# Chapter 10

# Photosynthesis

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PowerPoint® Lecture Presentations for

**Biology**

***Eighth Edition***

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# Overview: The Process That Feeds the Biosphere

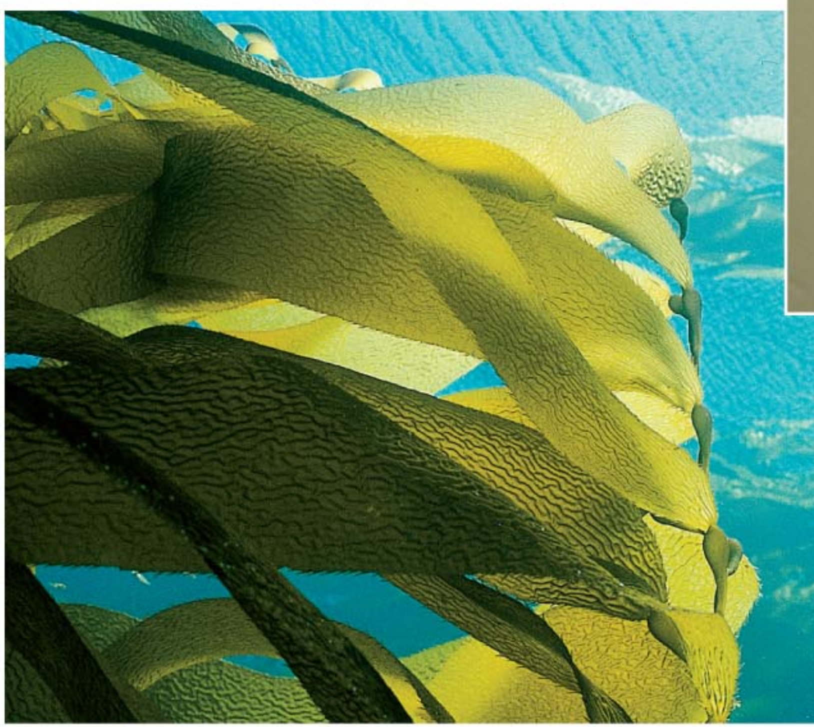
- **Photosynthesis** is the process that converts solar energy into chemical energy
- Directly or indirectly, photosynthesis nourishes almost the entire living world

- **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 $CO_2$

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

Fig. 10-2

(a) Plants



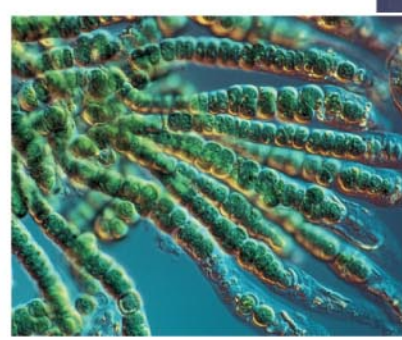
(b) Multicellular alga

(c) Unicellular protist

10 µm

(e) Purple sulfur bacteria

1.5 µm

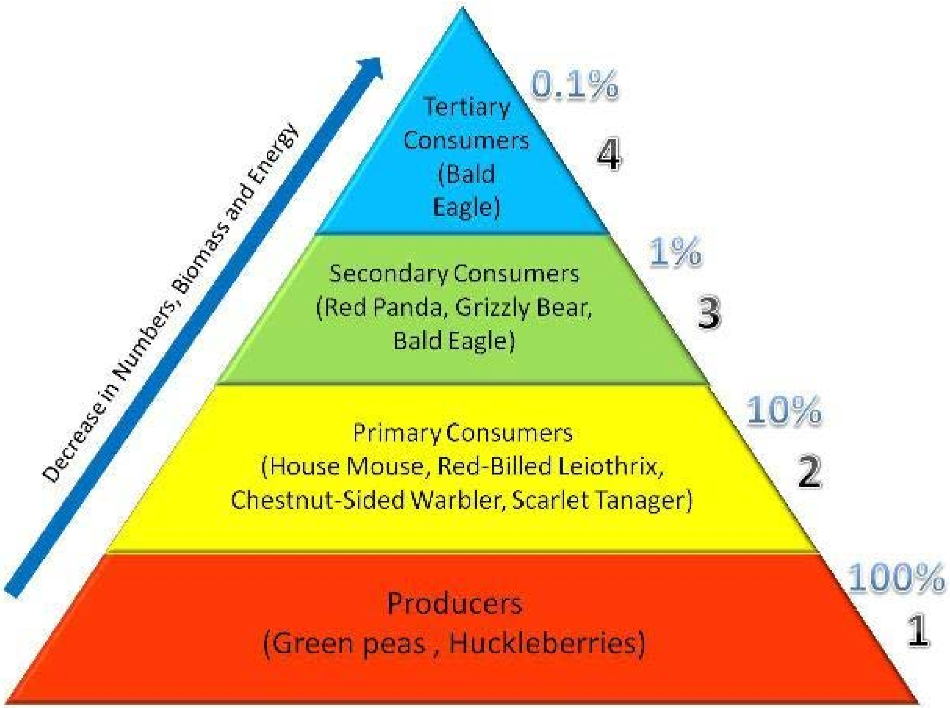


(d) Cyanobacteria

40 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 $O_2$

# Trophic Levels – Food Chains




## Major Trophic Levels

| Trophic Level | Source of Energy | Examples |
|---|---|---|
| Producers | Solar energy | Green plants, photosynthetic protists and bacteria |
| Herbivores | Producers | Grasshoppers, water fleas, antelope, termites |
| Primary Carnivores | Herbivores | Wolves, spiders, some snakes, warblers |
| Secondary Carnivores | Primary carnivores | Killer whales, tuna, falcons |
| Omnivores | Several trophic levels | Humans, rats, opossums, bears, racoons, crabs |
| Detritivores and Decomposers | Wastes and dead bodies of other organisms | Fungi, many bacteria, earthworms, vultures |

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

- Chloroplasts are structurally similar to and likely evolved from photosynthetic bacteria (endosymbiotic theory)
- 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
- 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 (stomates)**

- 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 analogous to the mitochondrial matrix

Fig. 10-3

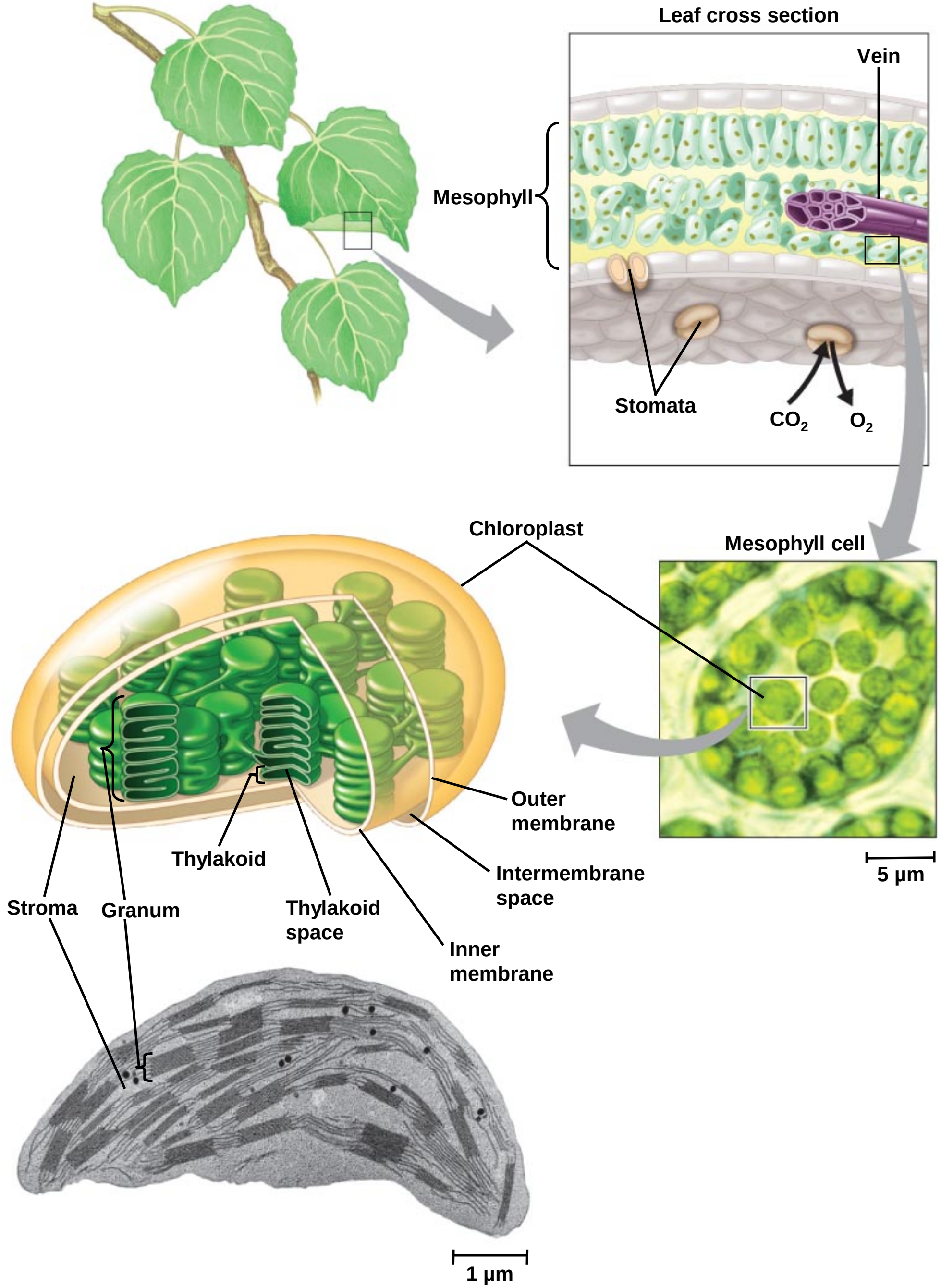

Leaf cross section
Vein
Mesophyll
Stomata
$CO_2$
$O_2$
Chloroplast
Mesophyll cell
5 µm
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Thylakoid space
Stroma
Granum
1 µm

Fig. 10-3a

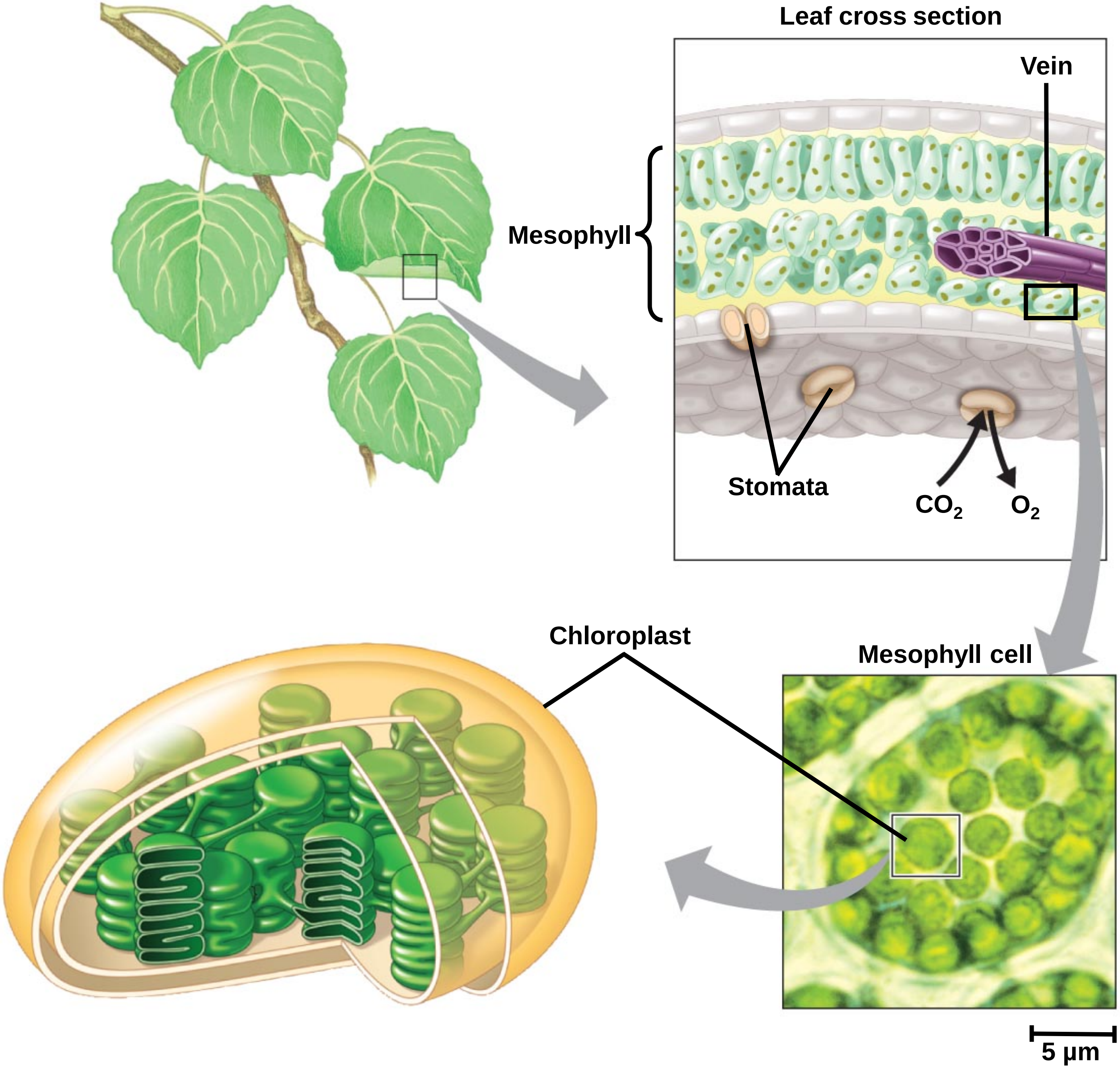
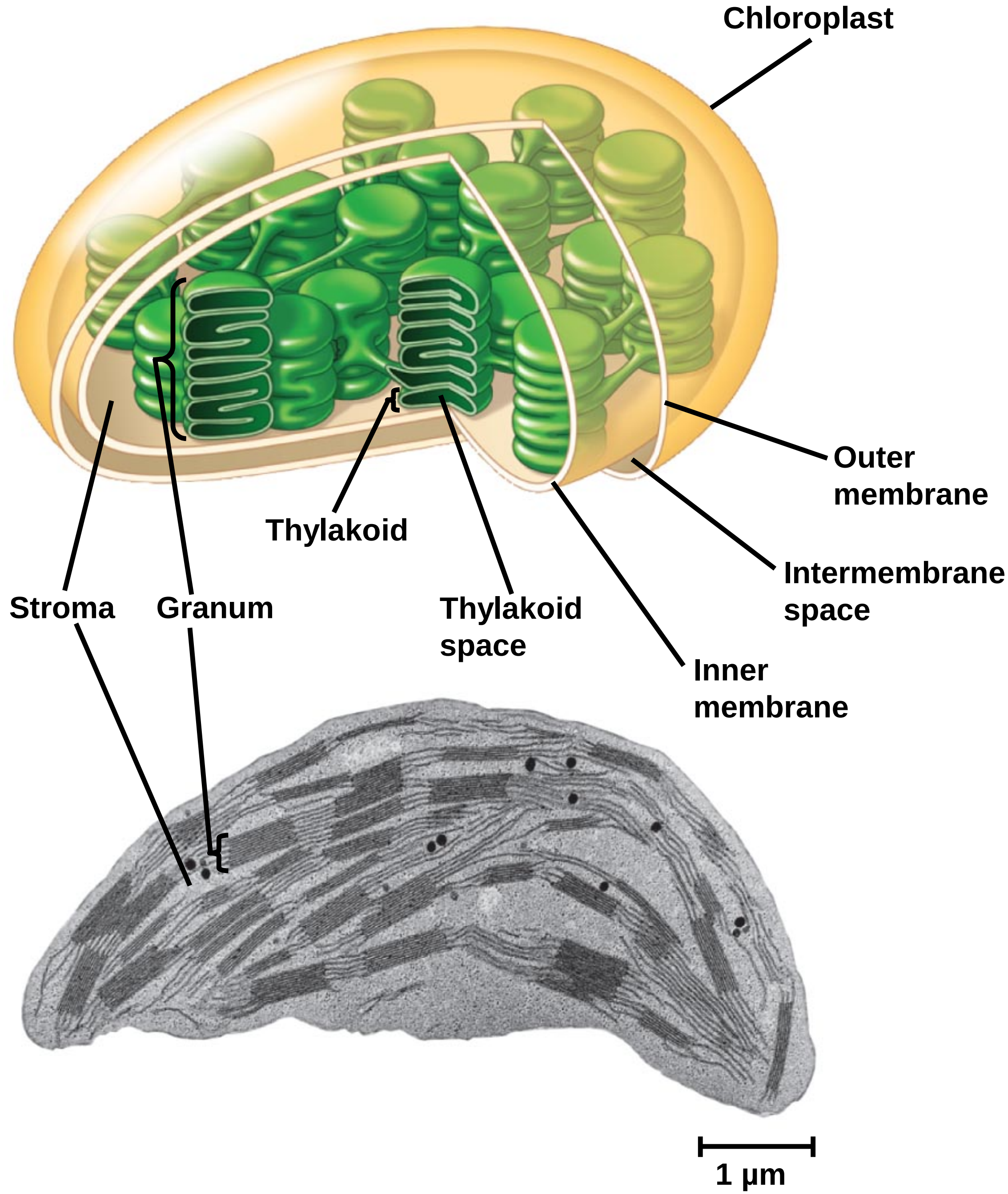

Leaf cross section
Vein
Mesophyll
Stomata
$CO_2$
$O_2$
Chloroplast
Mesophyll cell
5 µm

Fig. 10-3b


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

# Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

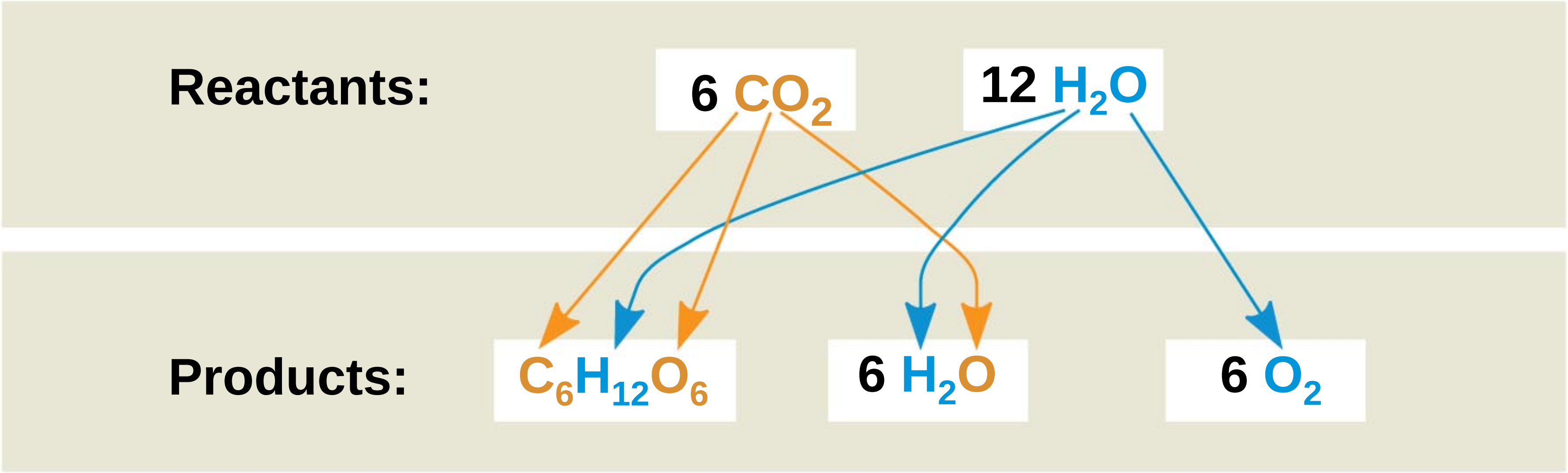
$$6\ CO_2 + 12\ H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

- The simplified equation:
- $6\ CO_2 + 6\ H_2O + \text{Light } \underline{\text{energy}} \rightarrow C_6H_{12}O_6 + 6\ O_2$
- Look familiar?

# *The Splitting of Water*

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

Fig. 10-4



# *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 (What is this carrying? To where? – not ETC!)
  - 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. 10-5-1

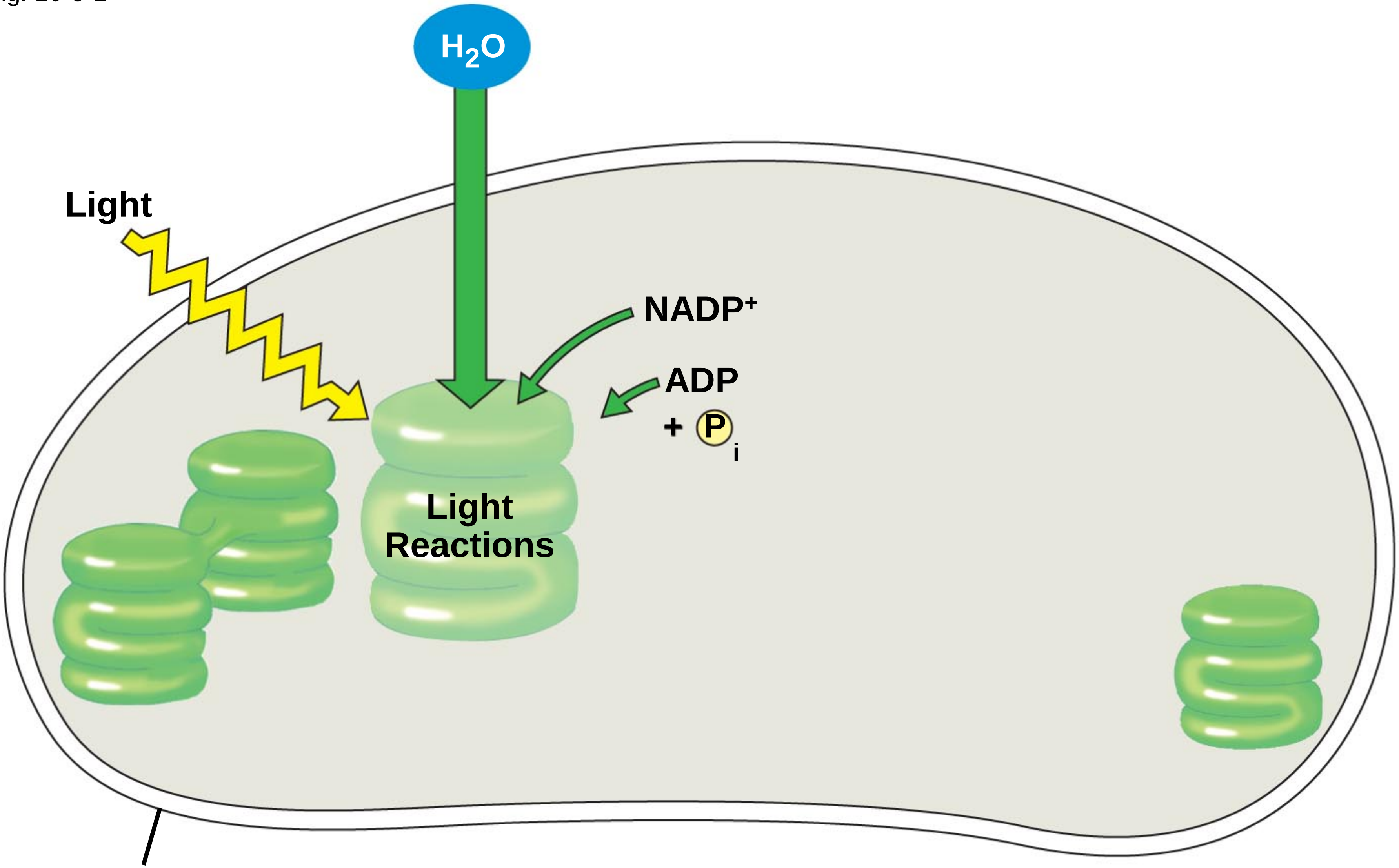
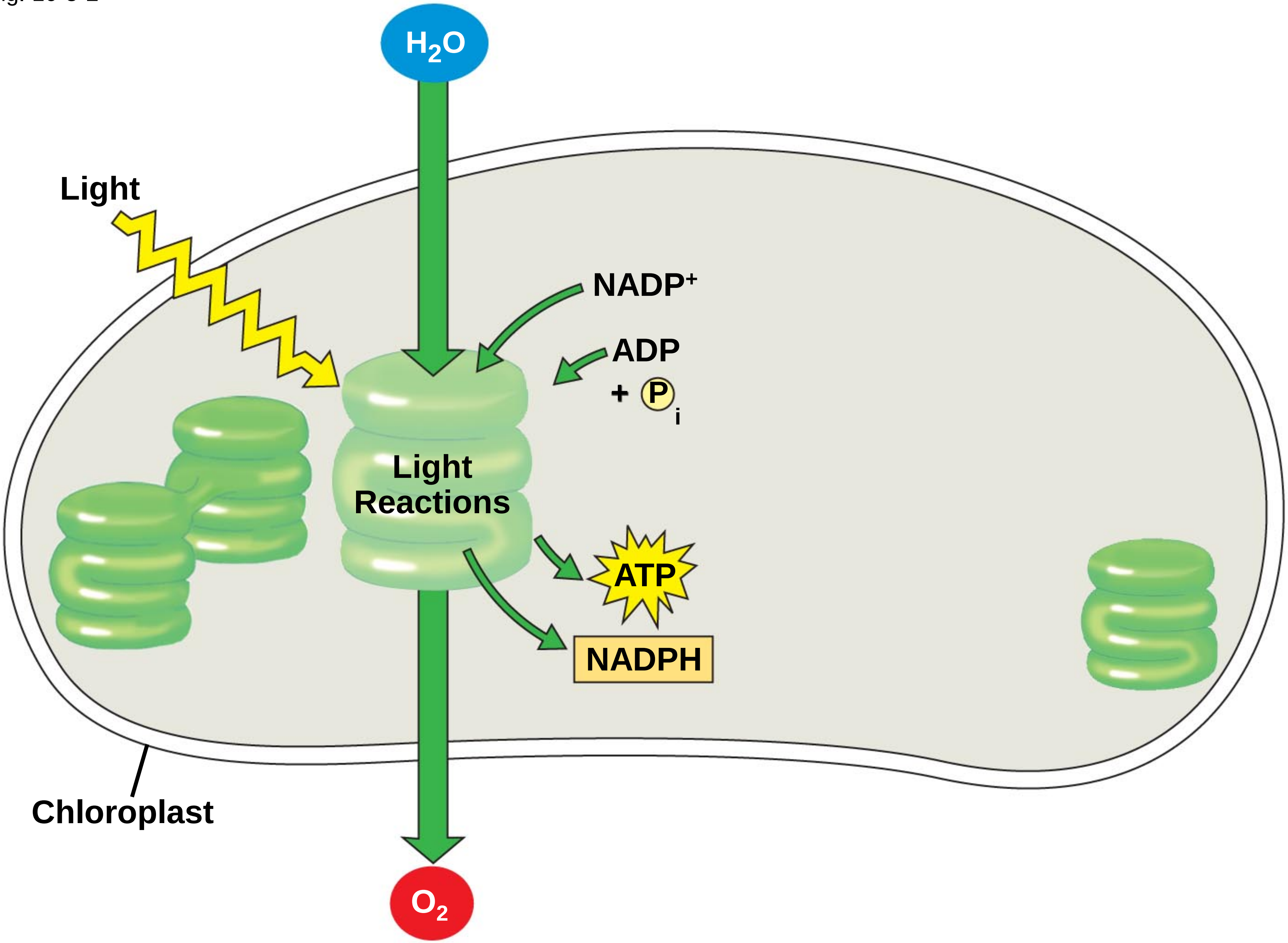
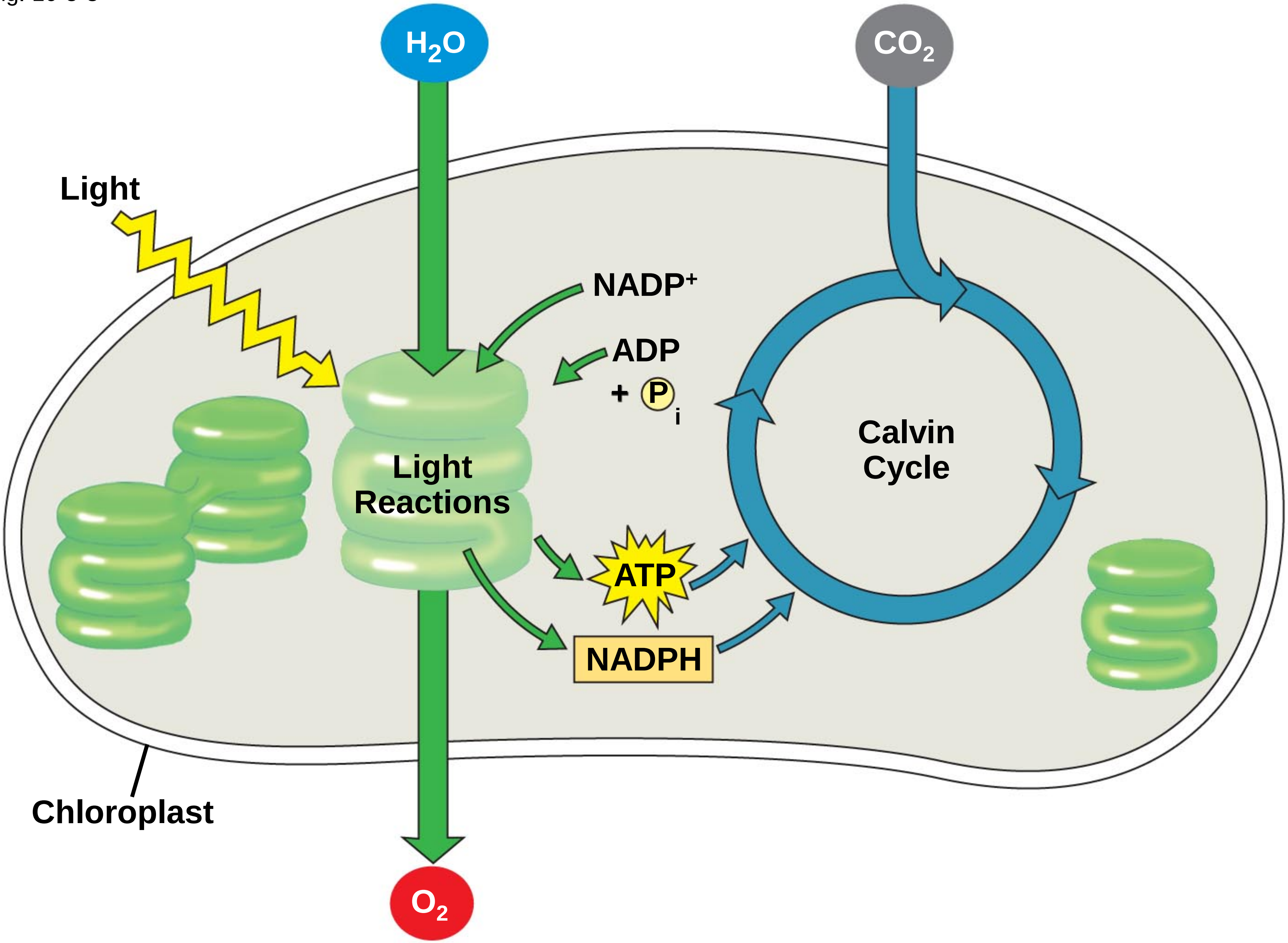


Fig. 10-5-2



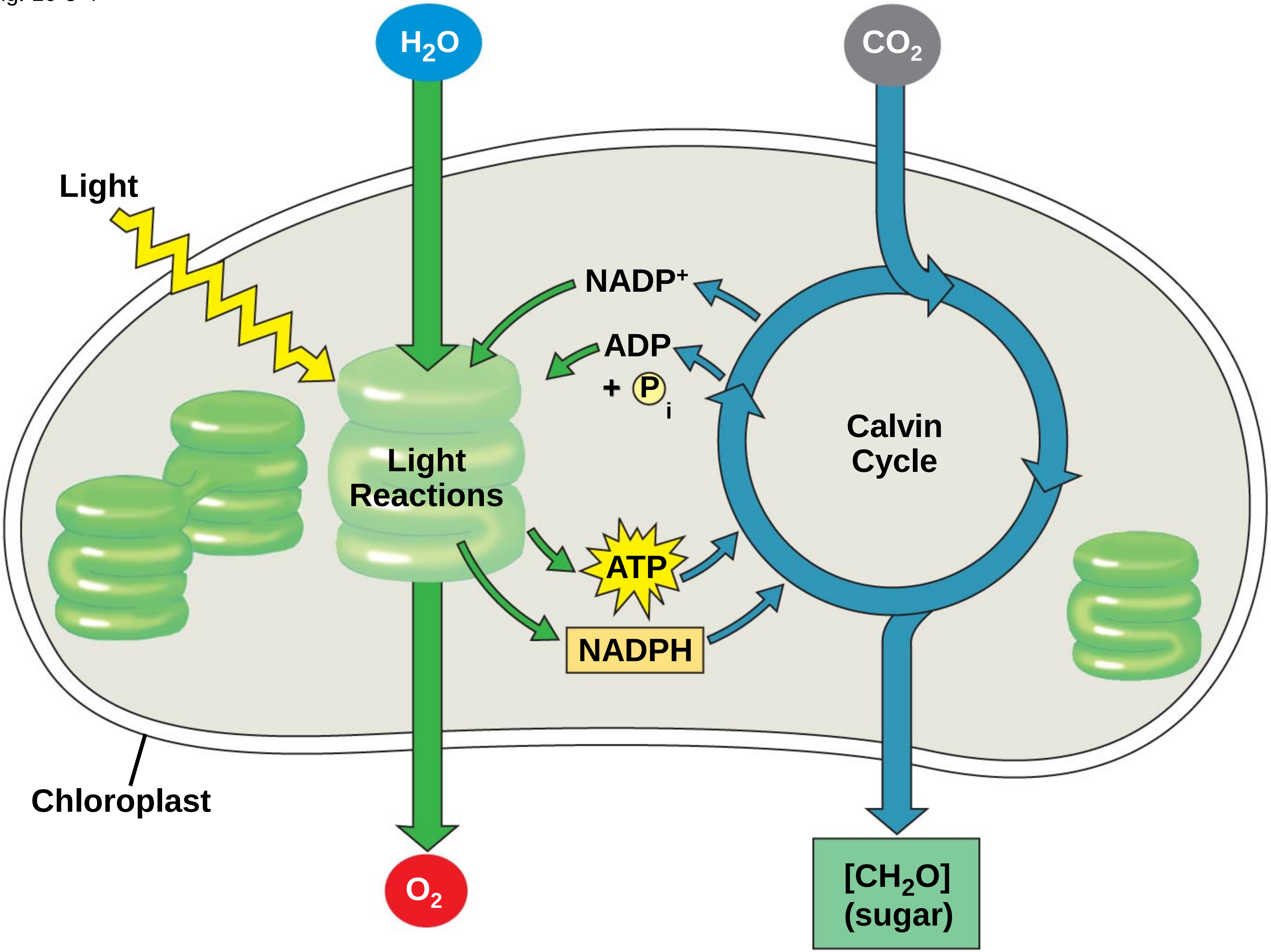
$H_2O$
Light
$NADP^+$
ADP
+ $P_i$
Light Reactions
ATP
NADPH
Chloroplast
$O_2$

Fig. 10-5-3



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

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

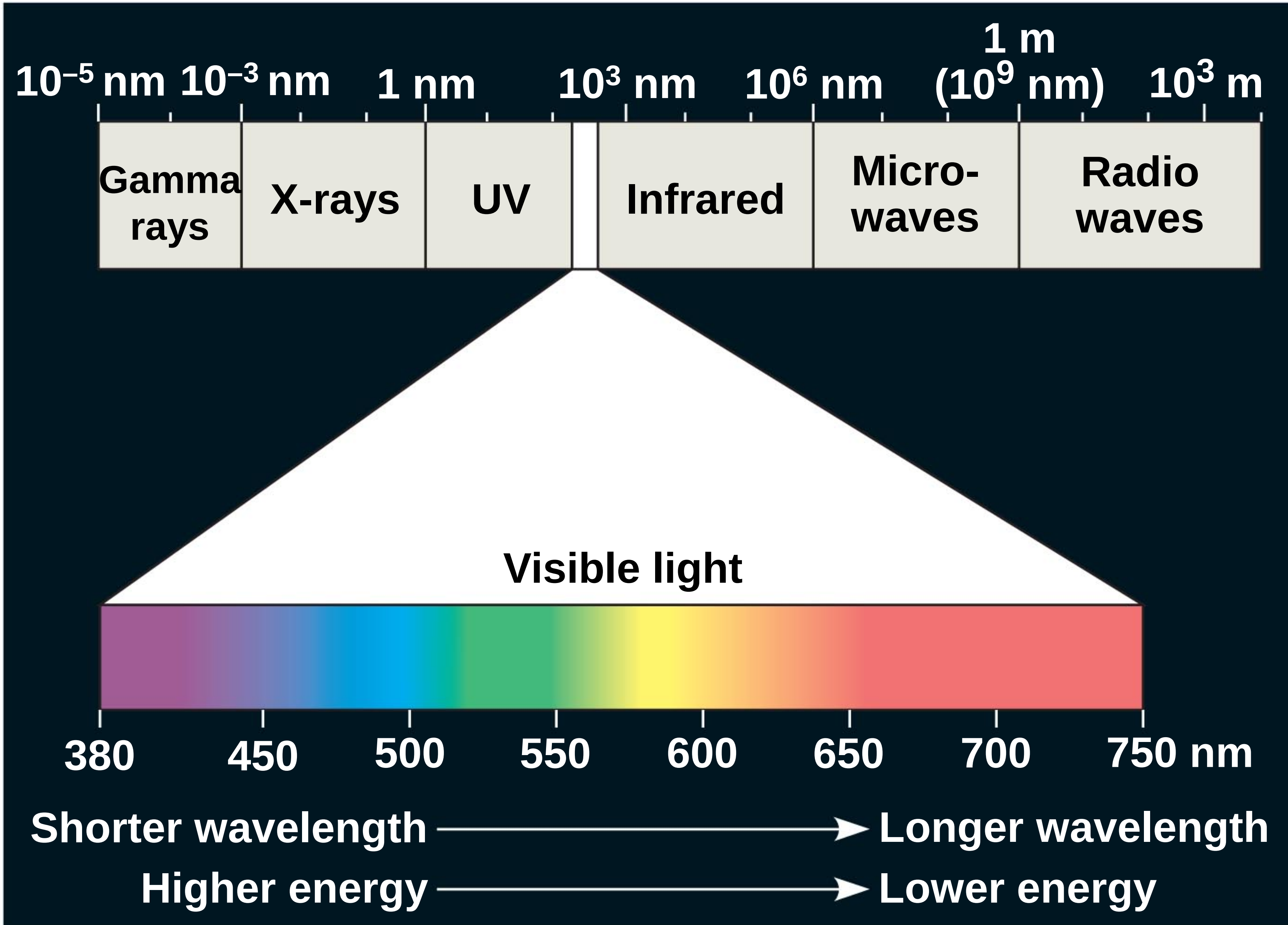
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

# 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 (peak to peak)
- 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 (ROY G BIV, really VIB G YOR!)
- Light also behaves as though it consists of discrete particles, called **photons**

Fig. 10-6

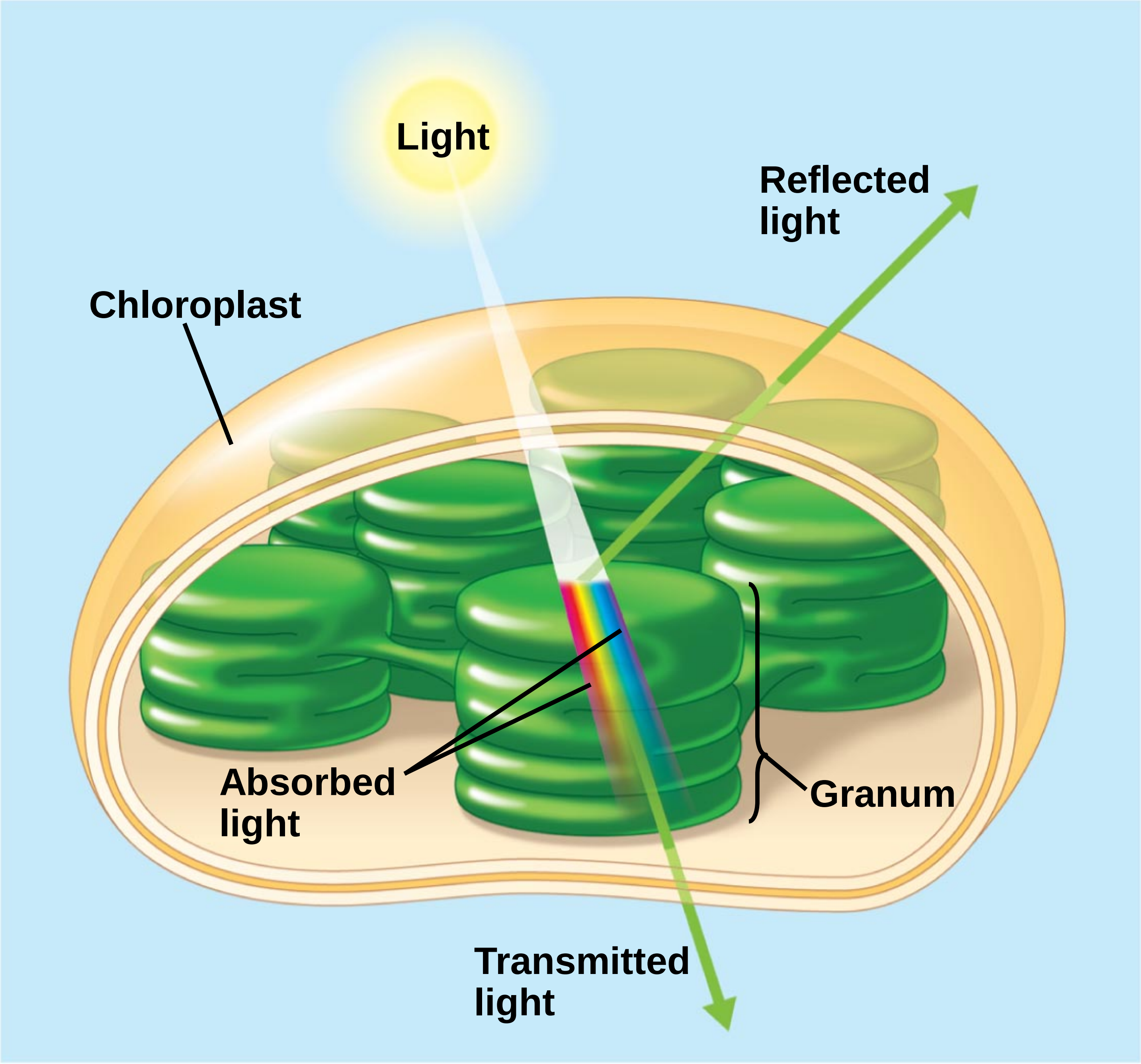


10–5 nm
10–3 nm
1 nm
103 nm
106 nm
1 m
(109 nm)
103 m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

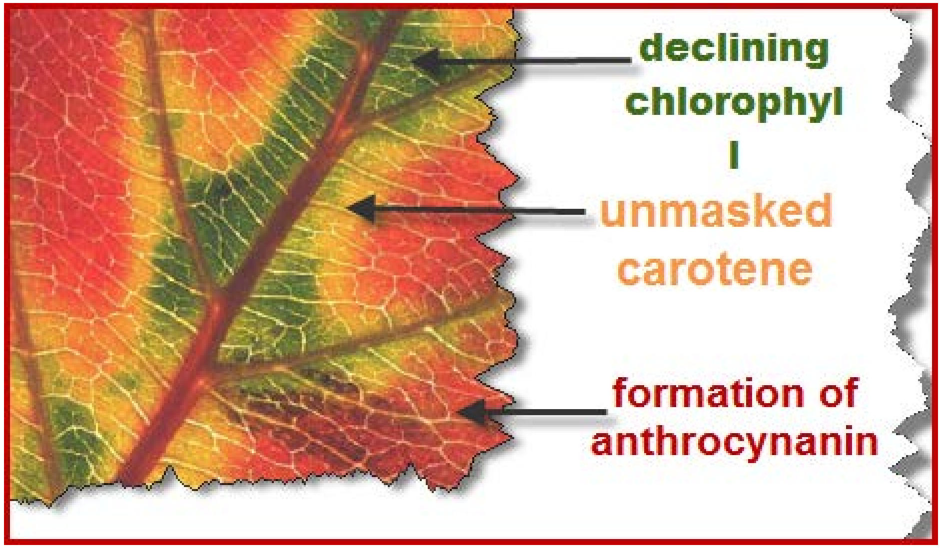
# Photosynthetic Pigments: The Light Receptors

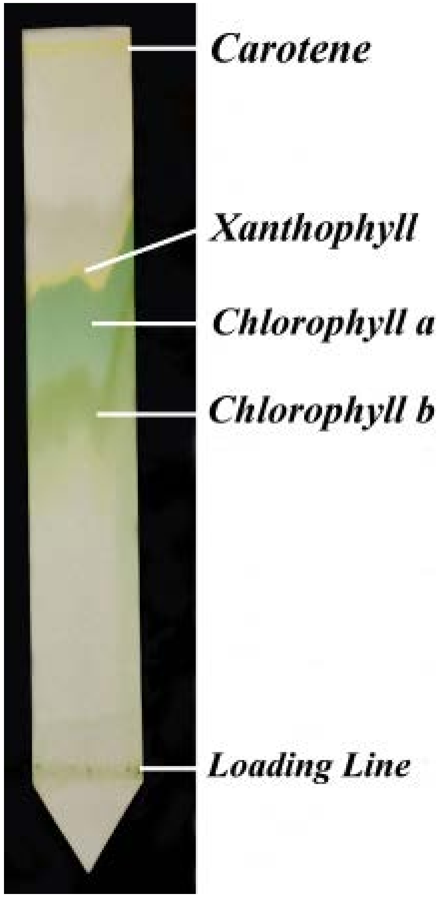
- Pigments are substances that absorb visible light
- Different pigments absorb different wavelengths
- Wavelengths that are not absorbed are reflected or transmitted (these are the colors that we see)
- Leaves appear green because chlorophyll reflects and transmits green light

Fig. 10-7


Light
Reflected light
Chloroplast
Absorbed light
Granum
Transmitted light

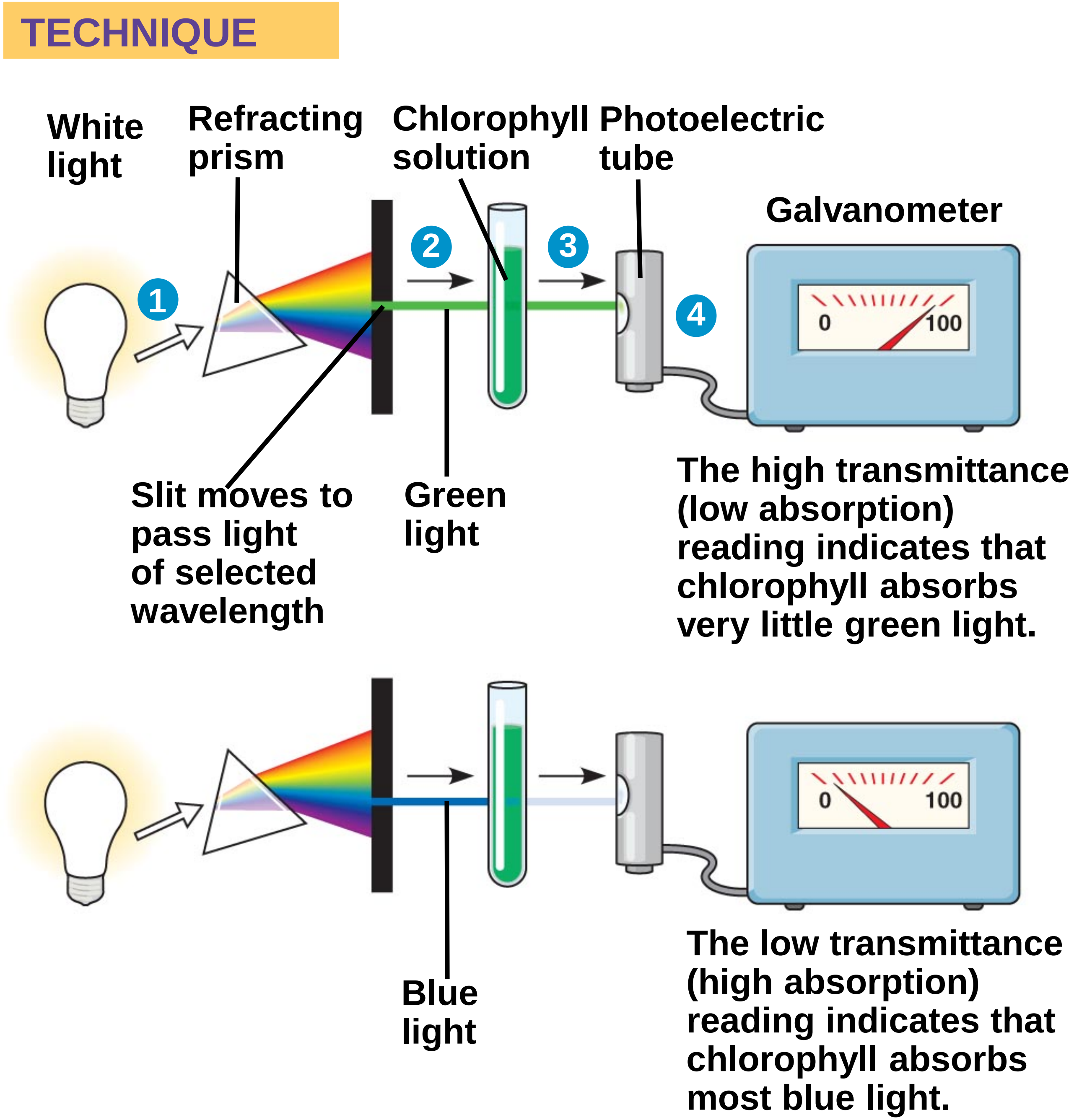
# Leaf Pigments Separated by Chromotography



- 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

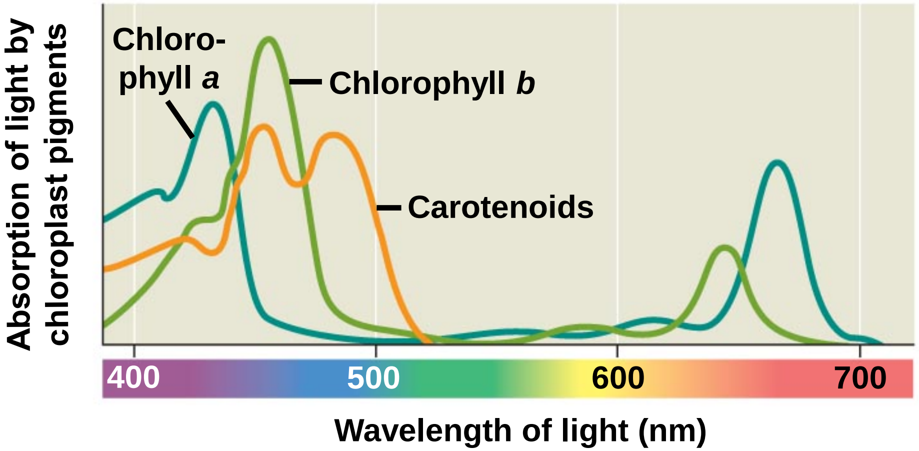
Fig. 10-8


TECHNIQUE
White light
Refracting prism
Chlorophyll solution
Photoelectric tube
Galvanometer
1
2
3
4
0
100
Slit moves to pass light of selected wavelength
Green light
The high transmittance (low absorption) reading indicates that chlorophyll absorbs very little green light.
0
100
Blue light
The low transmittance (high absorption) reading indicates that chlorophyll absorbs most blue light.

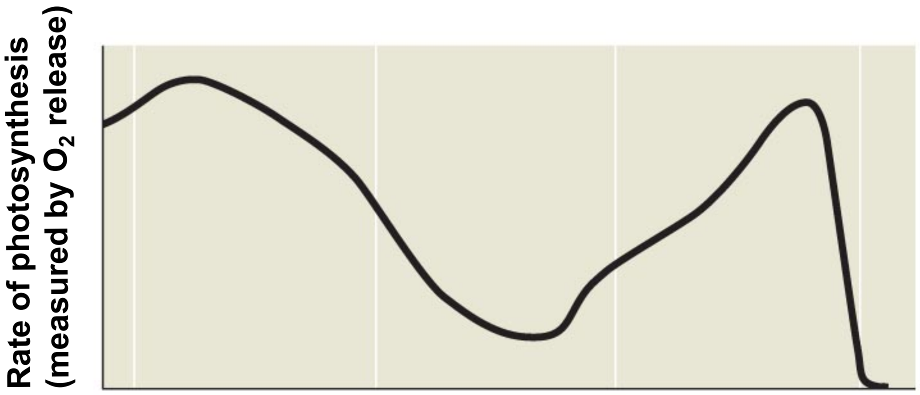
- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of **chlorophyll *a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of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

Fig. 10-9

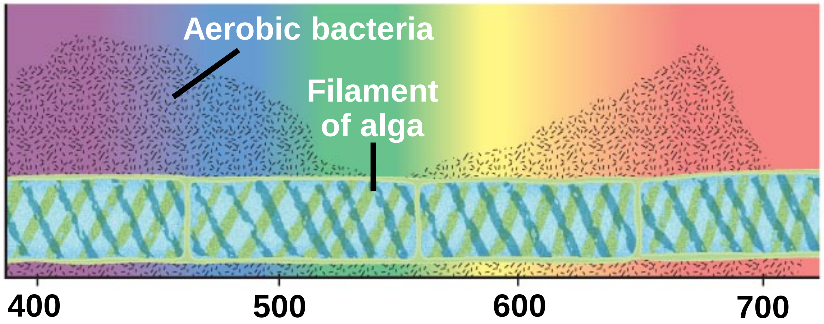
**RESULTS**




**(a) Absorption spectra**



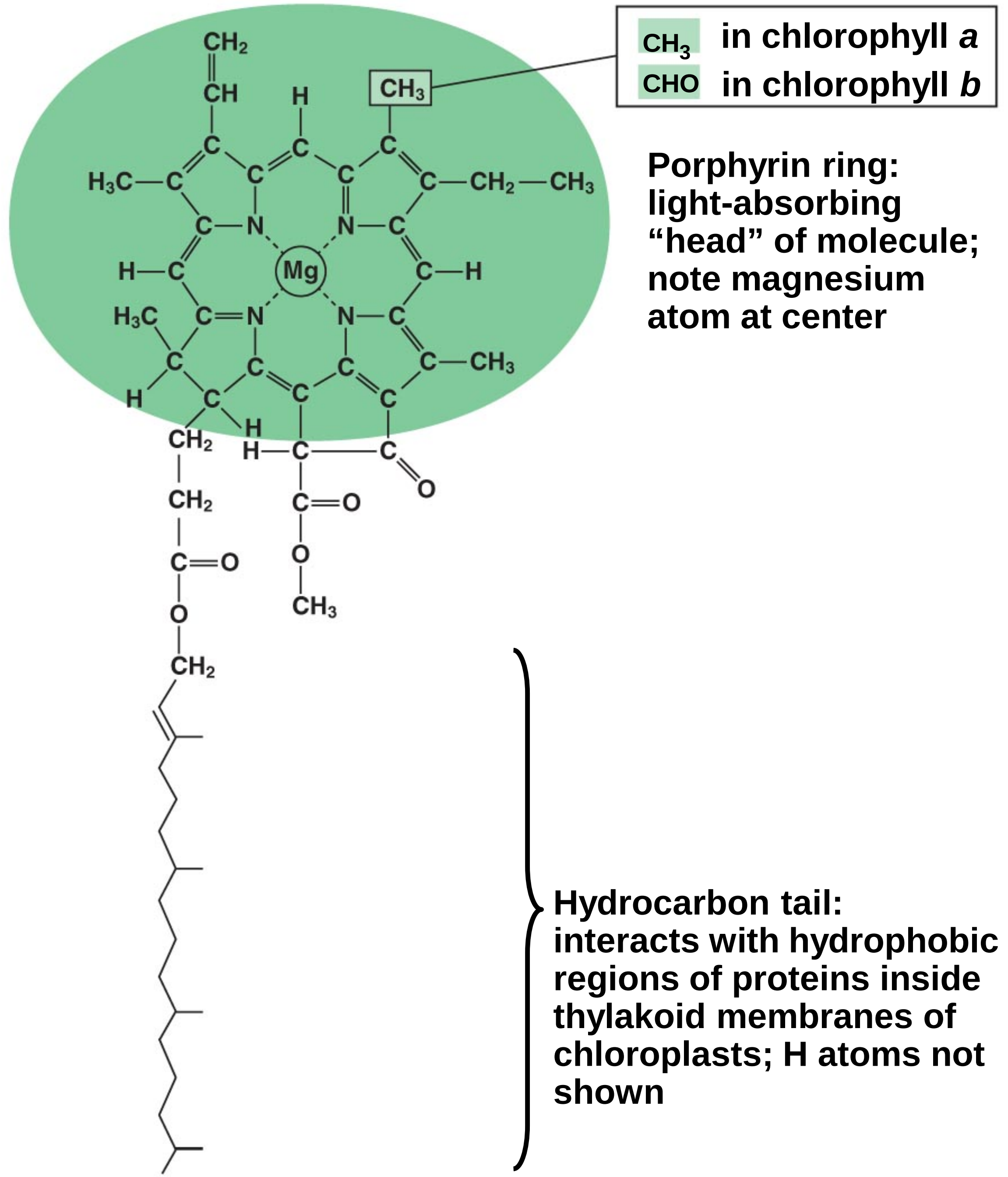

**(b) Action spectrum**




**(c) Engelmann's experiment**

- 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

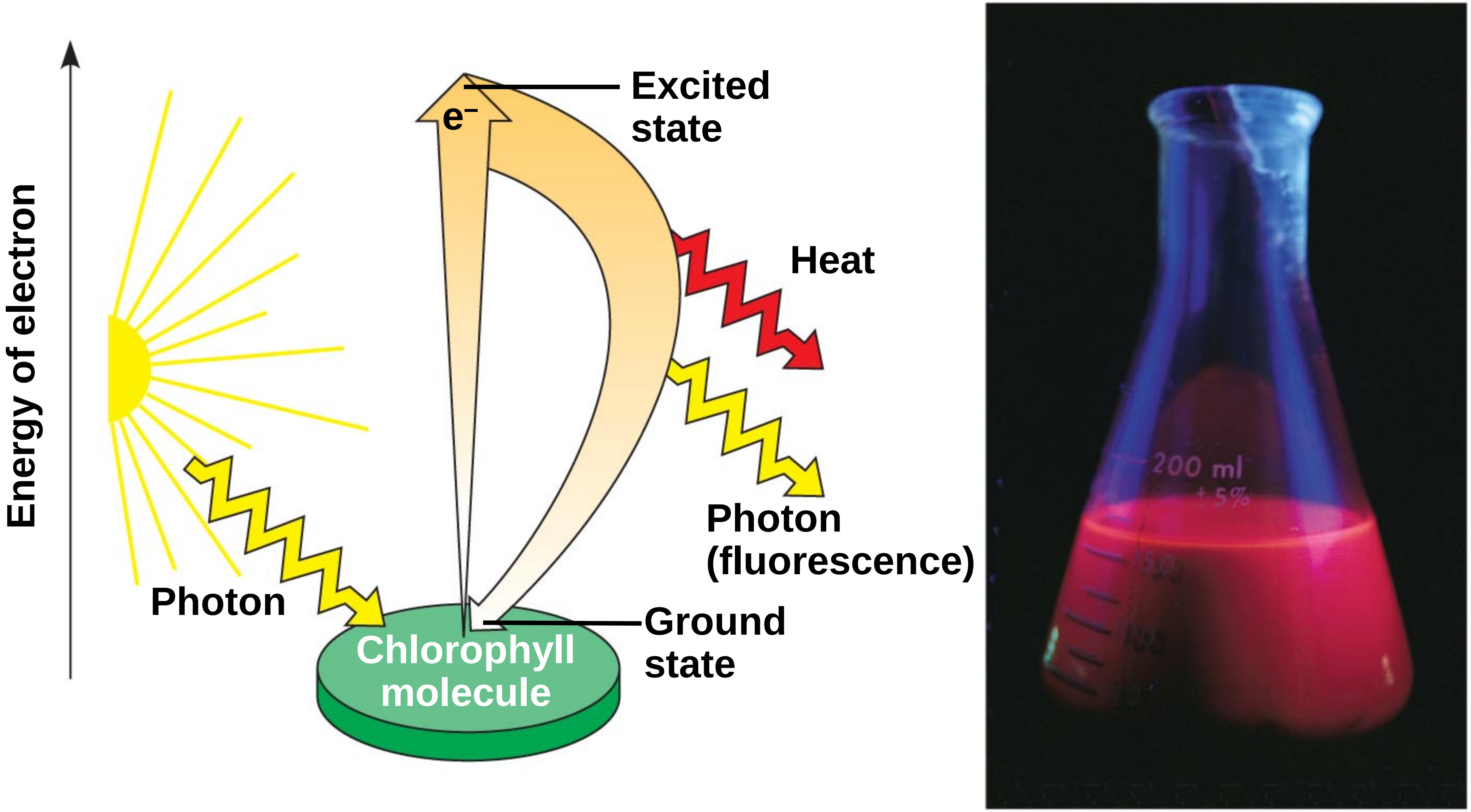
Fig. 10-10


$CH_3$ 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

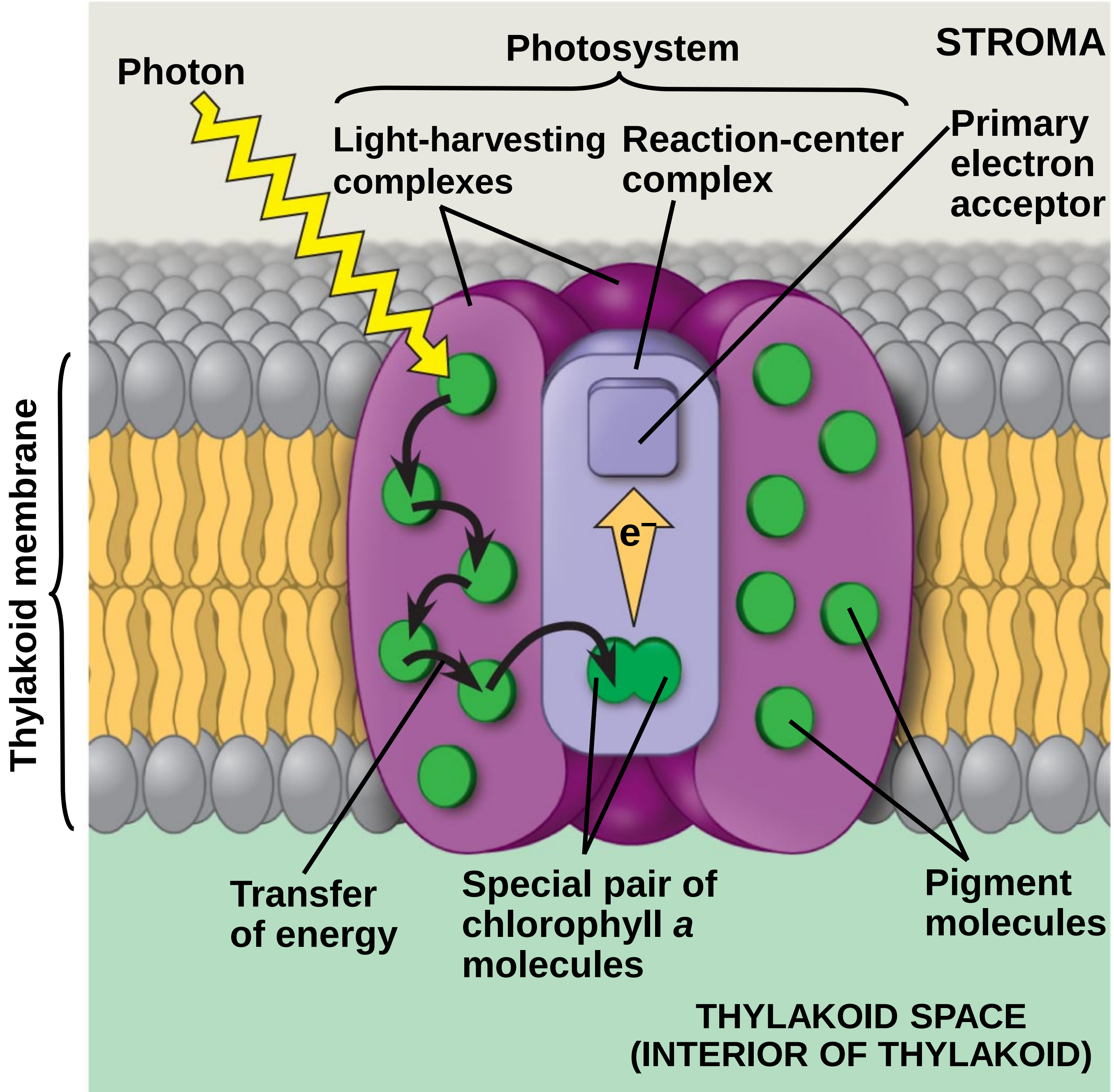
(b) Fluorescence

# 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

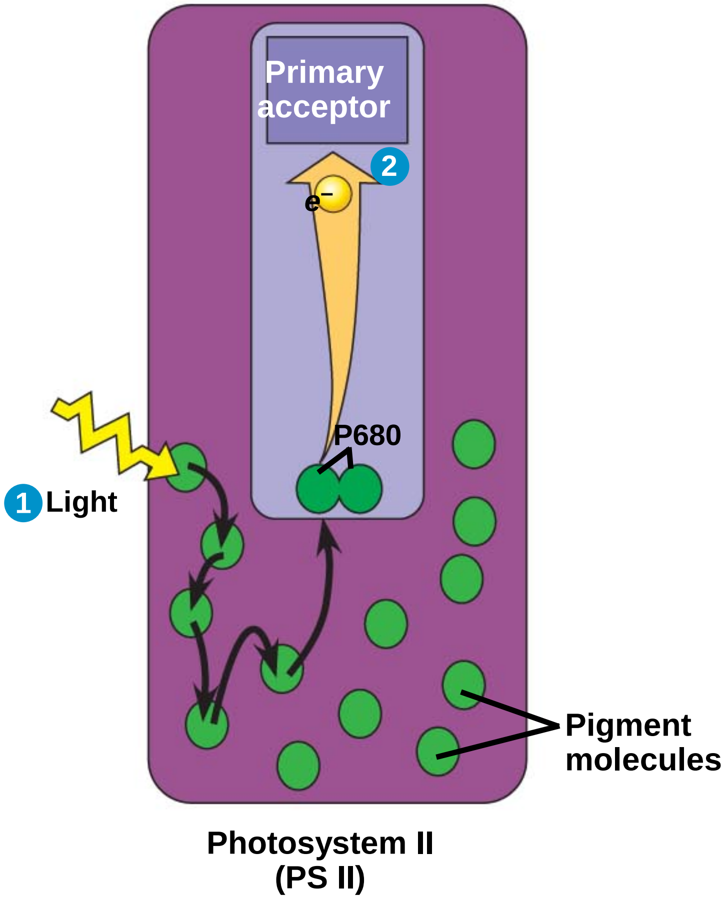
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll *a* of PS I is called P700

# 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

- A photon hits a pigment and its energy is passed among pigment molecules until it excites P680 (reaction center)
- An excited electron from P680 is transferred to the primary electron acceptor

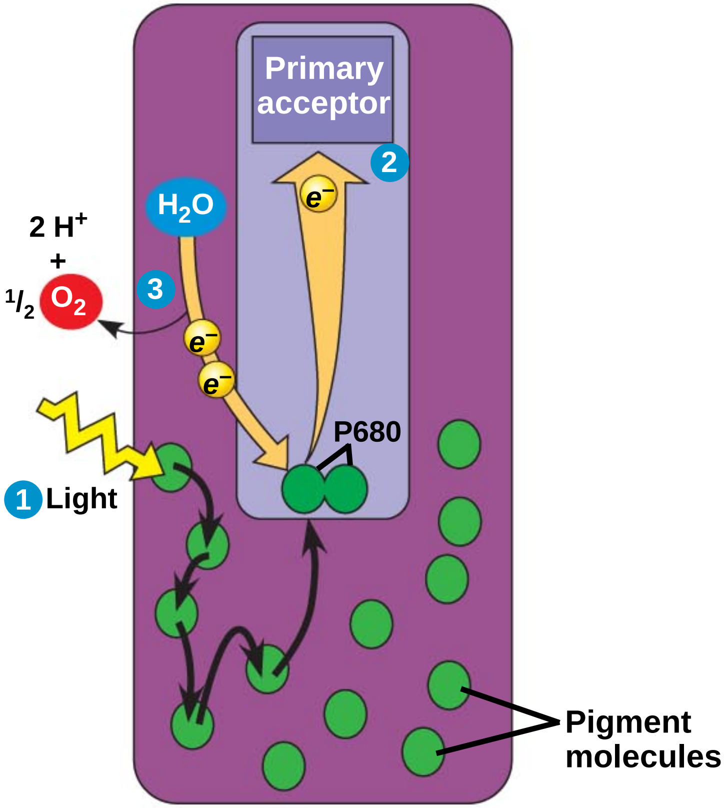
Fig. 10-13-1



Primary acceptor
2
e⁻
P680
1 Light
Pigment molecules
Photosystem II (PS II)

- $P680^+$ (P680 that is missing an electron) 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

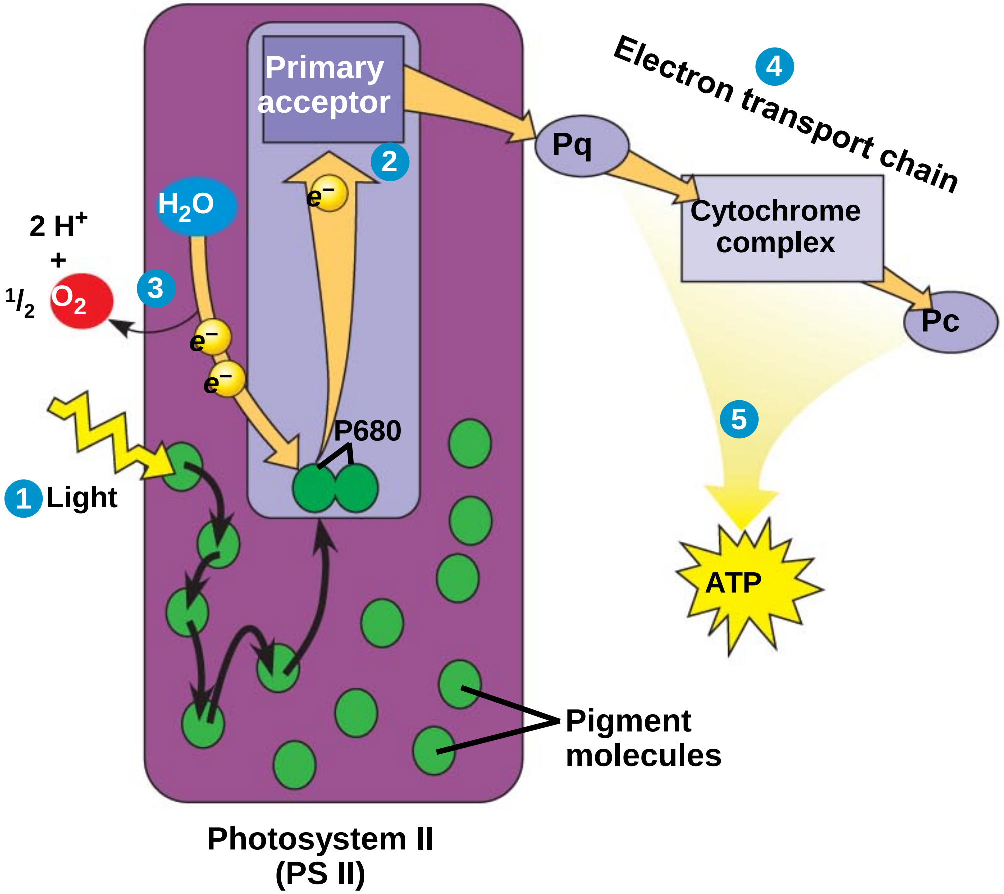
Fig. 10-13-2




Photosystem II
(PS II)

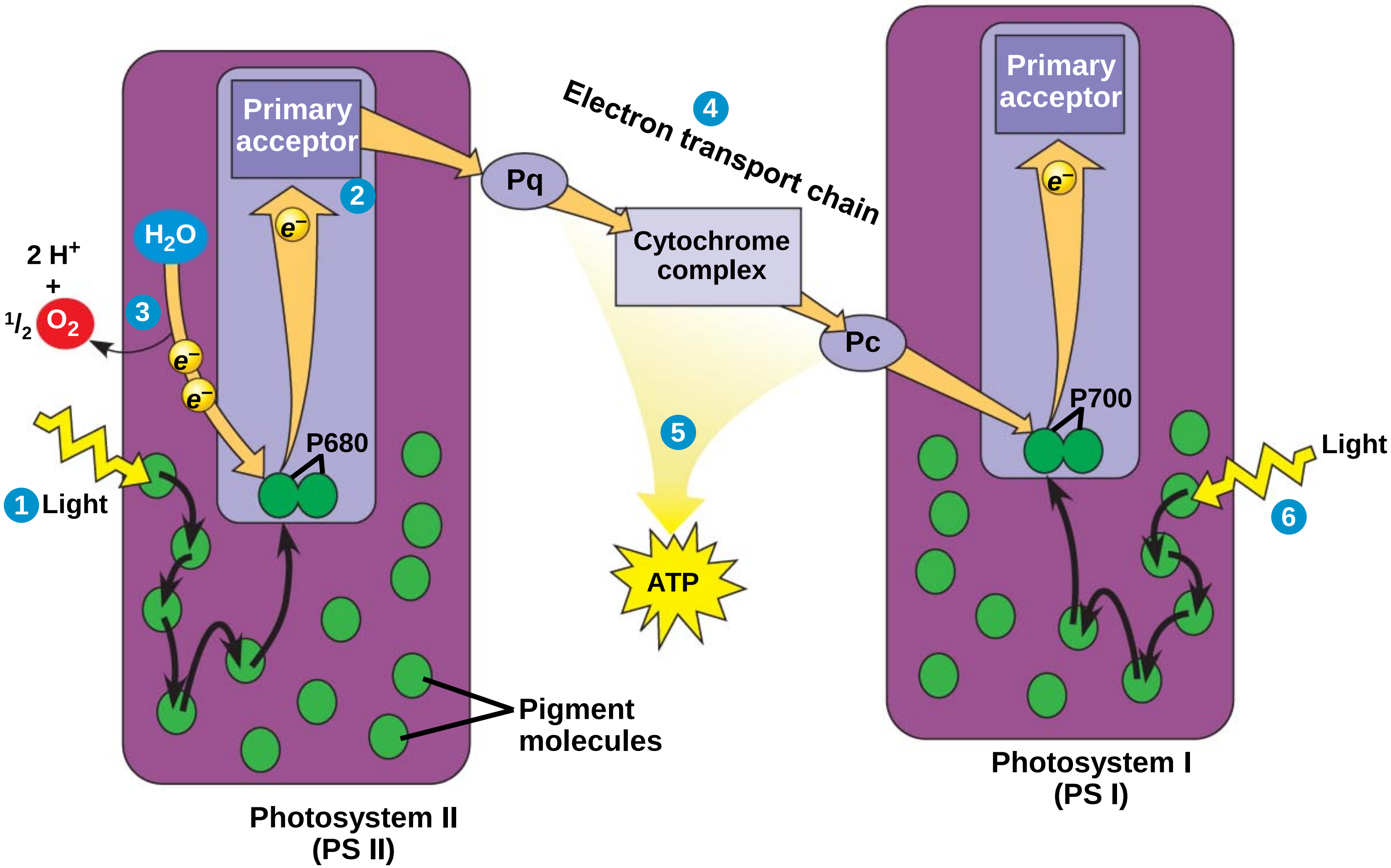
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of $H^+$ (protons) across the membrane drives ATP synthesis

Fig. 10-13-3


Primary acceptor
Pq
4 Electron transport chain
Cytochrome complex
Pc
2
e⁻
$H_2O$
2 $H^+$
+
$^1/_2$ $O_2$
3
e⁻
e⁻
P680
5
1 Light
ATP
Pigment molecules
Photosystem II
(PS II)

- In PS I (like PS II), transferred light energy excites P700 (reaction center), 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

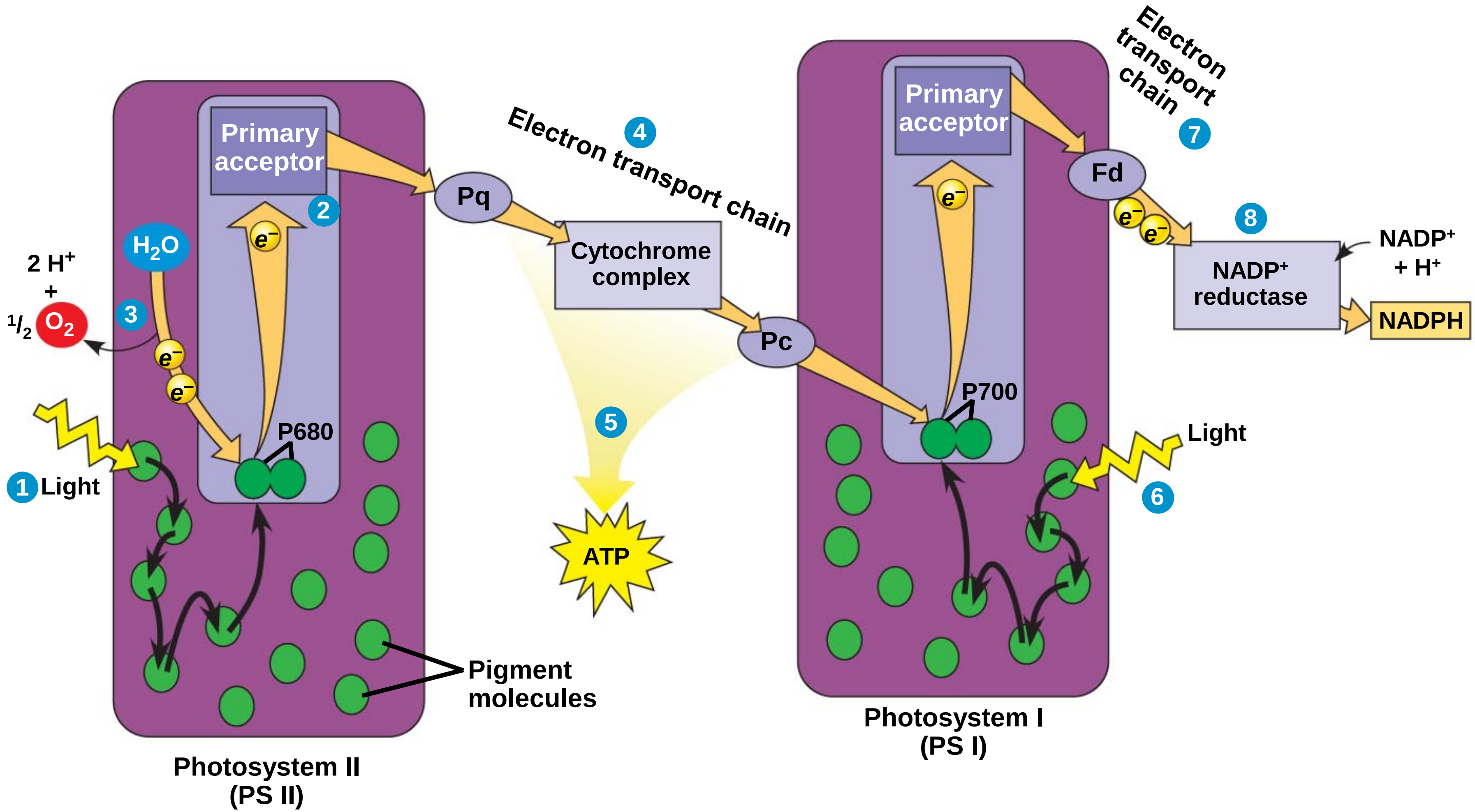
Fig. 10-13-4



Electron transport chain
4
Primary acceptor
Primary acceptor
2
$e^-$
$H_2O$
2 $H^+$
+
$^1/_2$ $O_2$
3
$e^-$
$e^-$
P680
1 Light
Pq
Cytochrome complex
Pc
$e^-$
P700
Light
6
5
ATP
Pigment molecules
Photosystem II (PS II)
Photosystem I (PS I)

- 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

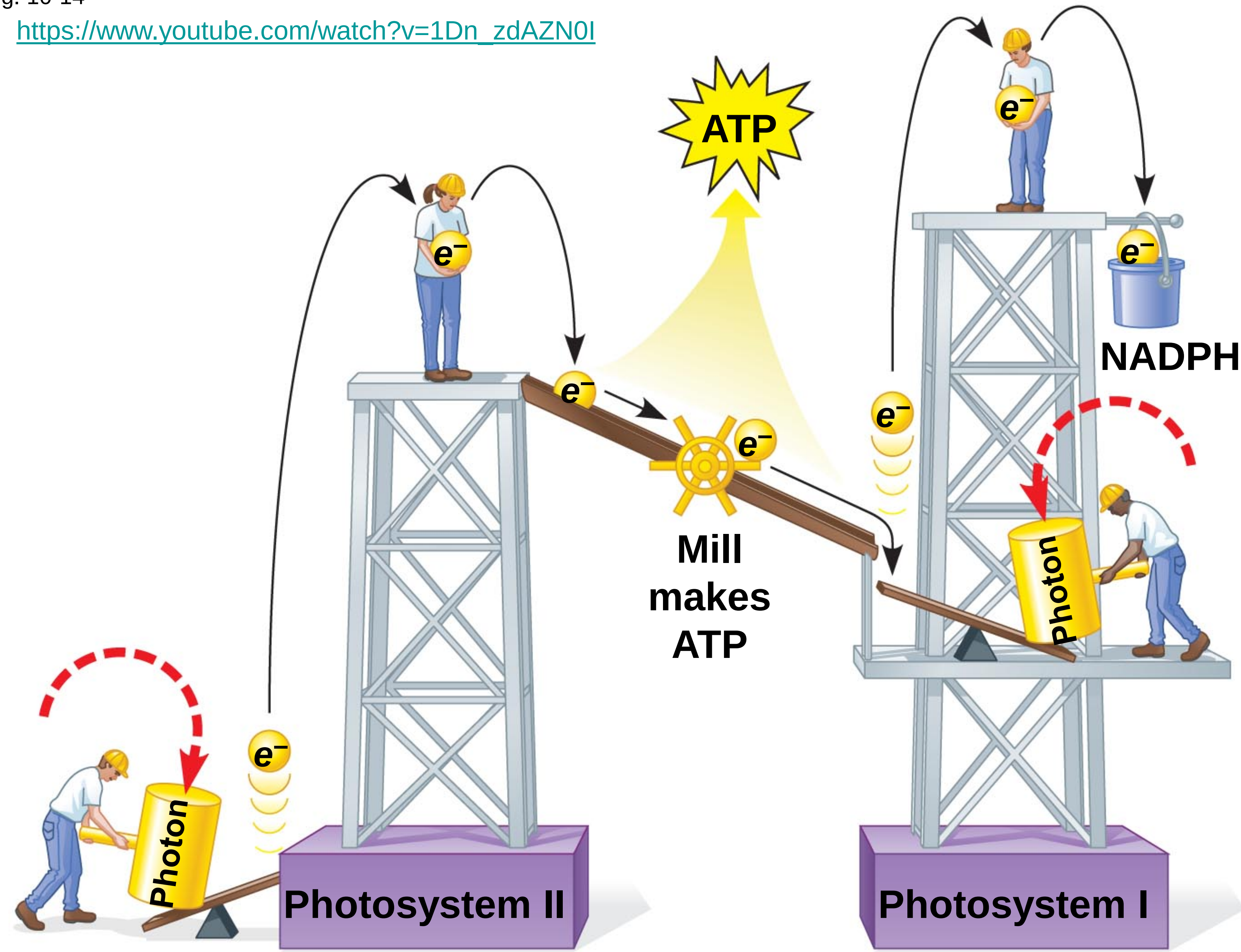
Fig. 10-13-5



Electron transport chain
4
Primary acceptor
2
Pq
Cytochrome complex
H₂O
2 H⁺ + ½ O₂
3
e⁻
e⁻
e⁻
P680
1 Light
5
ATP
Pc
Pigment molecules
Photosystem II (PS II)
Electron transport chain
7
Primary acceptor
e⁻
Fd
e⁻
e⁻
8
NADP⁺ + H⁺
NADP⁺ reductase
NADPH
P700
Light
6
Photosystem I (PS I)

Fig. 10-14

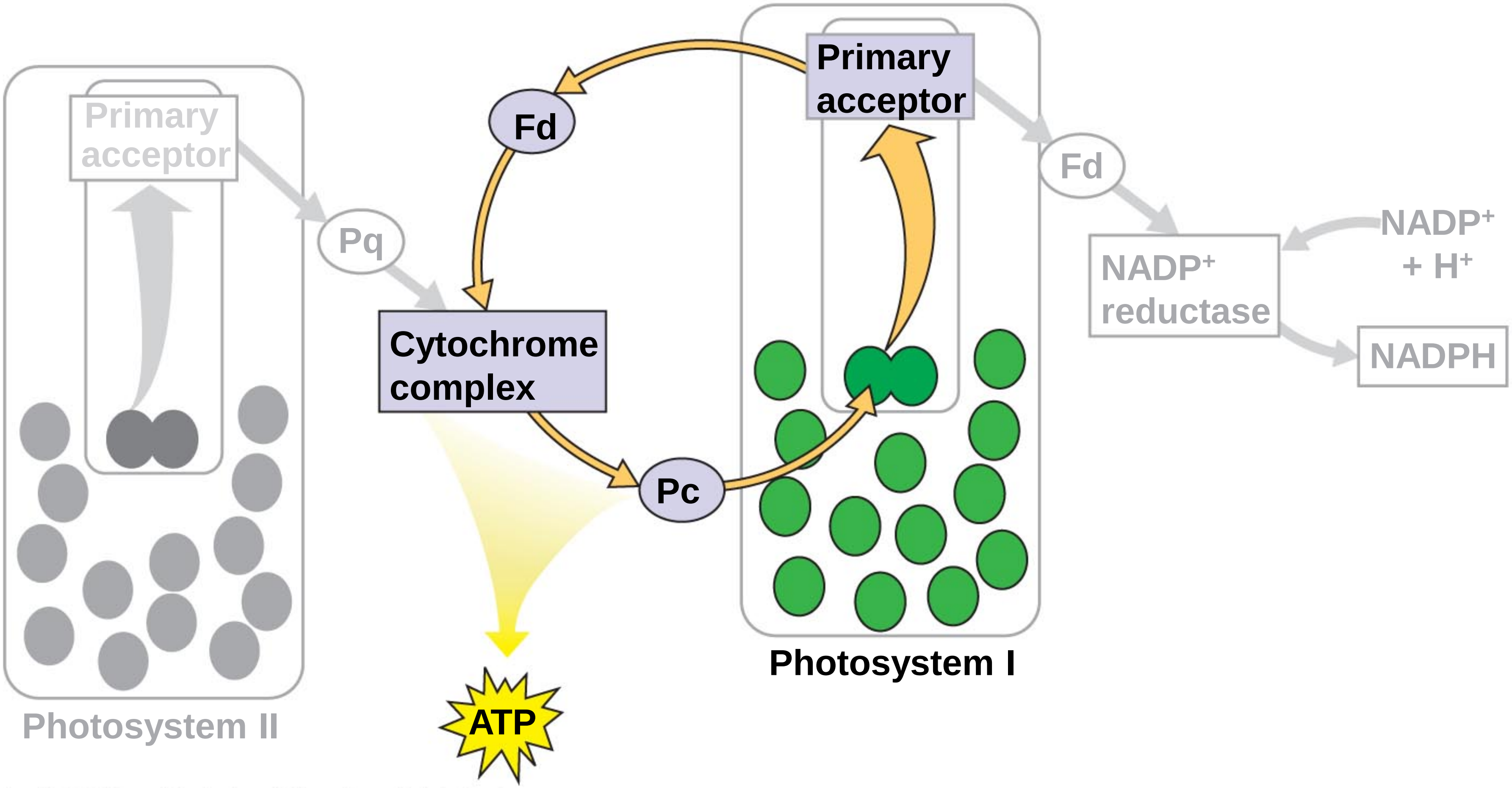
https://www.youtube.com/watch?v=1Dn_zdAZN0I



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

# Light Causes Damage to Photosystems

- The absorption of light (photons) causes damage to photosystems especially PSII
- Damage leads to photoinhibition (reduction in photosysthesis)
- Normally photosystems are rapidly repaired by the cell
- All light intensities cause damage but damage increases with increasing intensity

# Light Causes Damage to Photosystems

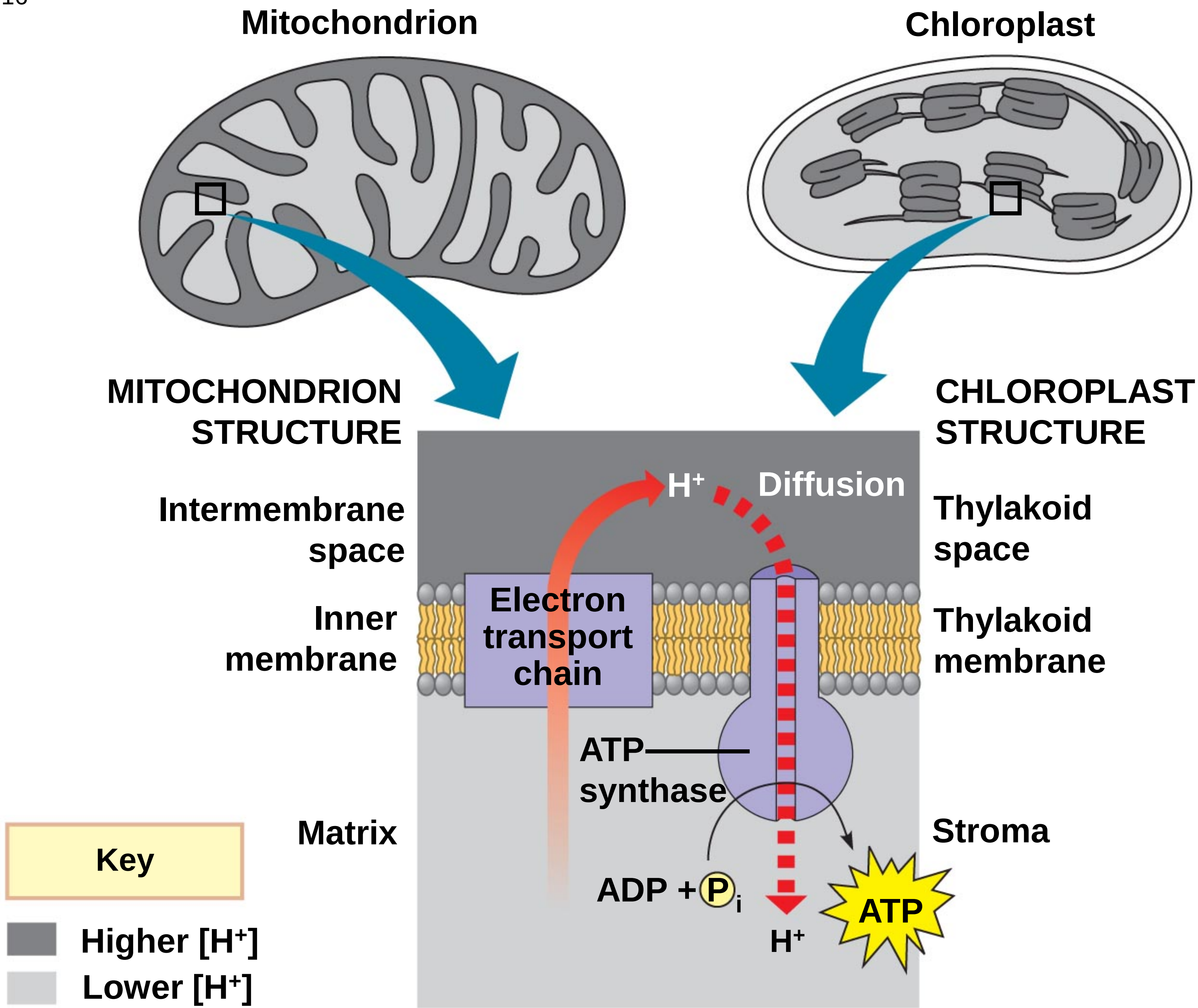
- Reactive Oxygen Species (ROS)
- Free radicals – cause damage
- UV radiation contributes to damage

# 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

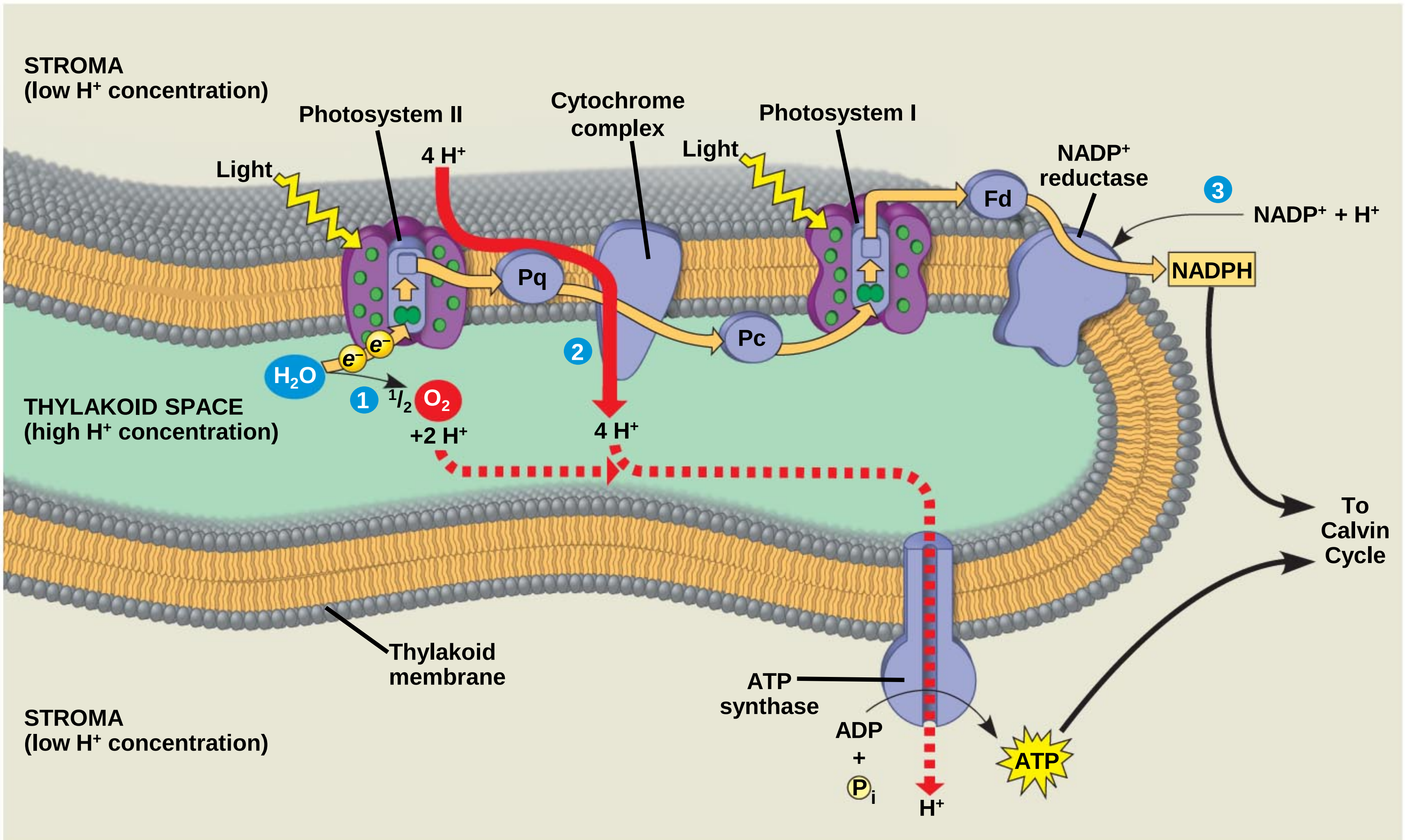
Fig. 10-16



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



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

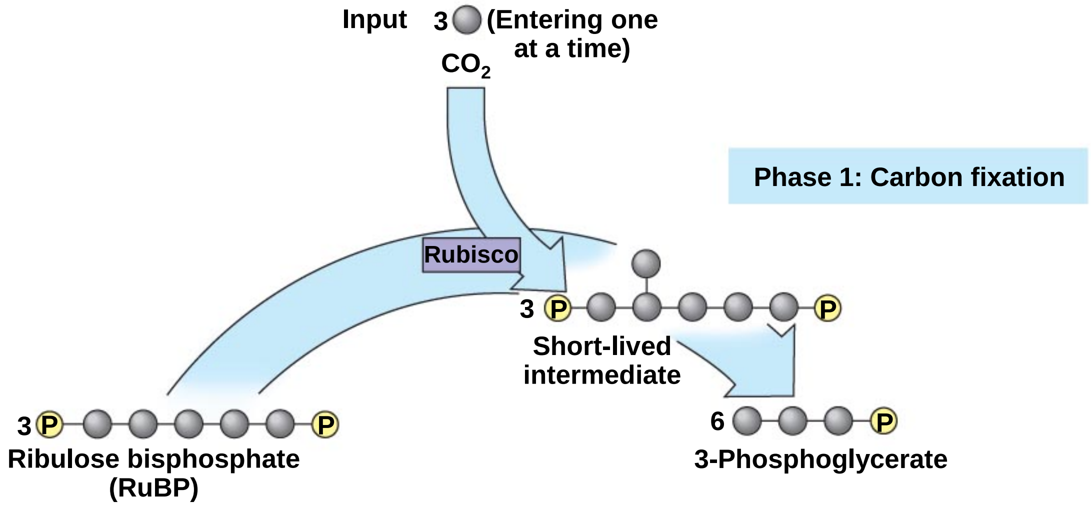
# Concept 10.3: The Calvin cycle uses ATP and NADPH to convert $CO_2$ to sugar

- 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

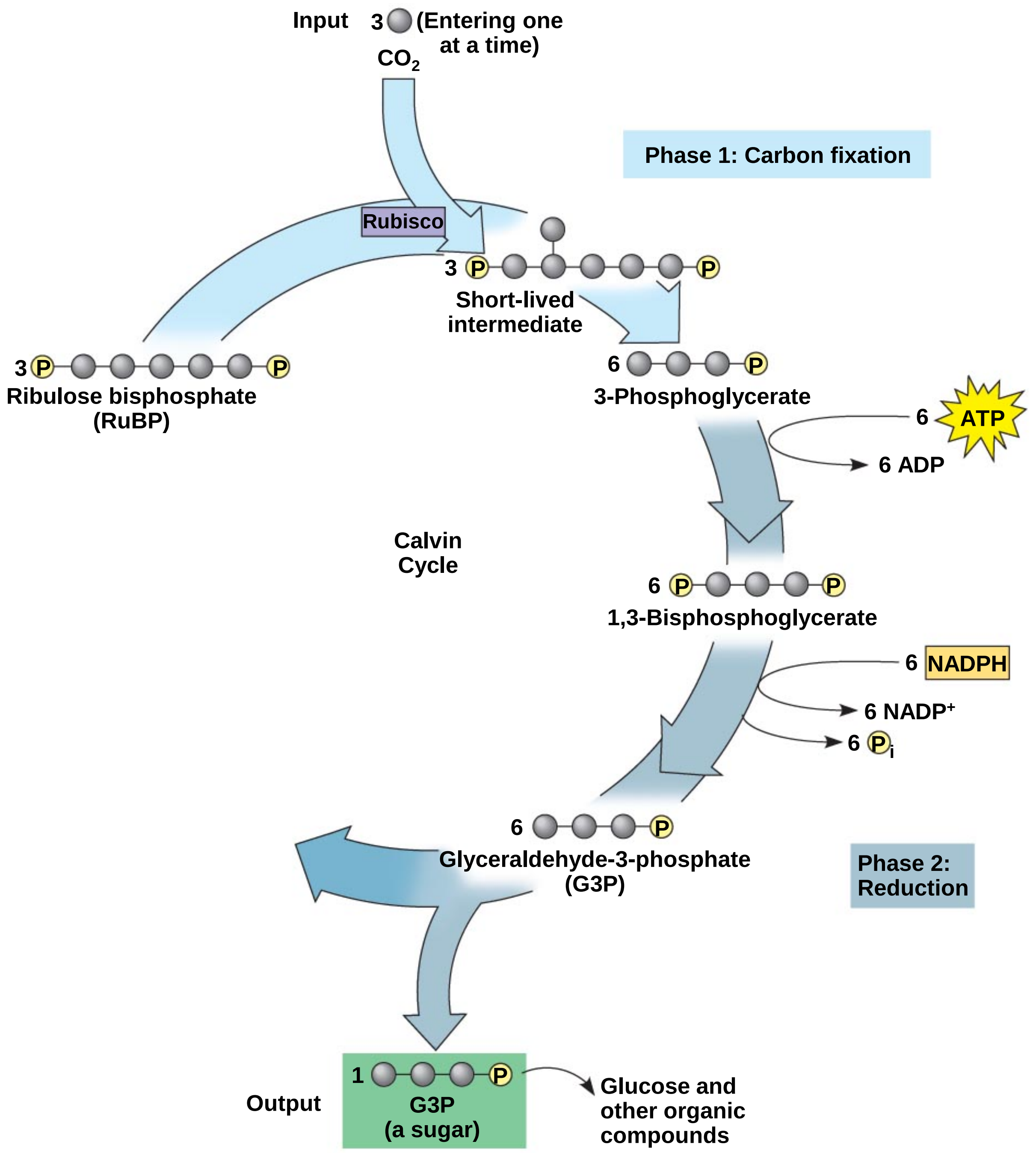
- Carbon enters the cycle as $CO_2$ and leaves as a sugar named **glyceraldehyde-3-phospate (G3P)**
- For net synthesis of 1 G3P, the cycle must take place three times, fixing 3 molecules of $CO_2$
- The Calvin cycle has three phases:
  - **Carbon fixation** (catalyzed by **rubisco - Ribulose-1,5-bisphosphate carboxylase/oxygenase**)
  - **Reduction**
  - **Regeneration of the $CO_2$ acceptor (RuBP)**

Fig. 10-18-1



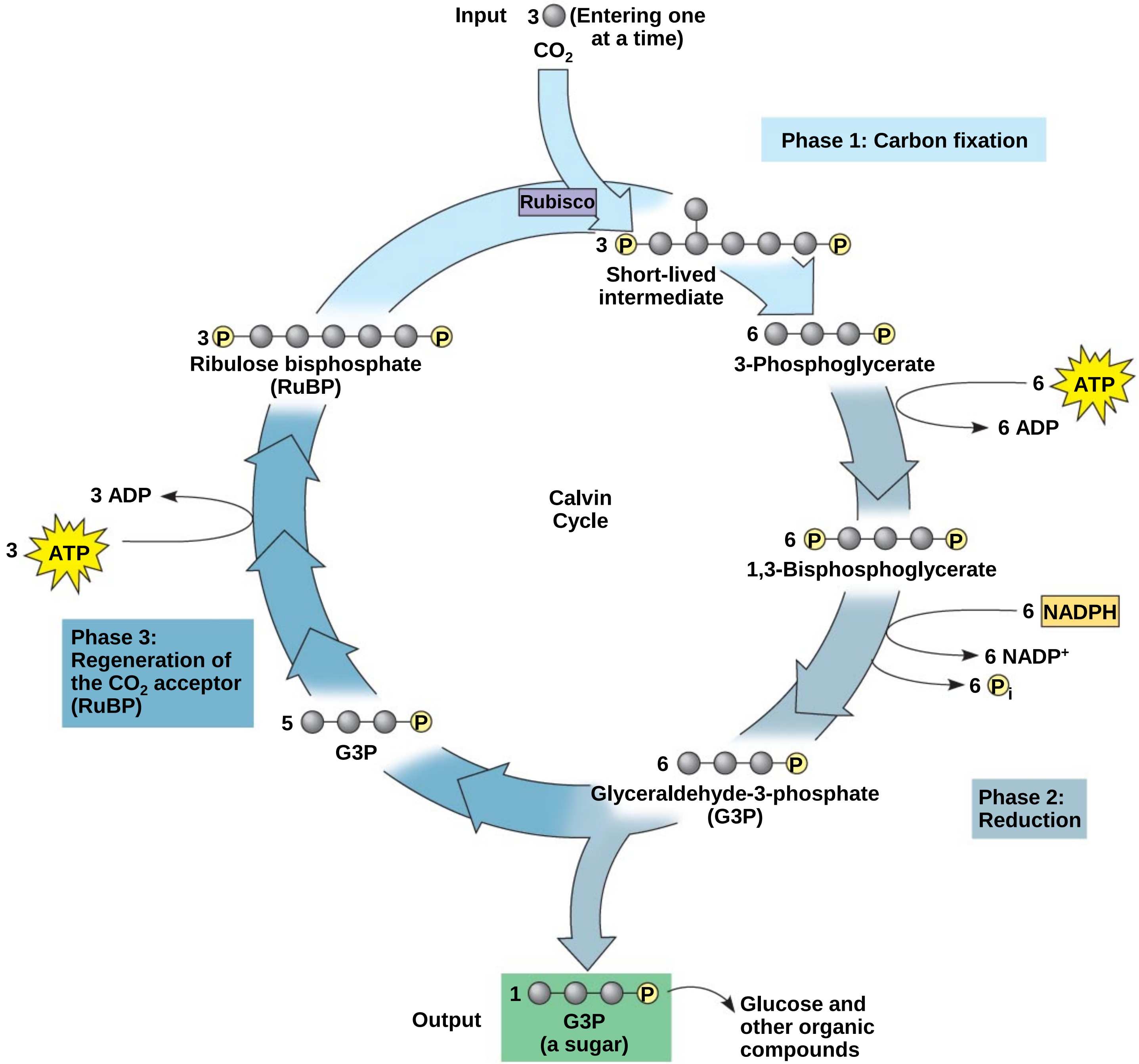
Input
3
(Entering one at a time)
$CO_2$
Phase 1: Carbon fixation
Rubisco
3
P
P
Short-lived intermediate
3
P
P
Ribulose bisphosphate (RuBP)
6
P
3-Phosphoglycerate

Fig. 10-18-2



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

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
3 P P
Ribulose bisphosphate (RuBP)
Calvin Cycle
3 ADP
3 ATP
6 P P
1,3-Bisphosphoglycerate
6 NADPH
6 $NADP^+$
6 $P_i$
Phase 3: Regeneration of the $CO_2$ acceptor (RuBP)
5 P
G3P
6 P
Glyceraldehyde-3-phosphate (G3P)
Phase 2: Reduction
Output
1 P
G3P (a sugar)
Glucose and other organic compounds

- Calvin Cycle Summary
- Steps
- The steps in the cycle are as follows:
- 1. Grab: A five-carbon carbon catcher catches one molecule of carbon dioxide and forms a six-carbon molecule.
- 2. Split: the enzyme RuBisCO (with the energy of ATP and NADPH molecules) breaks the six-carbon molecule into two equal parts.

# Calvin Cycle Summary

- 3. Leave: A trio of three carbons leave and become sugar. The other trio moves on to the next step.
- 4. Switch: Using ATP and NADPH, the three carbon molecule is changed into a five carbon molecule.
- 5. The cycle starts over again.

# Calvin Cycle Summary

- The product
- The carbohydrate products of the Calvin cycle are three-carbon sugar phosphate molecules, or 'triose phosphates' (G3P). Each step of the cycle has its own enzyme which speeds up the reaction.

# 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

# CAM Plants

- Some plants, (including orchids, bromeliads, cacti, and 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

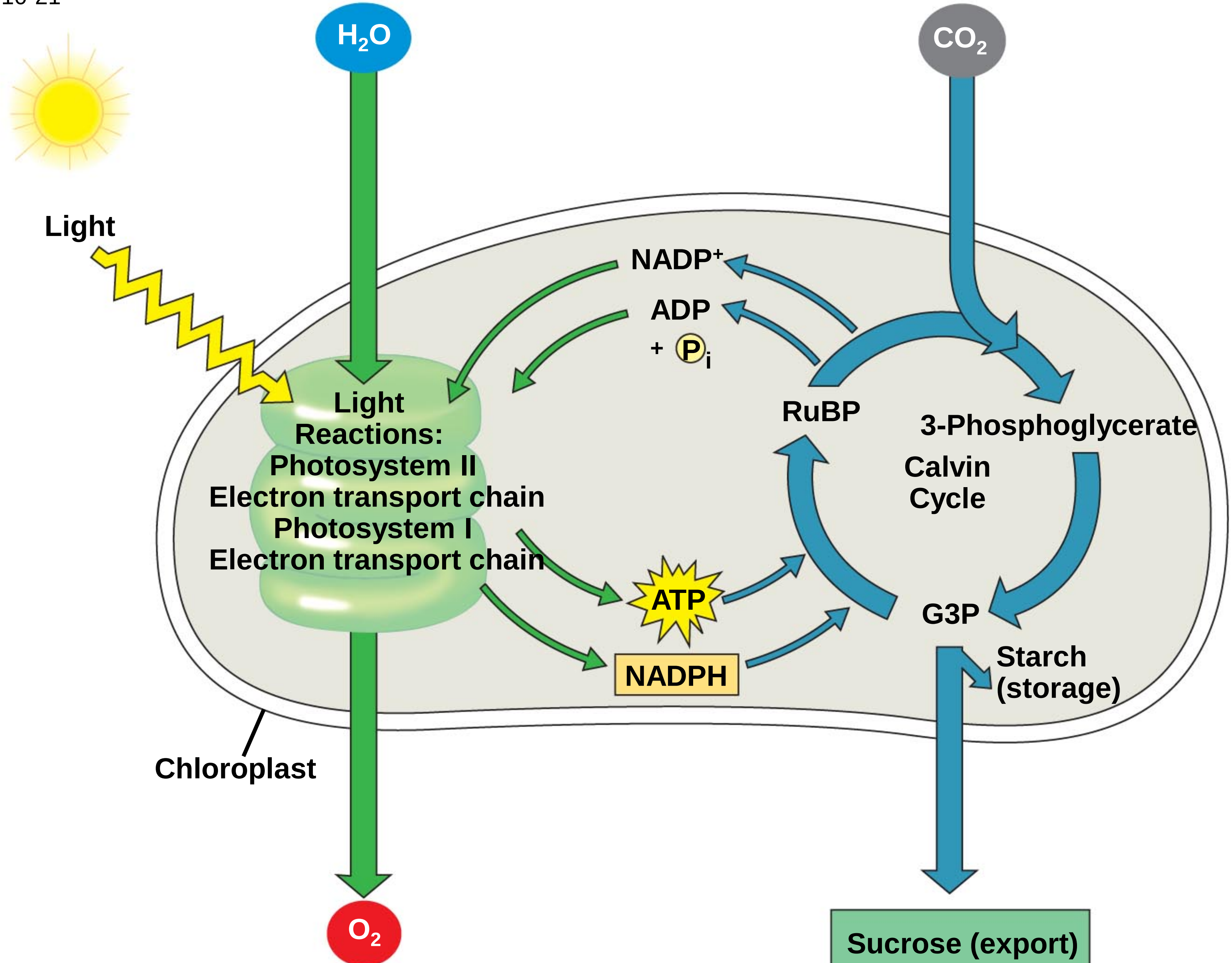
# Plants have Variety

- Most plants use $C_3$ metabolism.
- Some plants use only $C_3$ or $C_4$ or CAM.
- Some plants are flexible and can switch the type of metabolism depending on environmental conditions.

# 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


H₂O
CO₂
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
O₂
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