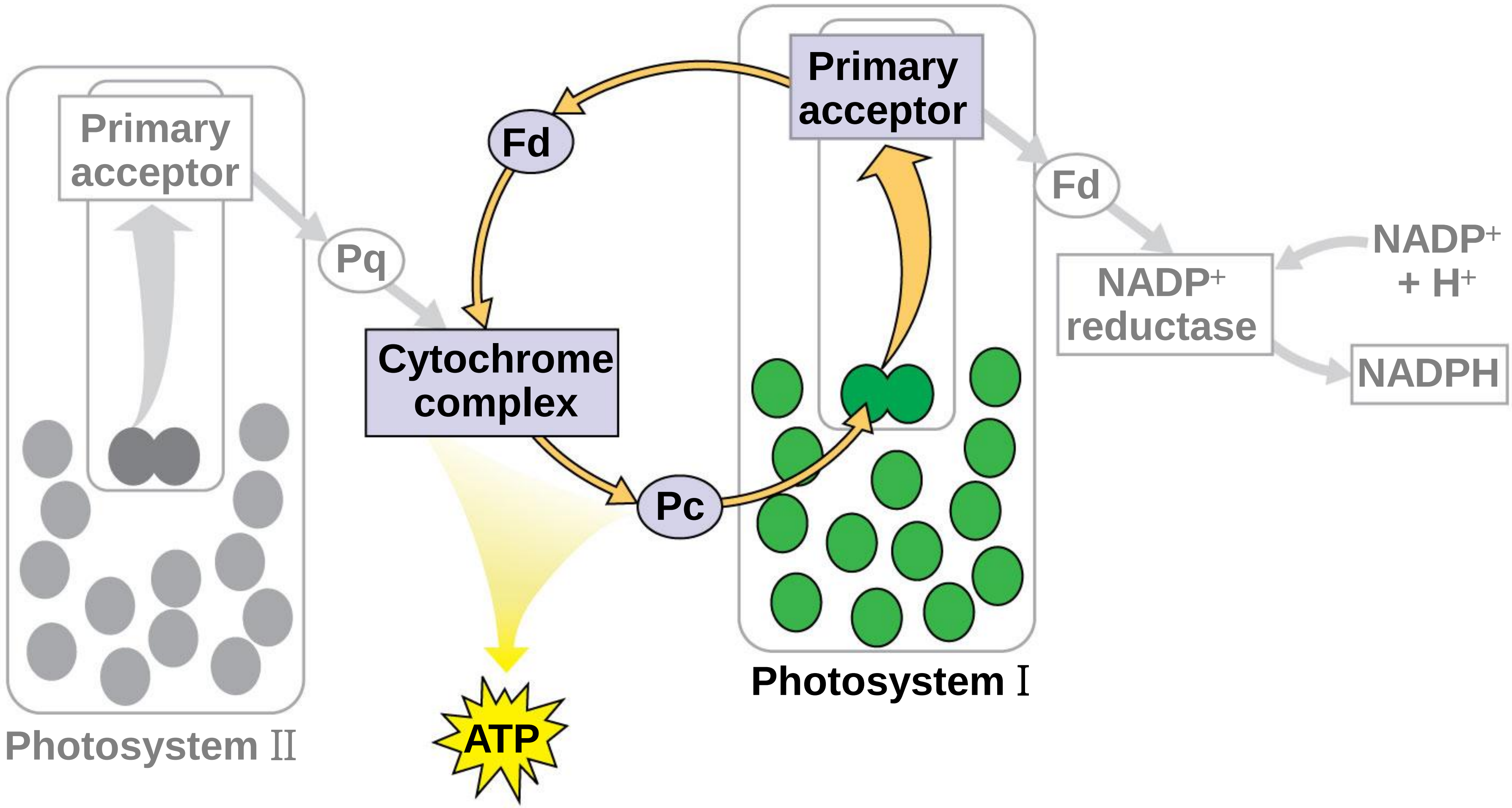


e⁻
Mill
makes
ATP
NADPH
Photon
Photon
ATP
Photosystem II
Photosystem I

Cyclic Electron Flow

- **Cyclic electron flow** uses only photosystem I and produces ATP, but not NADPH
- No oxygen is released
- Cyclic electron flow generates surplus ATP, satisfying the higher demand in the Calvin cycle

Figure 10.16



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

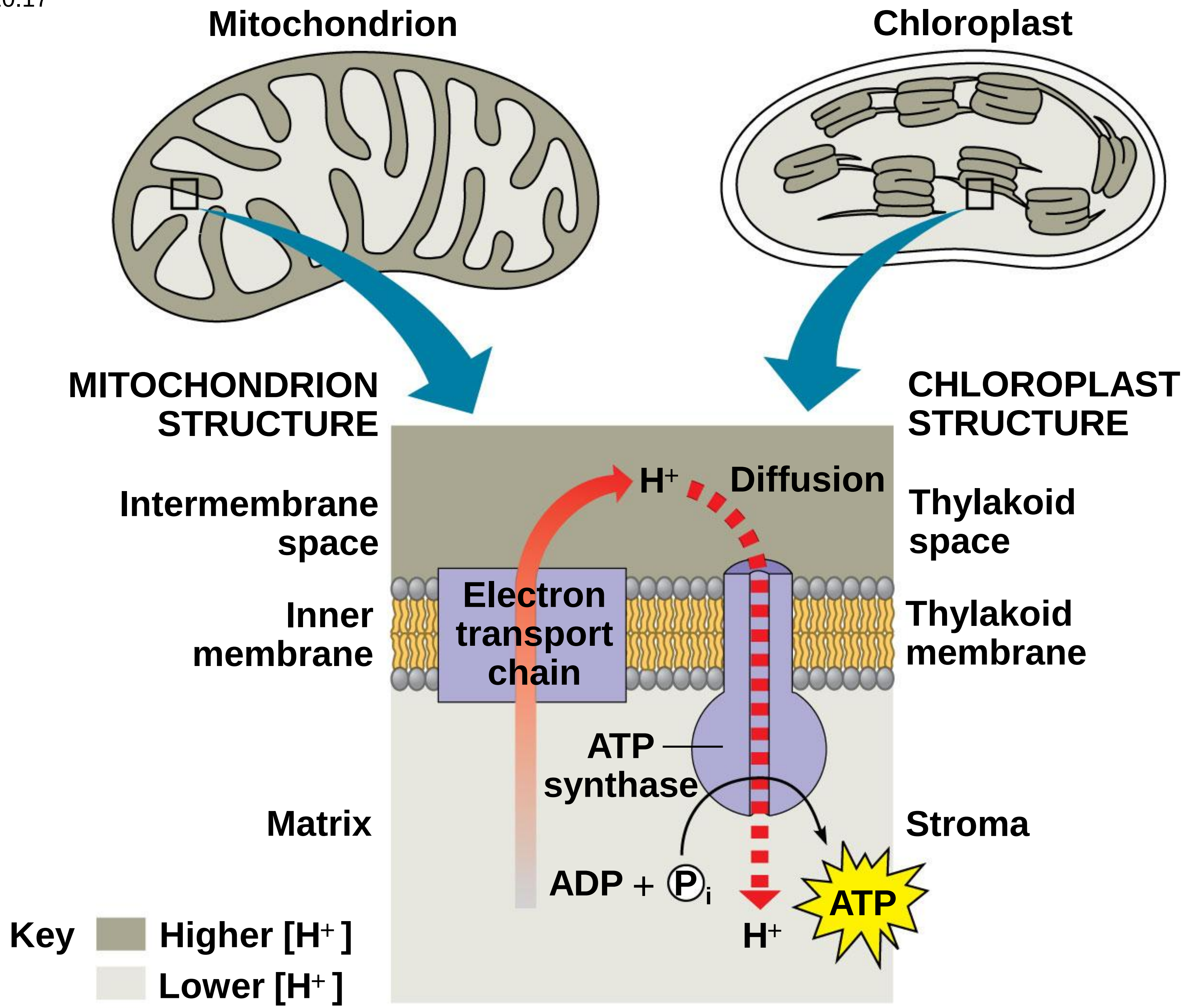
- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

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

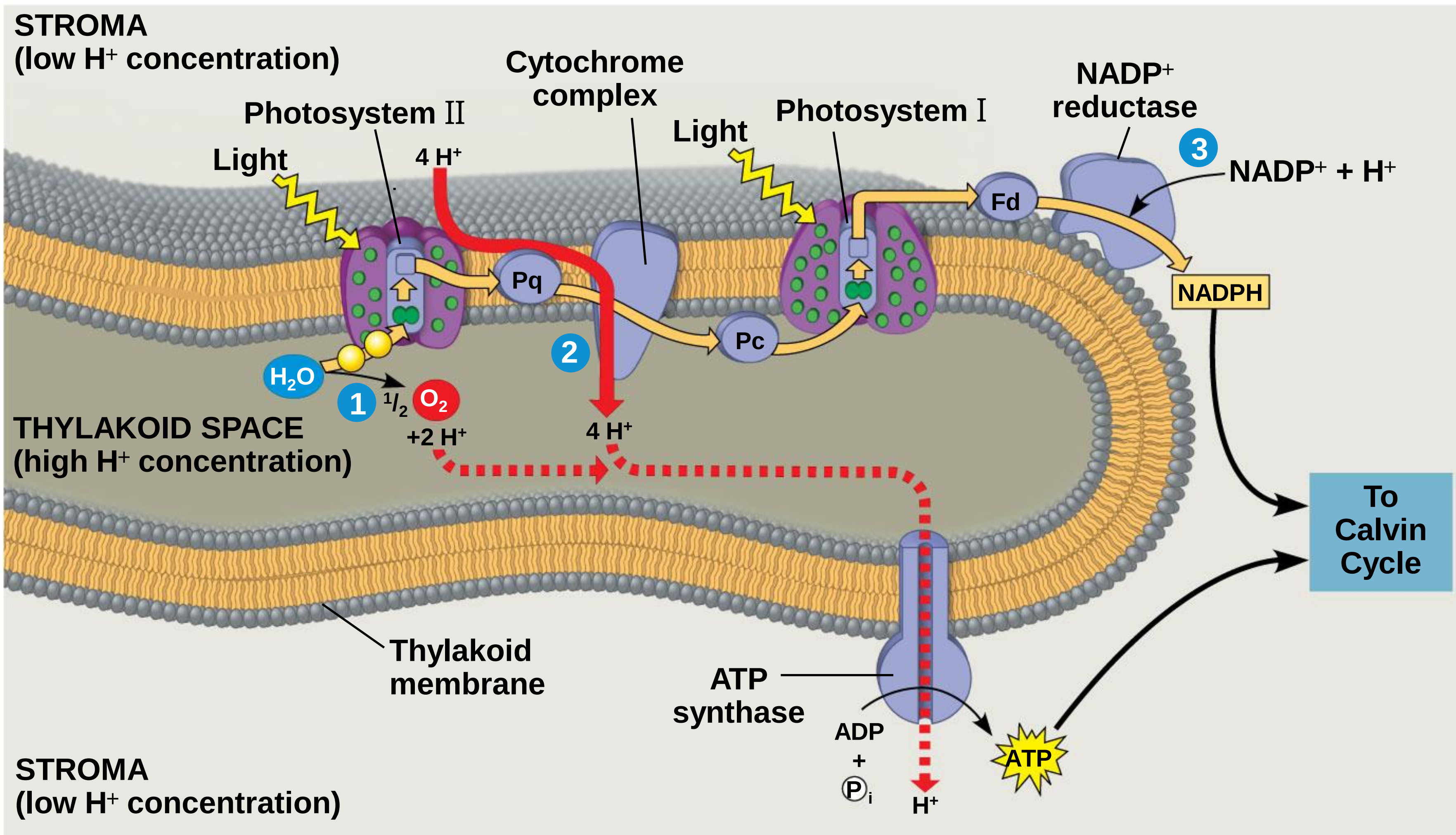
- In mitochondria, protons are pumped to the intermembrane space and drive ATP synthesis as they diffuse back into the mitochondrial matrix
- In chloroplasts, protons are pumped into the thylakoid space and drive ATP synthesis as they diffuse back into the stroma

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+]

- 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

Figure 10.18



STROMA
(low H+ concentration)
Photosystem II
Light
4 H+
Cytochrome complex
Light
Photosystem I
NADP+ reductase
3
NADP+ + H+
Fd
Pq
NADPH
Pc
2
H2O
1
1/2 O2
+2 H+
4 H+
THYLAKOID SPACE
(high H+ concentration)
To Calvin Cycle
Thylakoid membrane
ATP synthase
ADP
+
P i
ATP
H+
STROMA
(low H+ concentration)

Concept 10.3: The Calvin cycle uses the chemical energy of ATP and NADPH to reduce 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)**

Figure 10.19-1

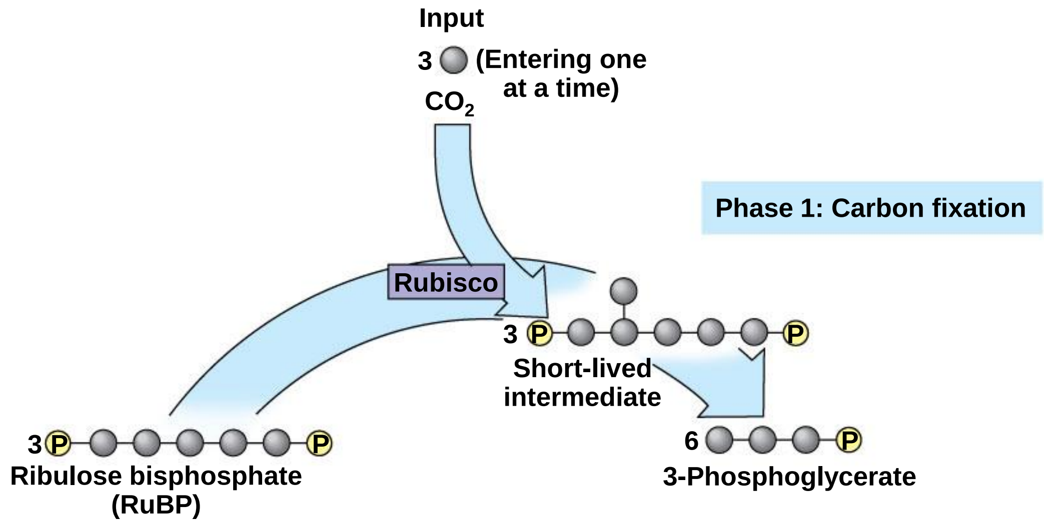


Figure 10.19-2

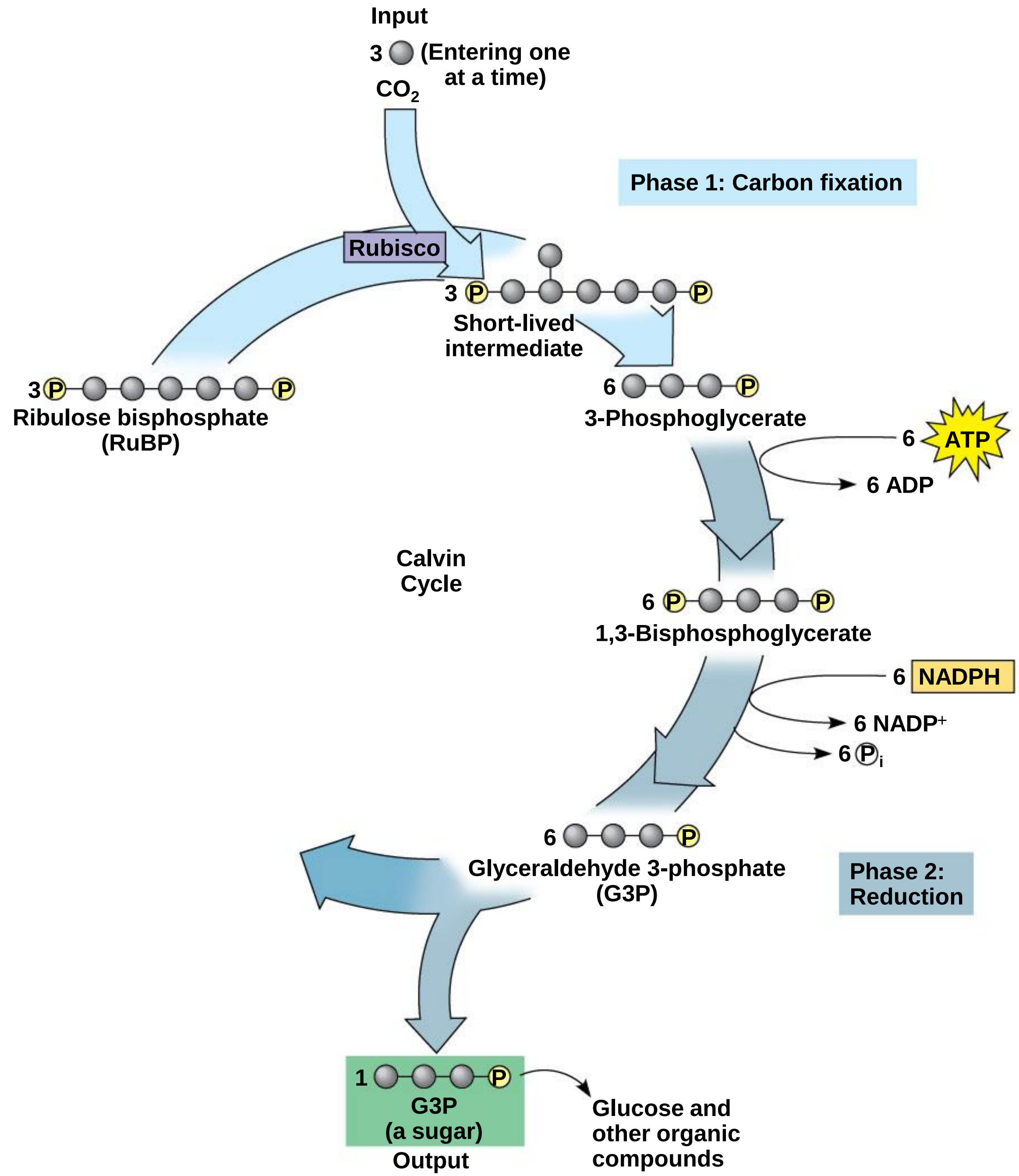


Figure 10.19-3