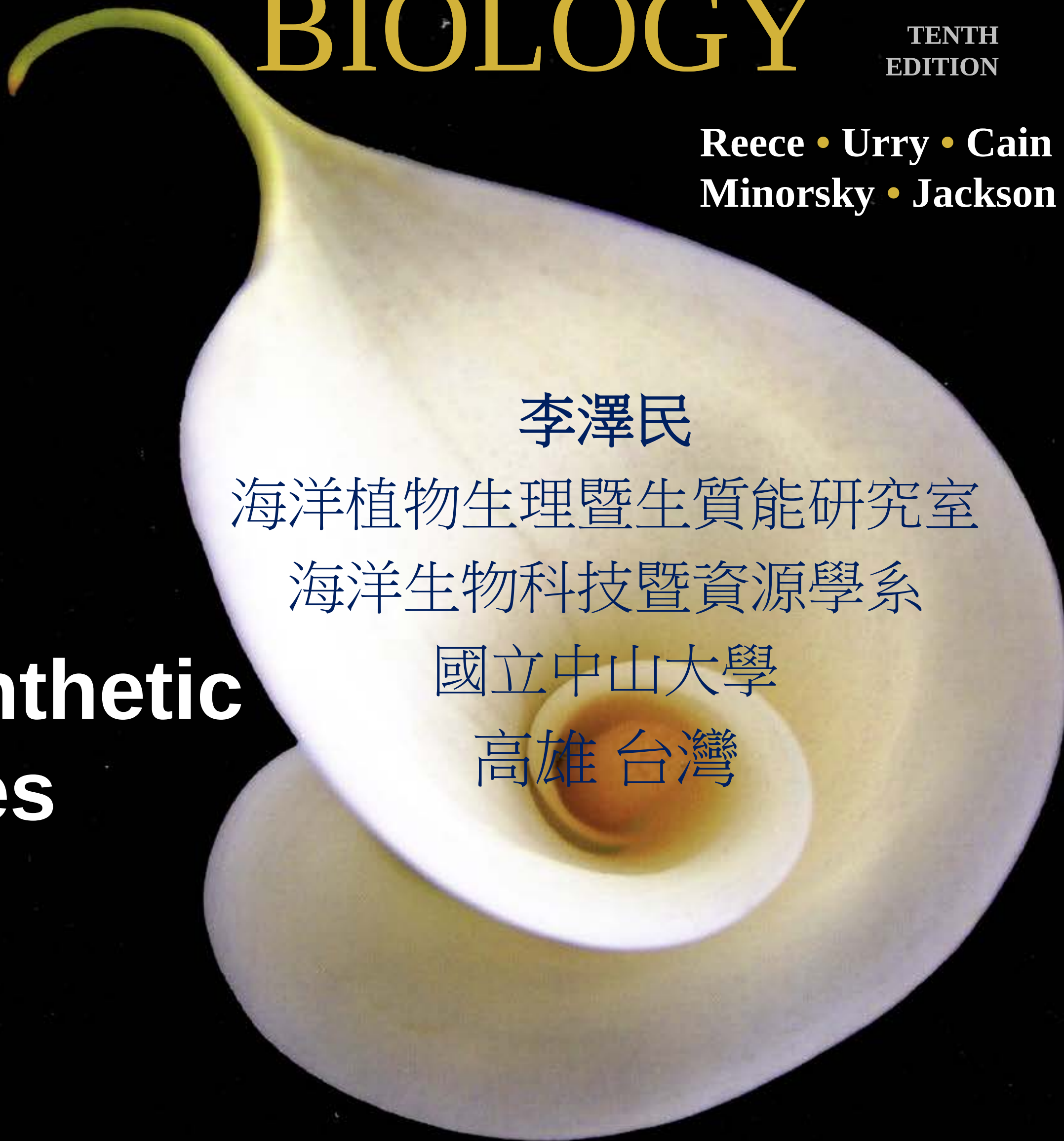
CAMPBELL

BIOLOGY

TENTH EDITION

Reece • Urry • Cain • Wasserman • Minorsky • Jackson



11

Photosynthetic Processes

李澤民
海洋植物生理暨生質能研究室
海洋生物科技暨資源學系
國立中山大學
高雄 台灣

Lecture Presentation by
Nicole Tunbridge and
Kathleen Fitzpatrick

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 11.1

Figure 11.1a

Other organisms also benefit from photosynthesis.

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

Figure 11.2

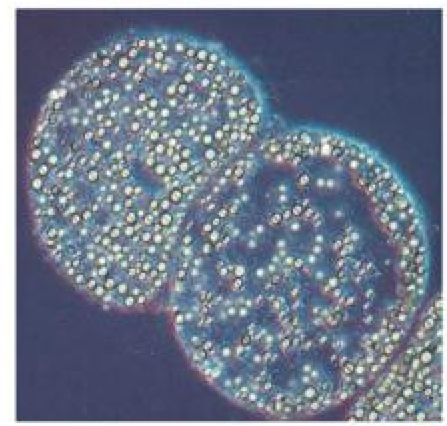
(a) Plants

(b) Multicellular alga

11 µm

(c) Unicellular eukaryotes

(d) Cyanobacteria 40 µm



1 µm

(e) Purple sulfur bacteria

Figure 11.2a

(a) Plants

(b) Multicellular alga

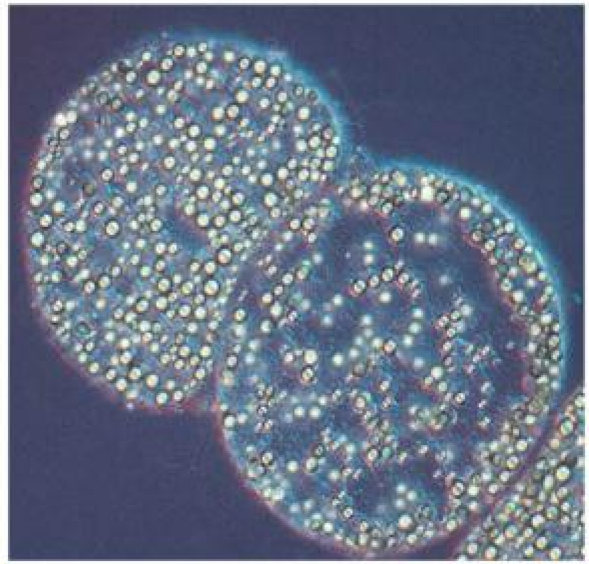
(c) Unicellular eukaryotes

Figure 11.2d

(d) Cyanobacteria 40 µm

Figure 11.2e

1 µm



(e) Purple sulfur bacteria

C.B. Van Niel – 1930's

- Observed photosynthesis in purple sulfur bacteria
- $CO_2 + 2H_2S$ + light energy => $(CH_2O) + H_2O + 2S$
- Van Niel then generalized this to the following reaction for all photosynthetic activity
- $CO_2 + 2H_2A$ + light energy => $(CH_2O) + H_2O + 2A$

- **相對於autotrophs**
- **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

- 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

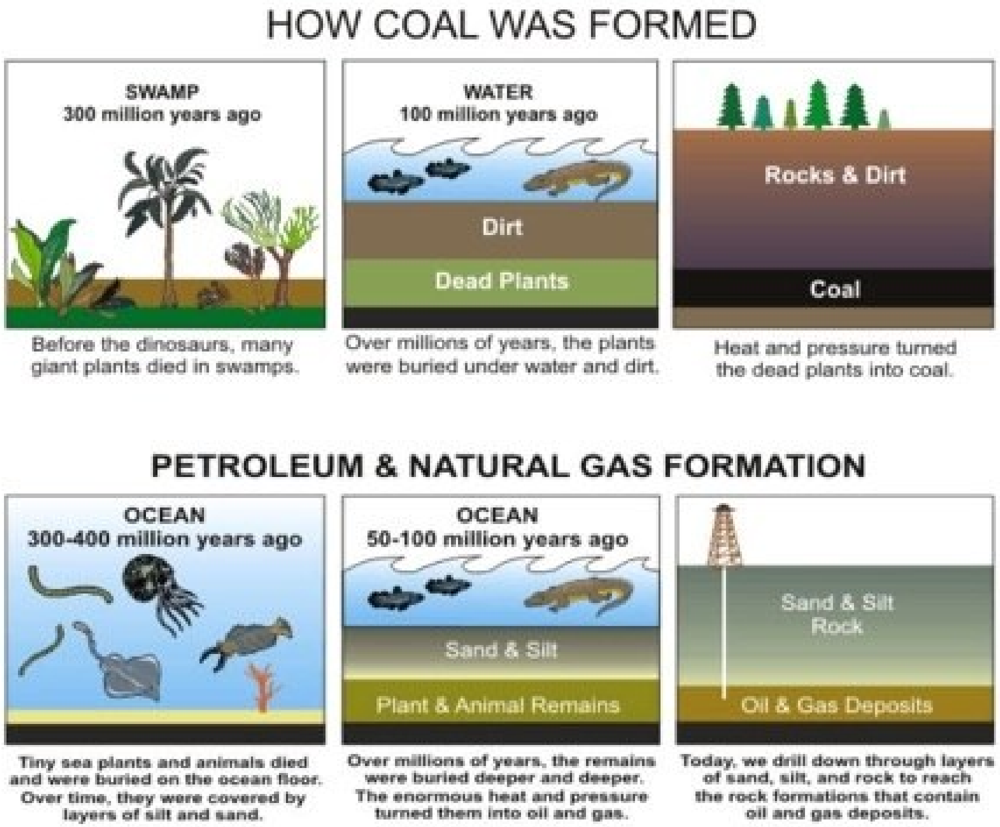


Figure 11.3


Carbon dioxide, nutrients and sunlight
Oxygen
BODIESEL
1 Fats (oils) grow inside algae
2 Algae oil is extracted
3 Algae oil converted to biodiesel
4 Algae bodiesel placed in the market

Concept 11.1: Photosynthesis converts light energy to the chemical energy of food

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

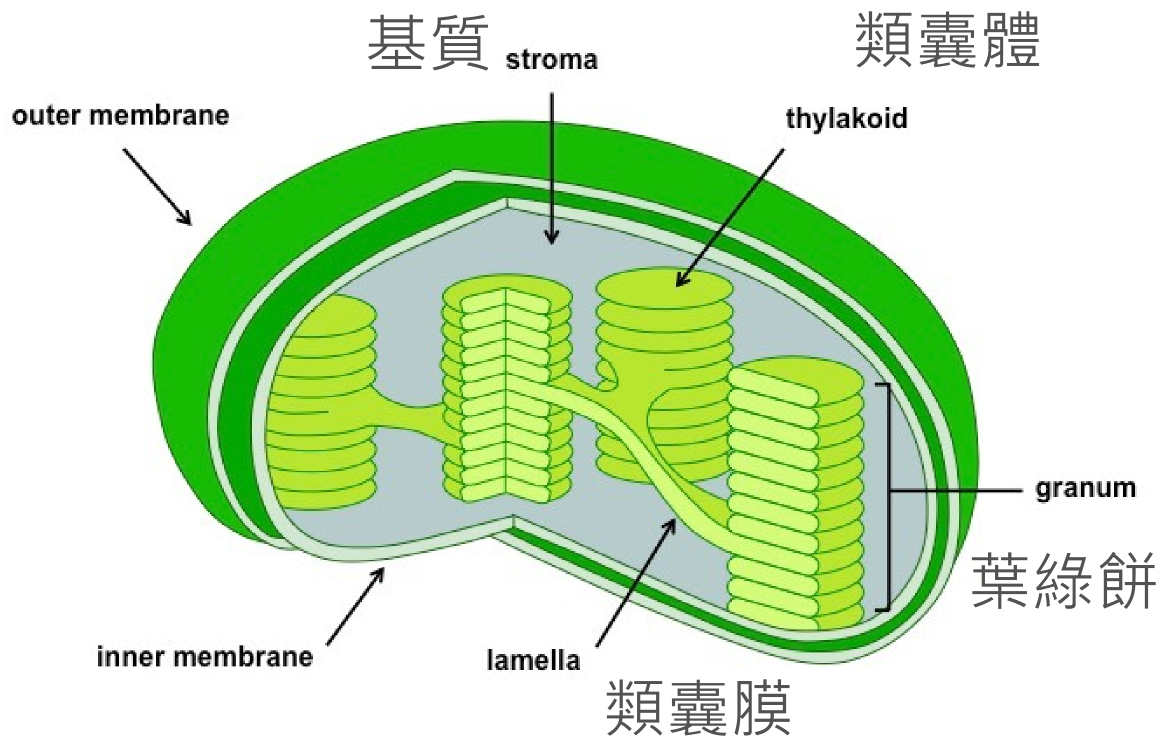
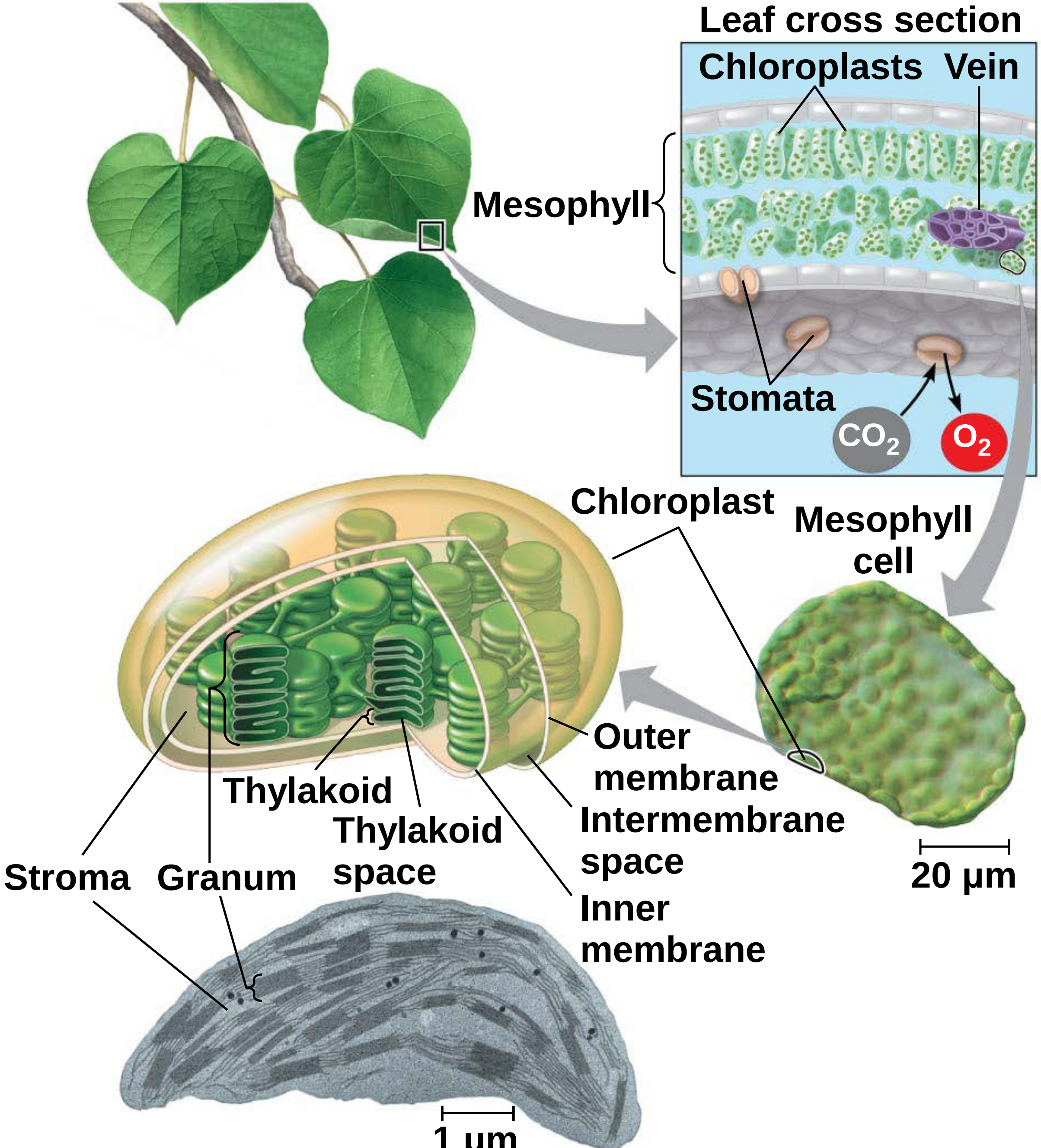


Figure 11.4

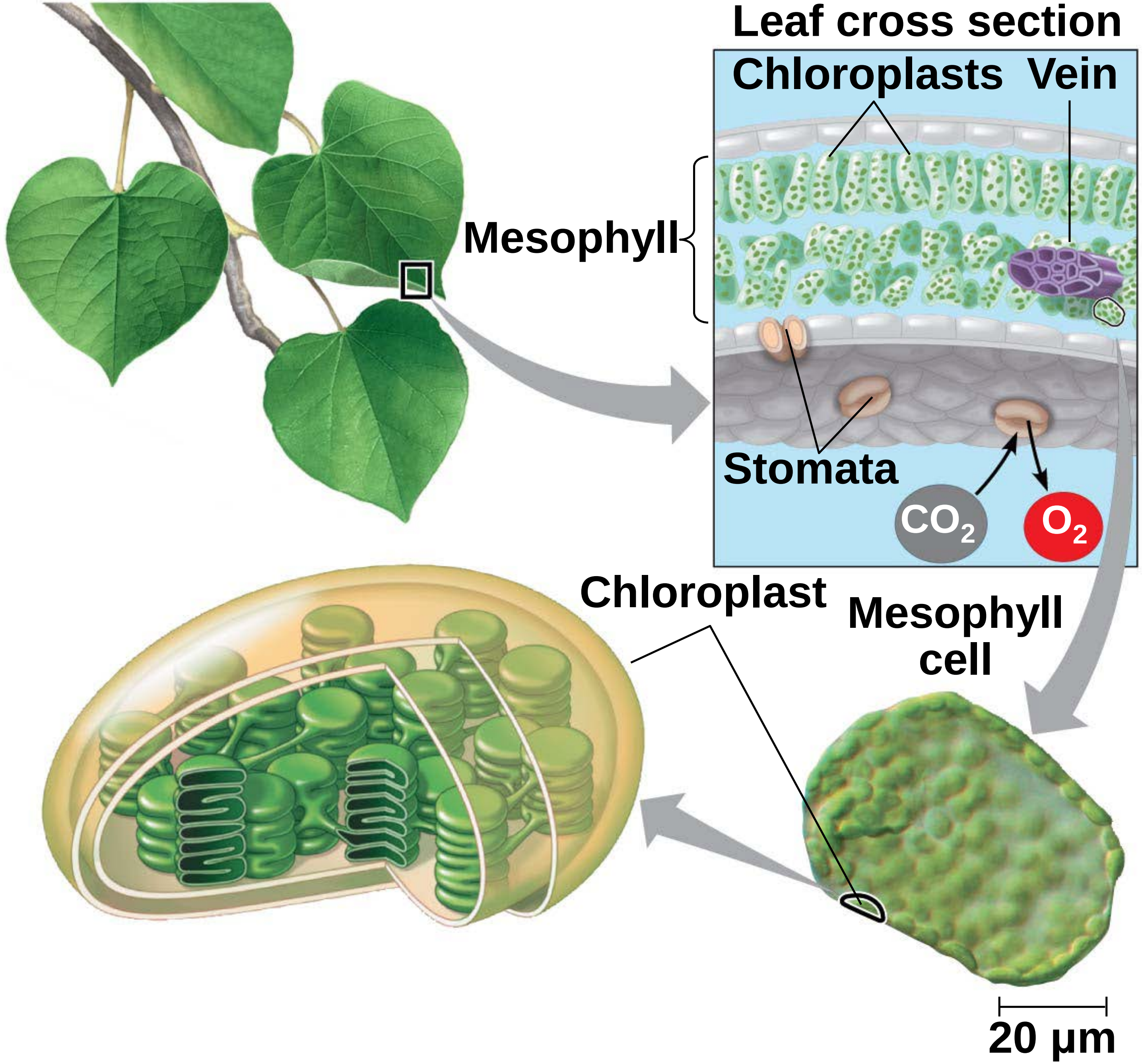


Leaf cross section
Chloroplasts
Vein
Mesophyll
Stomata
CO_2
O_2
Chloroplast
Mesophyll cell
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Thylakoid space
Stroma
Granum
20 μm
1 μm

Chloroplasts: The Sites of Photosynthesis in Plants

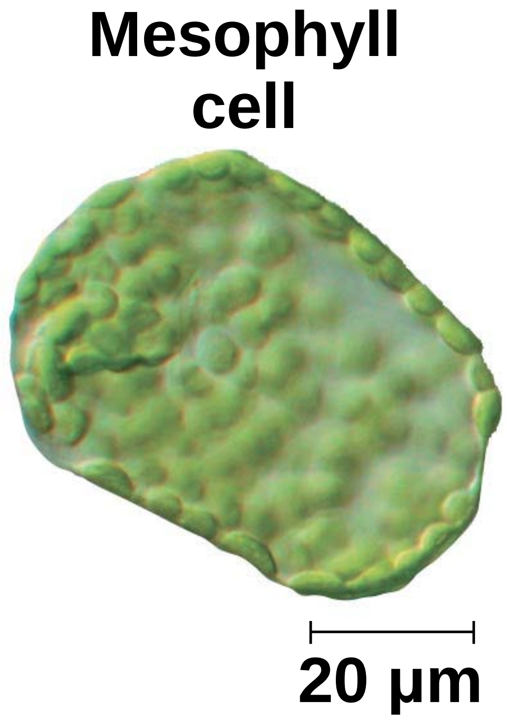
- Leaves are the major locations of photosynthesis
- Chloroplasts are found mainly in cells of the mesophyll, the interior tissue of the leaf
- Each mesophyll cell contains 30–40 chloroplasts
- CO_2 enters and O_2 exits the leaf through microscopic pores called **stomata**

Figure 11.4a



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

Figure 11.4d



- A chloroplast has an envelope of two membranes surrounding a dense fluid called the **stroma**
- **Thylakoids** are connected sacs in the chloroplast which compose a third membrane system
- Thylakoids may be stacked in columns called grana
- **Chlorophyll**, the pigment which gives leaves their green colour, resides in the thylakoid membranes

Figure 11.4b

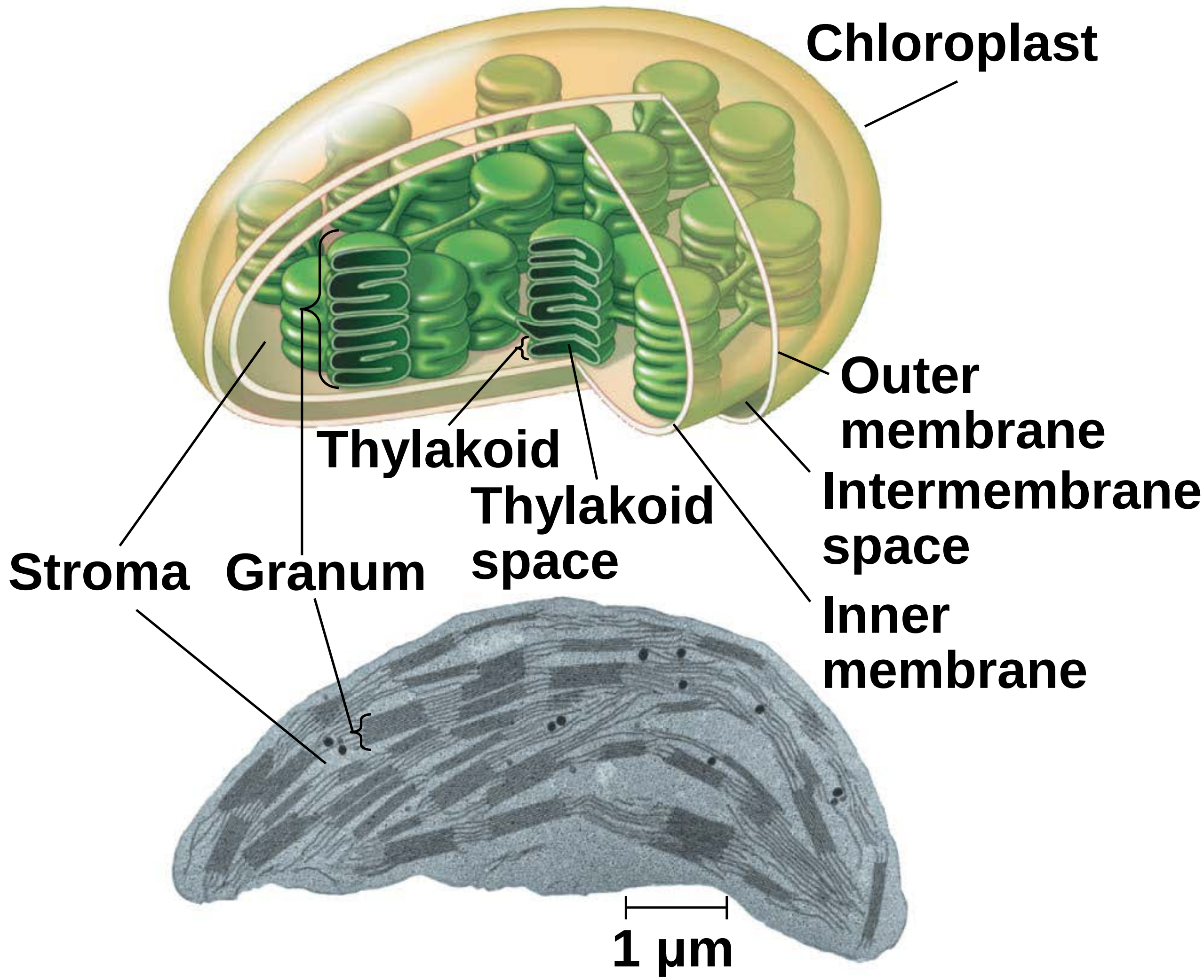
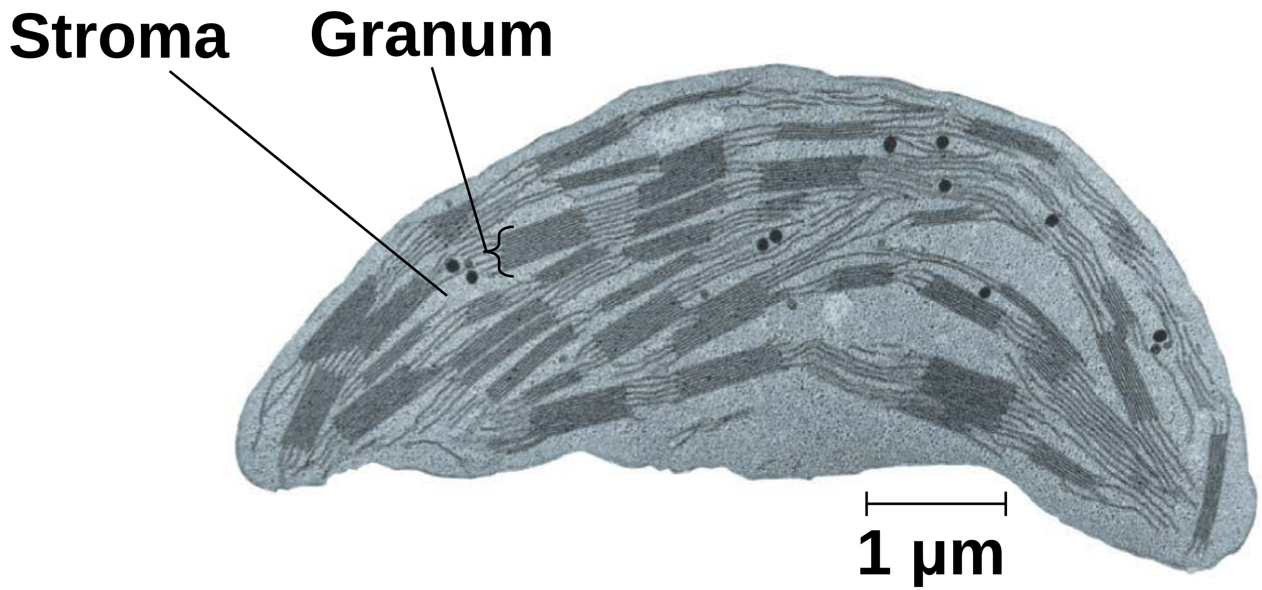

Chloroplast
Outer membrane
Intermembrane space
Inner membrane
Thylakoid
Thylakoid space
Stroma
Granum
1 µm

Figure 11.4c



Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

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

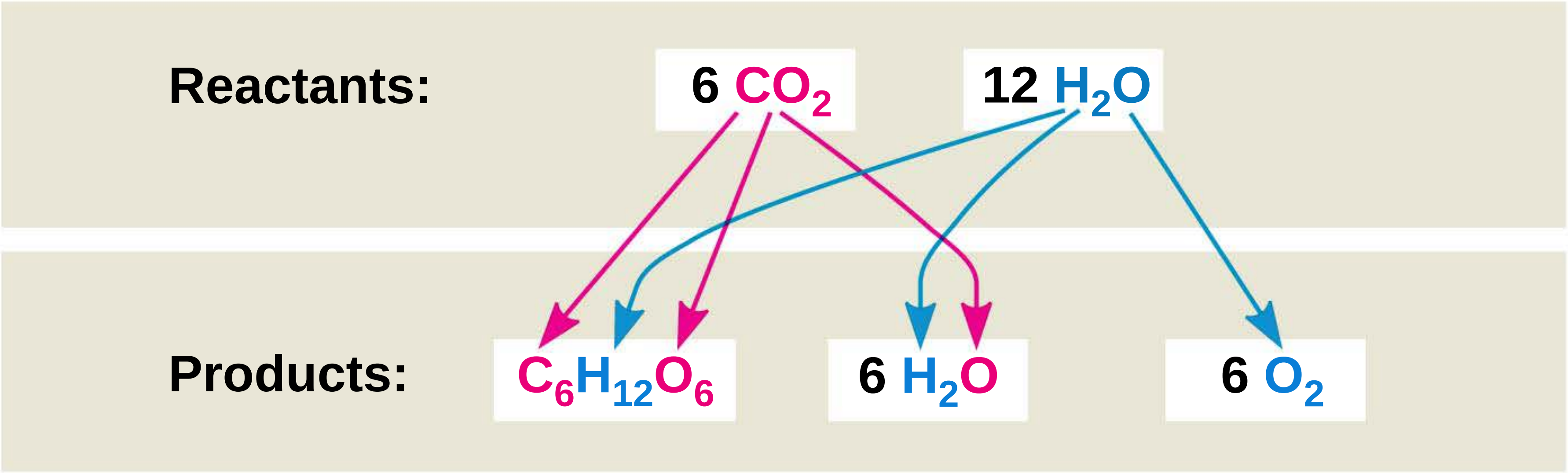
$$6\ CO_2 + 12\ H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

- The overall chemical change during photosynthesis is the reverse of the one that occurs during cellular respiration

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 11.5



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 11.UN01

becomes reduced

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

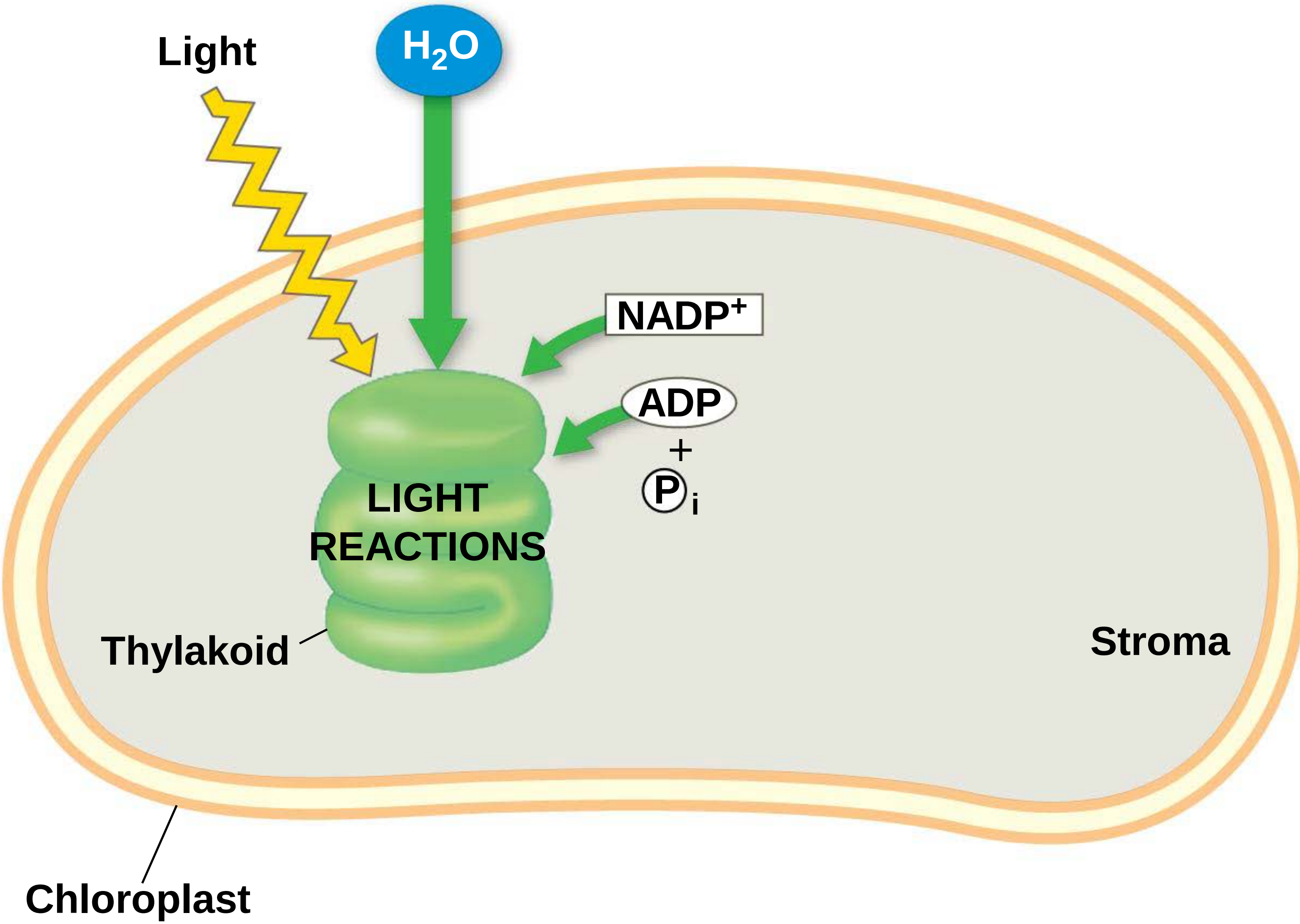
becomes oxidized

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 the electron acceptor **NADP**$^+$ to NADPH
  - Generate ATP from ADP by **photophosphorylation**

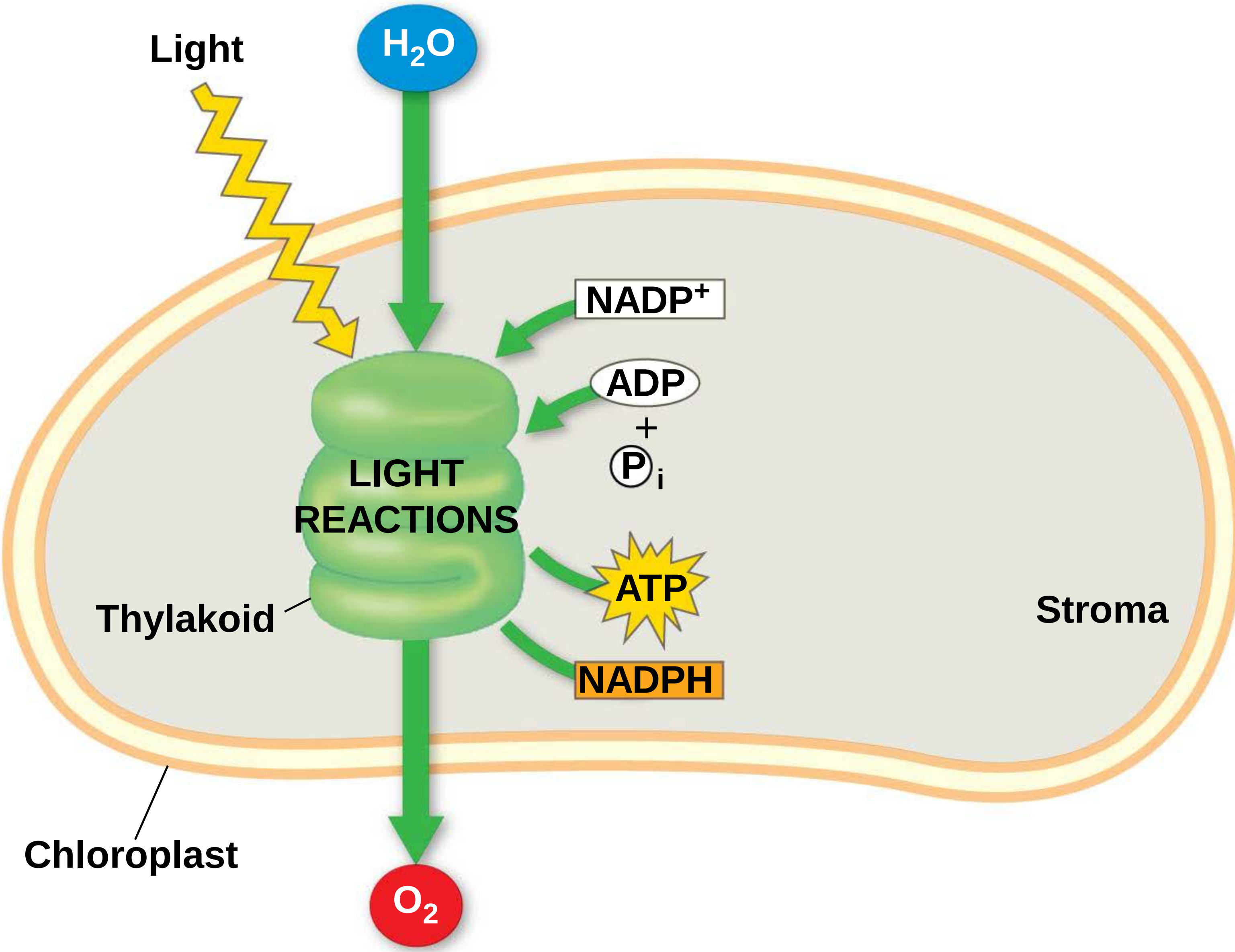
- The Calvin cycle (in the stroma) forms sugar from CO_2, using ATP and NADPH
- The Calvin cycle begins with **carbon fixation**, **incorporating CO_2 into organic molecules**

Figure 11.6-1



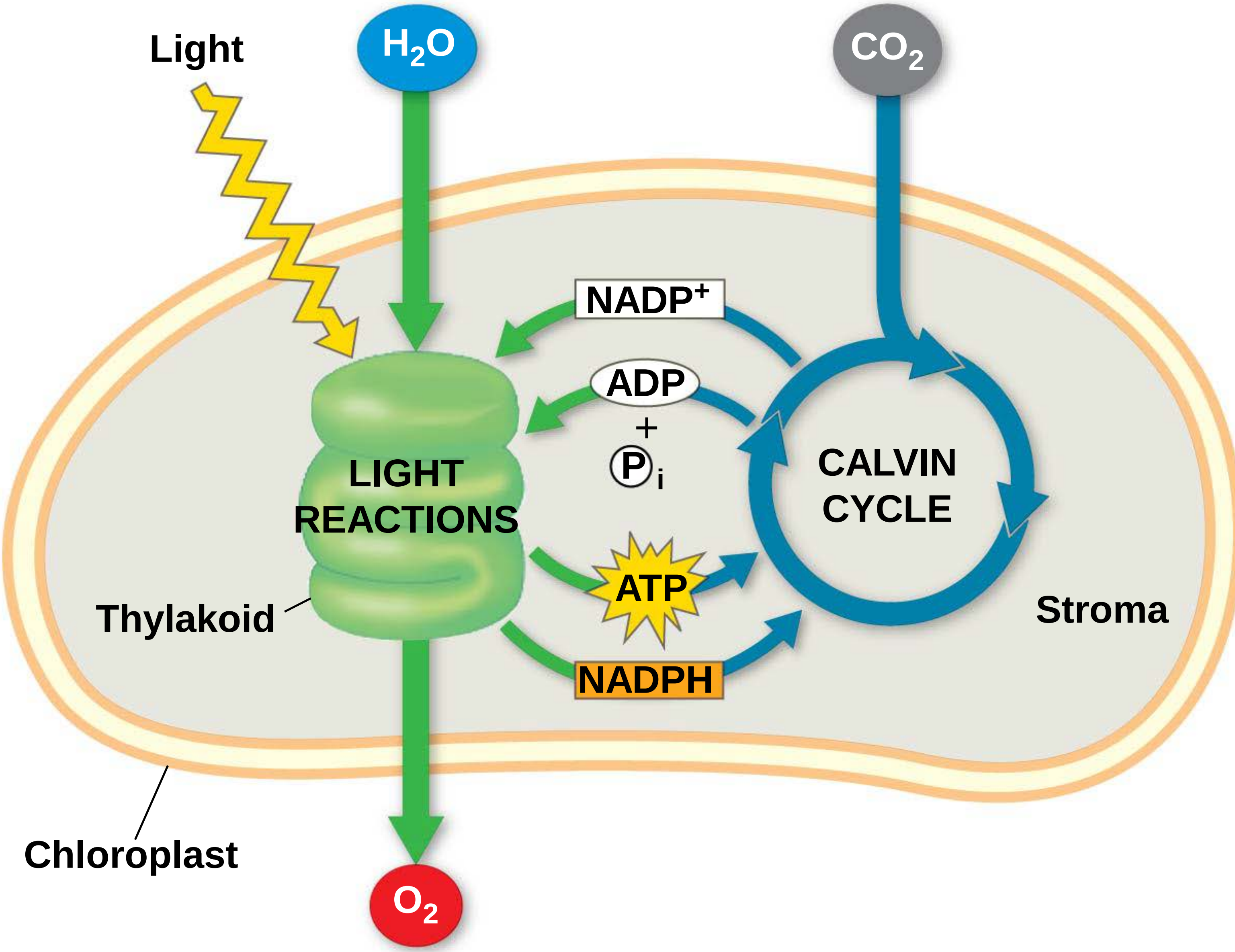
Light
H_2O
$NADP^+$
ADP
+
P i
LIGHT REACTIONS
Thylakoid
Stroma
Chloroplast

Figure 11.6-2



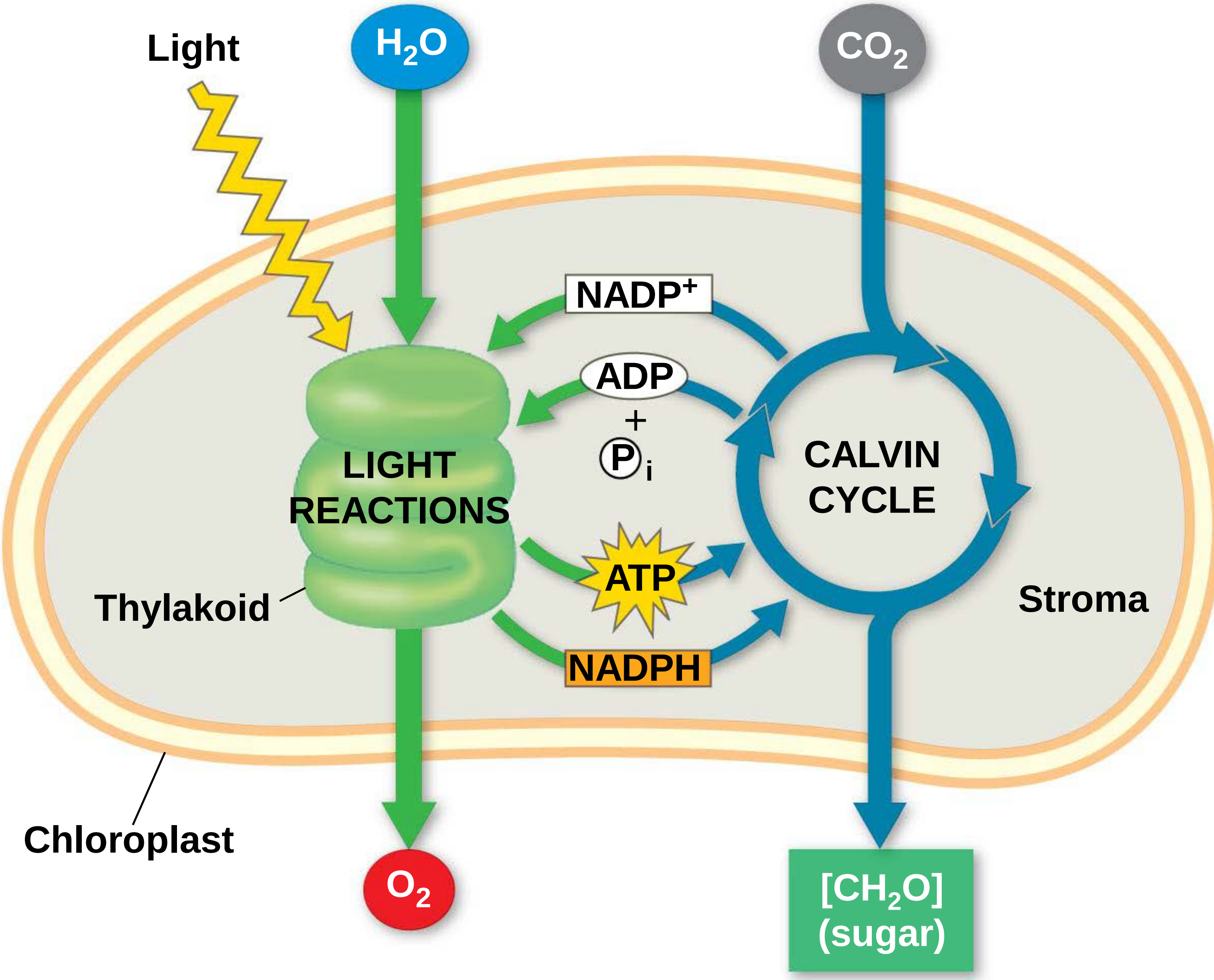
Light
H_2O
$NADP^+$
ADP
+
Ⓟi
LIGHT REACTIONS
ATP
NADPH
Thylakoid
Stroma
Chloroplast
O_2

Figure 11.6-3



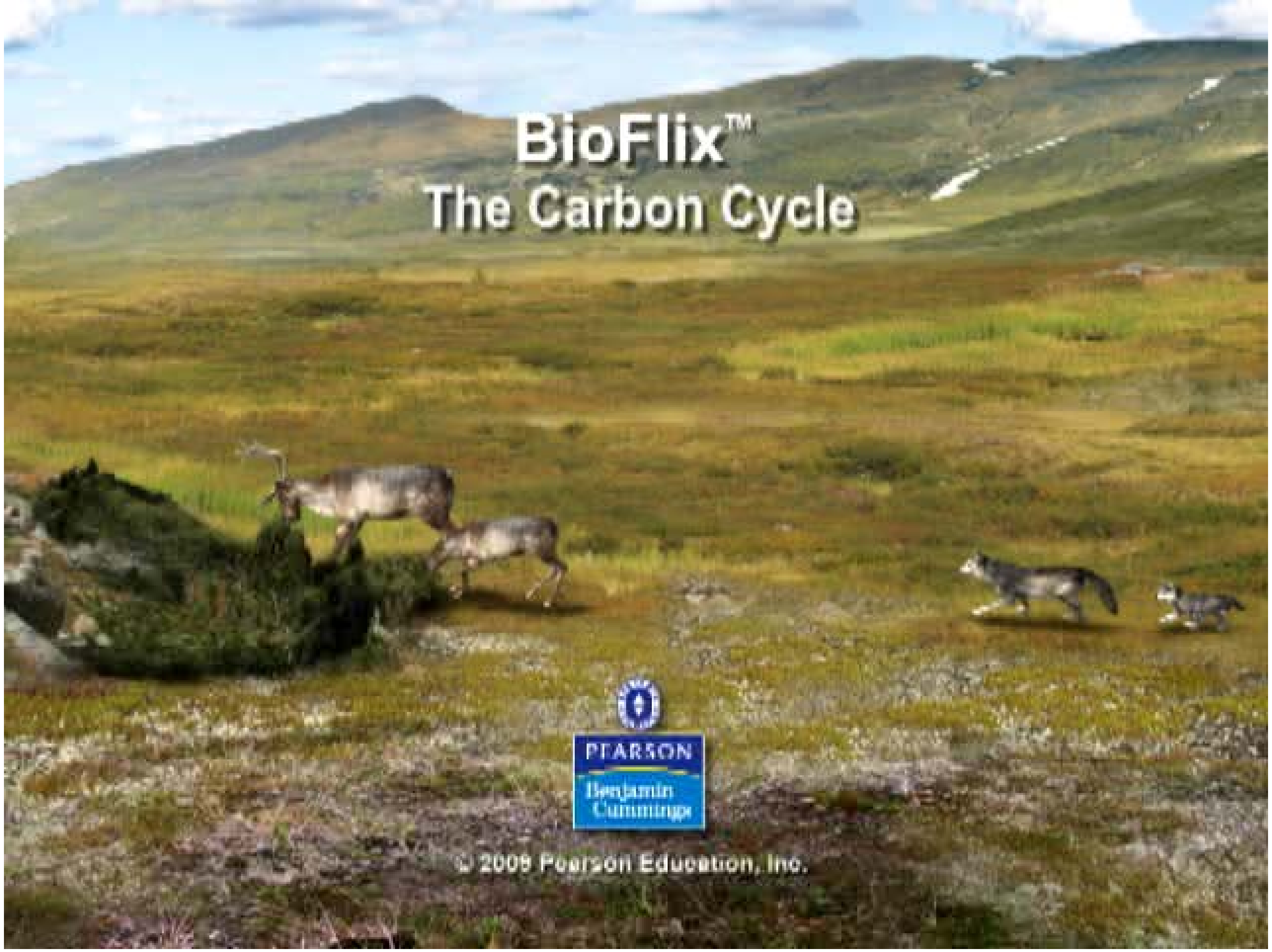
Light
H_2O
CO_2
$NADP^+$
ADP
+
Ⓟ i
LIGHT
REACTIONS
CALVIN
CYCLE
ATP
NADPH
Thylakoid
Stroma
Chloroplast
O_2

Figure 11.6-4

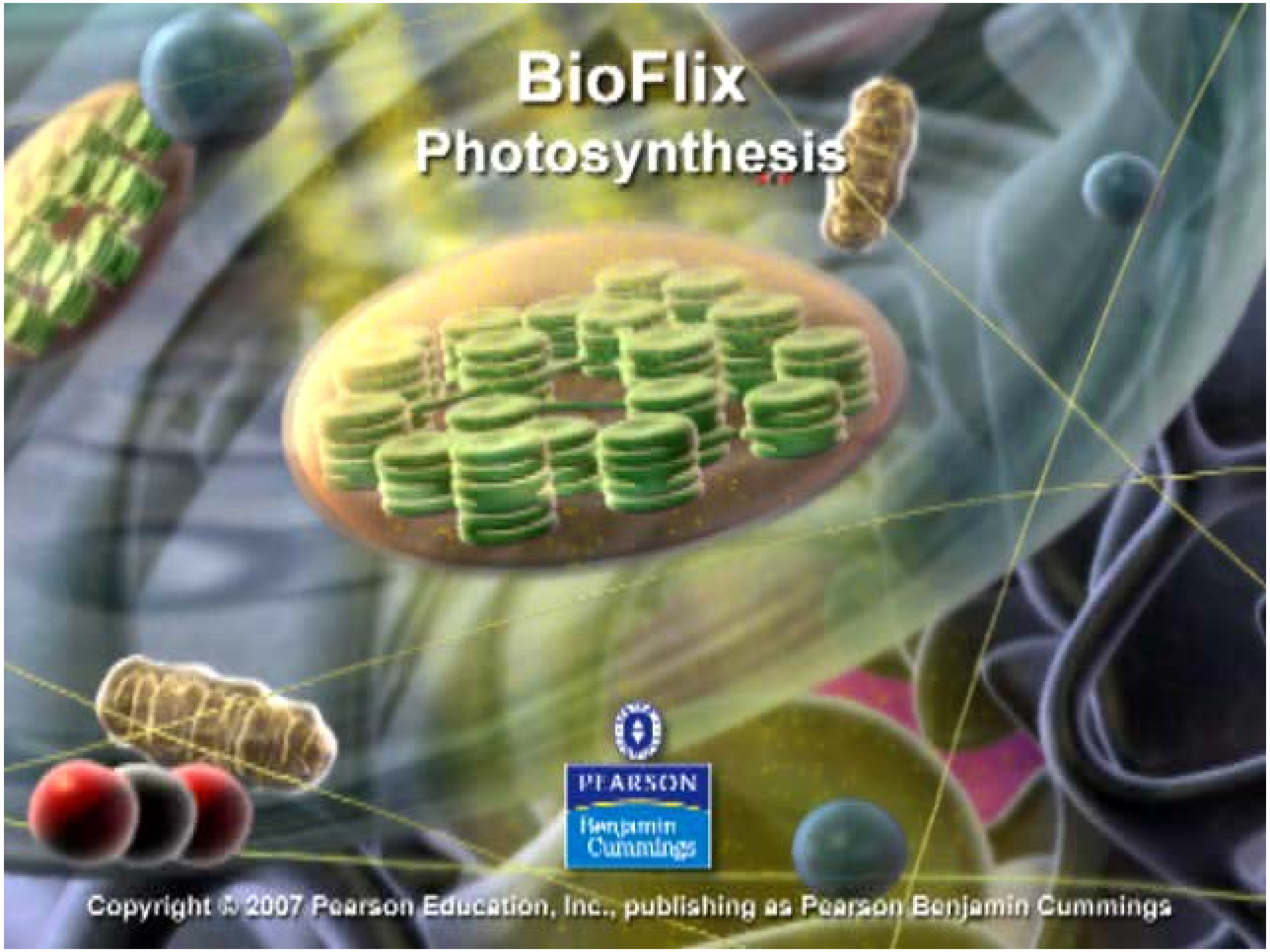


Light
H_2O
CO_2
$NADP^+$
ADP
+
P_i
LIGHT REACTIONS
CALVIN CYCLE
ATP
NADPH
Thylakoid
Stroma
Chloroplast
O_2
$[CH_2O]$ (sugar)

BioFlix: The Carbon Cycle

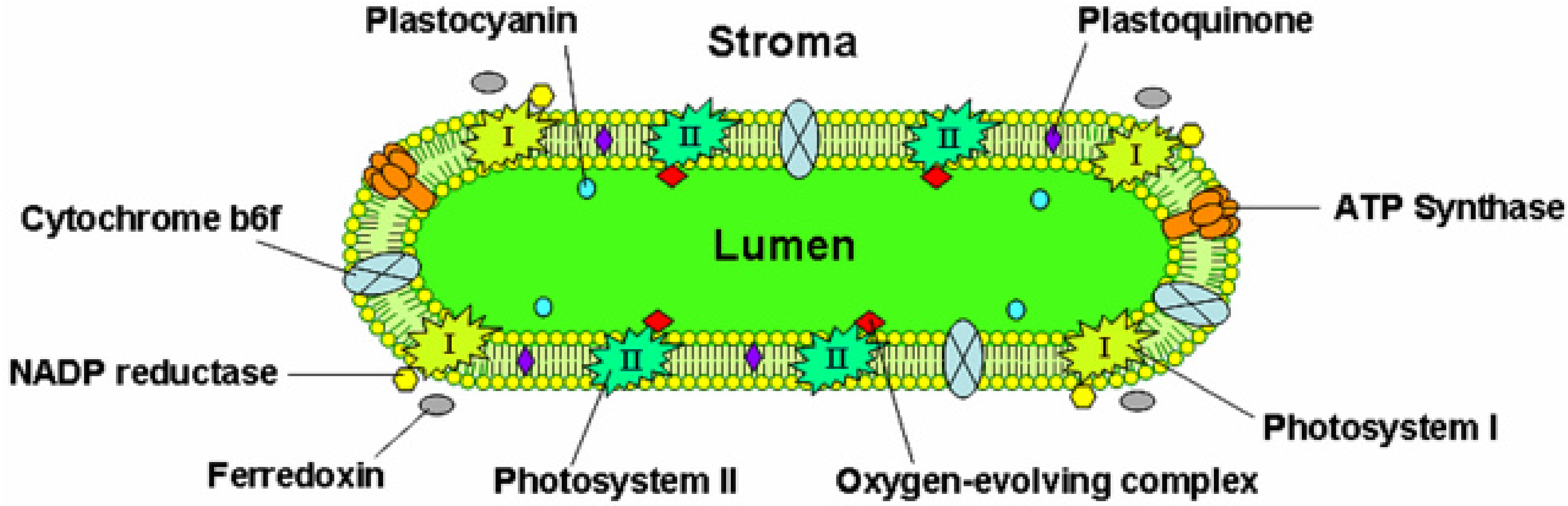


BioFlix: Photosynthesis



Concept 11.2: 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

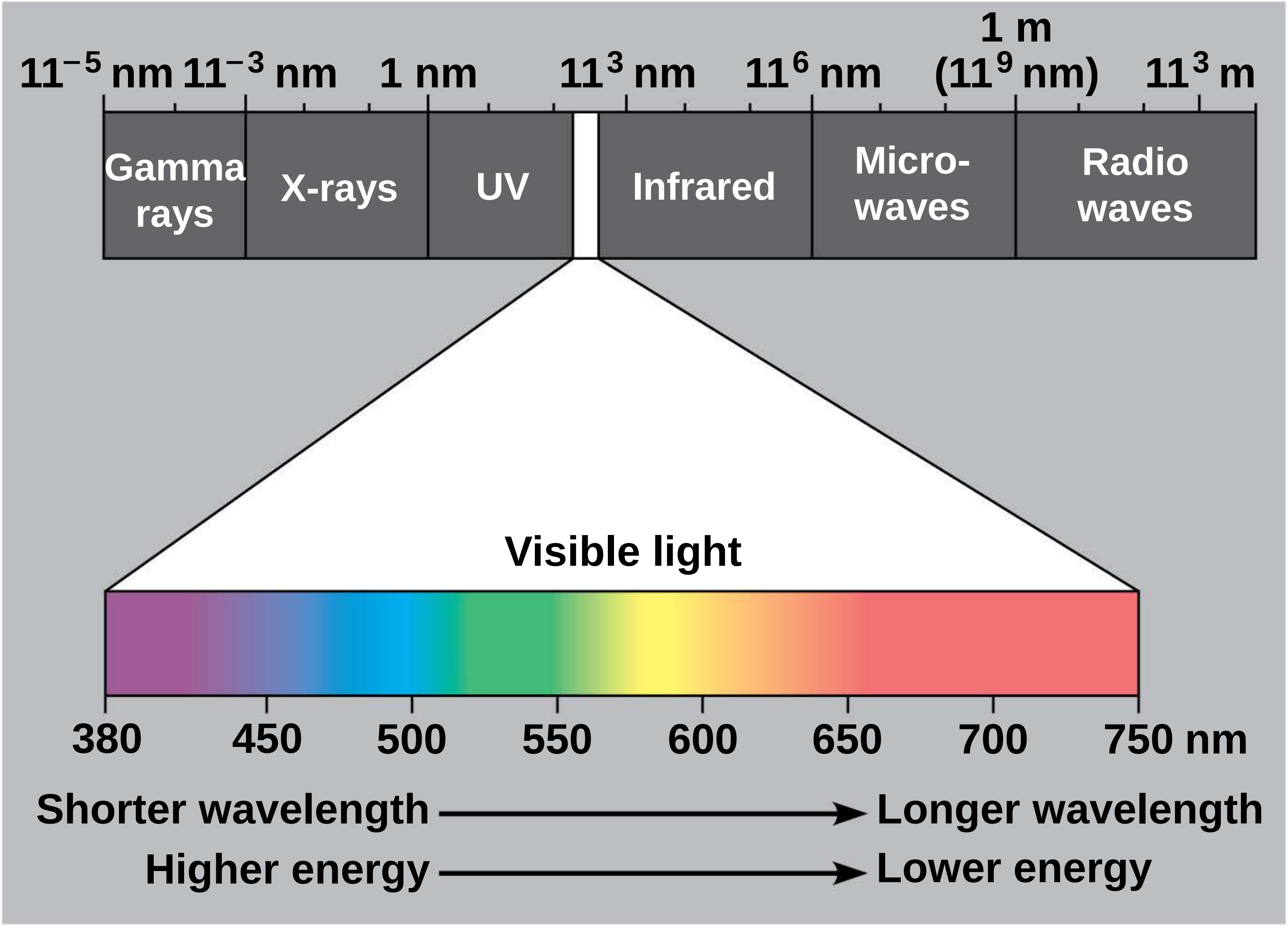


The Nature of Sunlight

- 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 11.7



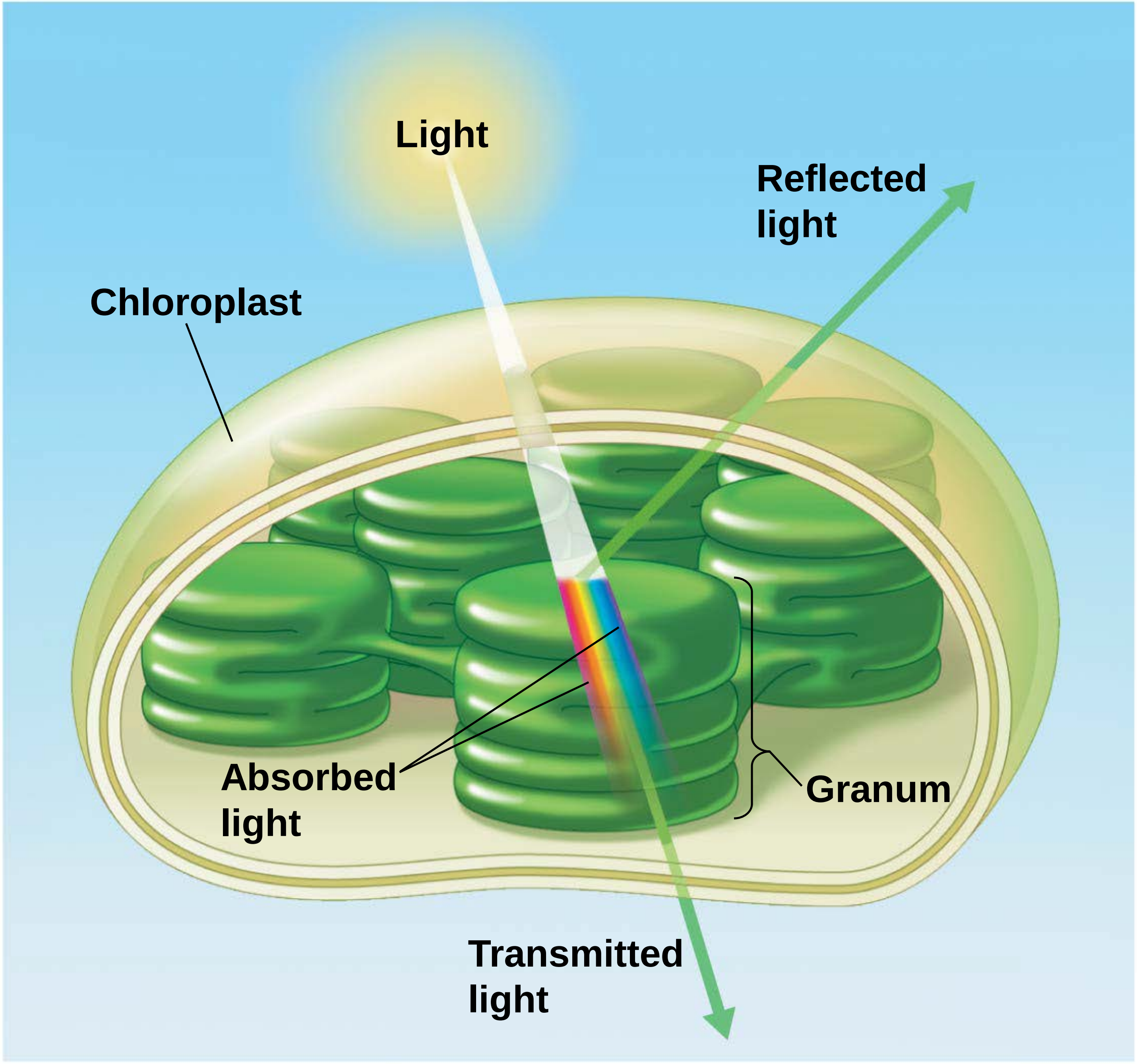
11^{-5} nm
11^{-3} nm
1 nm
11^{3} nm
11^{6} nm
1 m
(11^{9} nm)
11^{3} m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Longer wavelength
Higher energy
Lower energy

Photosynthetic Pigments: The Light Receptors

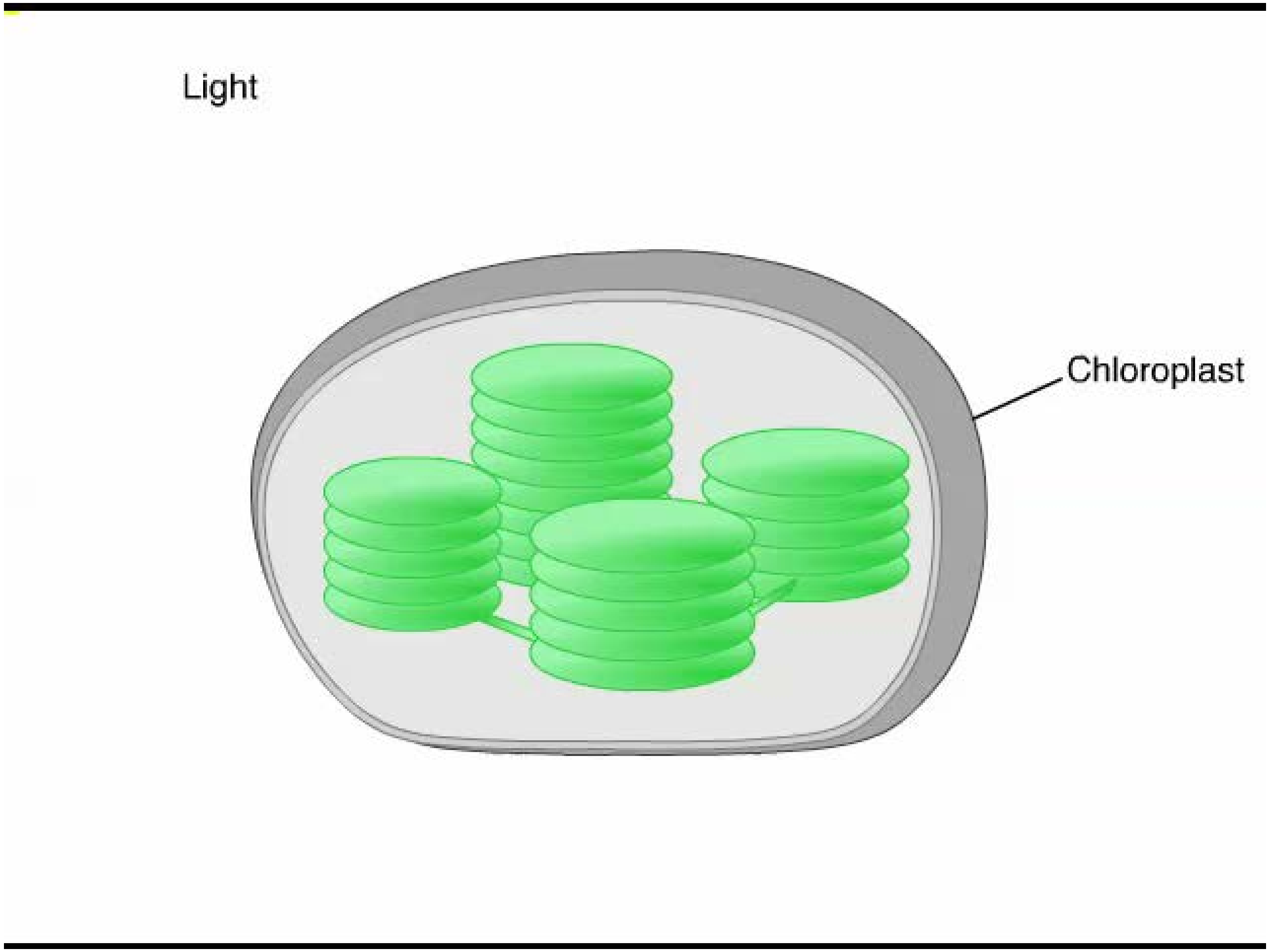
色素

- 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

Figure 11.8


Light
Reflected light
Chloroplast
Absorbed light
Granum
Transmitted light

Animation: Light and Pigments



- 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

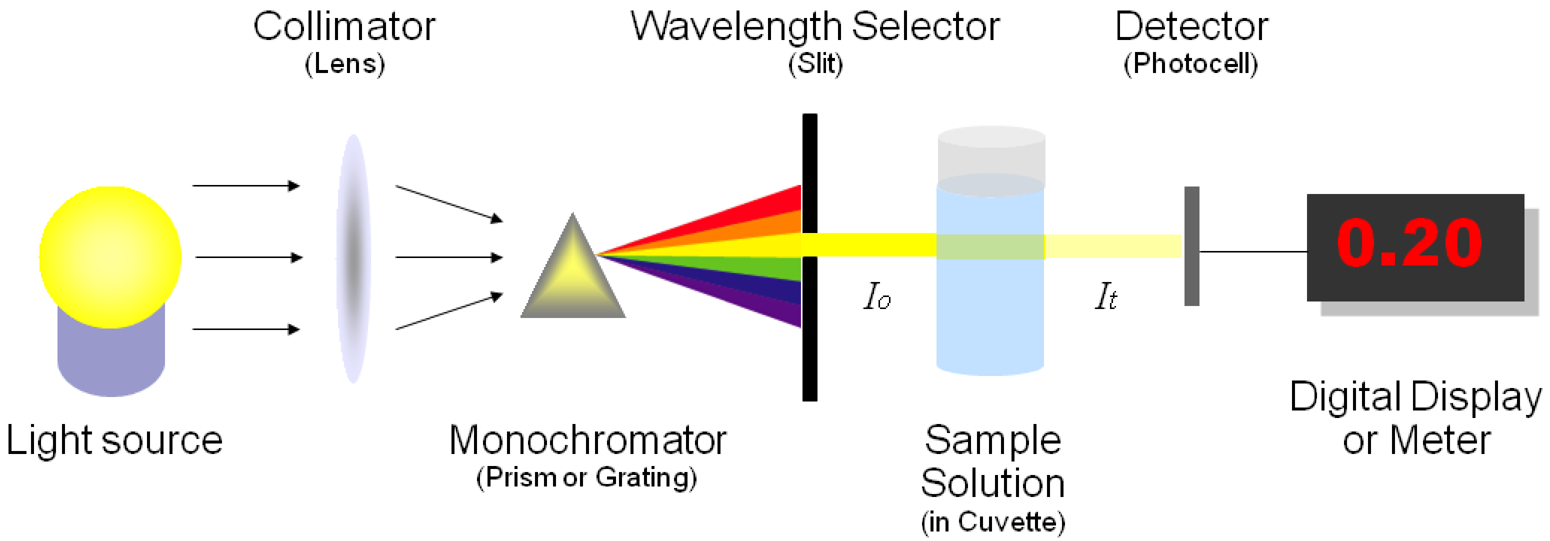


Figure 11.9

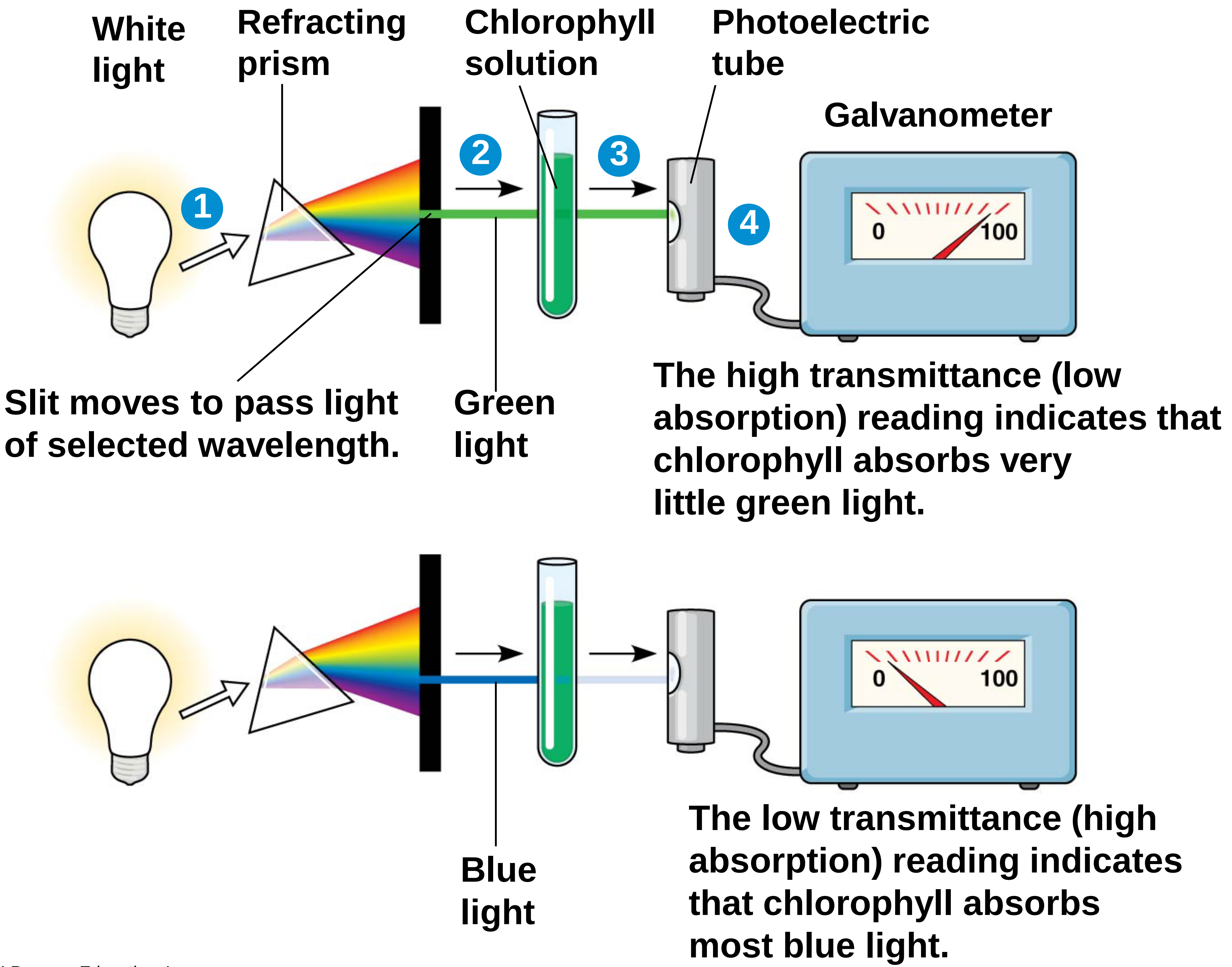
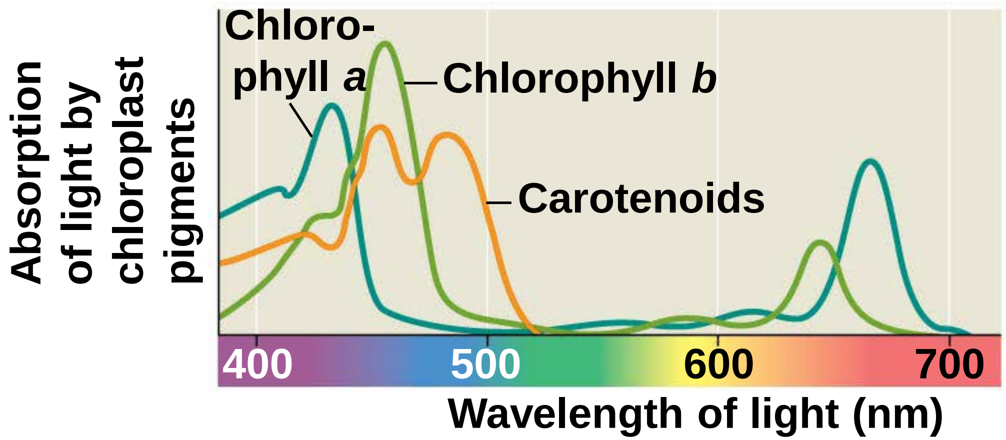
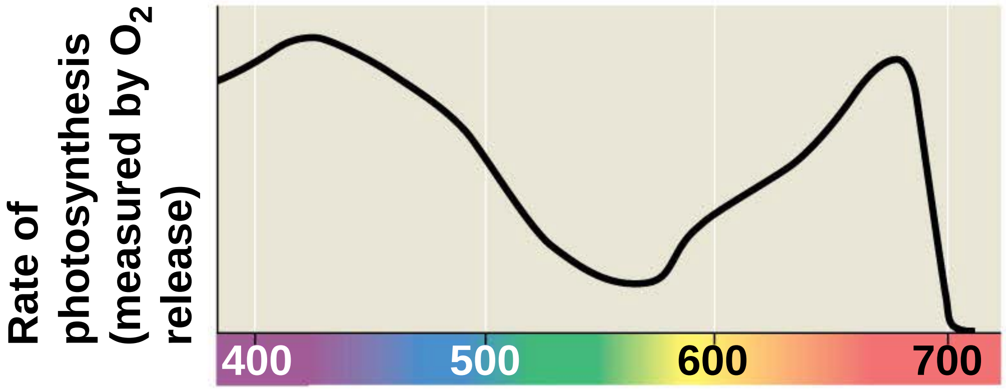

White light
Refracting prism
Chlorophyll solution
Photoelectric tube
Galvanometer
1
2
3
4
0
100
Slit moves to pass light of selected wavelength.
Green light
The high transmittance (low absorption) reading indicates that chlorophyll absorbs very little green light.
0
100
Blue light
The low transmittance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

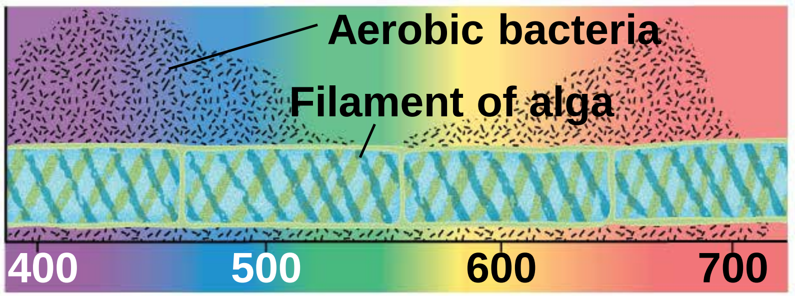
Figure 11.10



(a) Absorption spectra



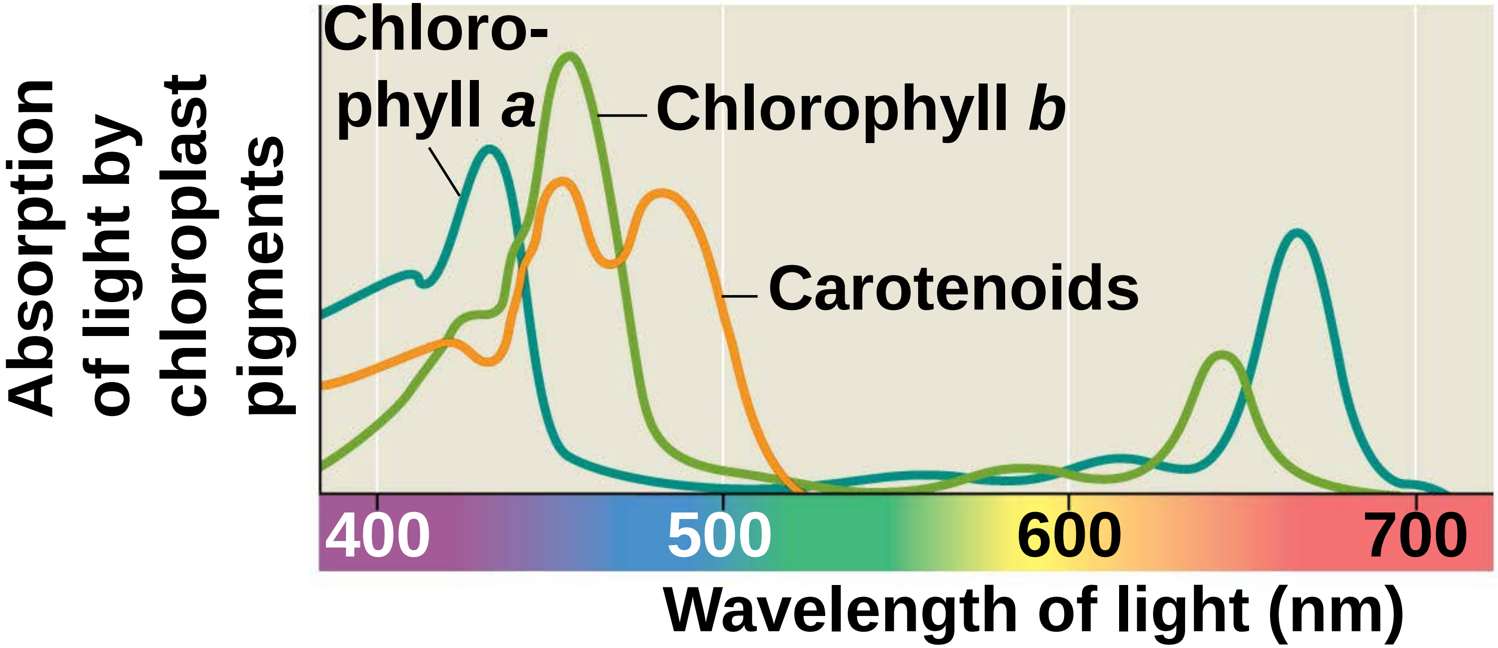
(b) Action spectrum



(c) Engelmann's experiment

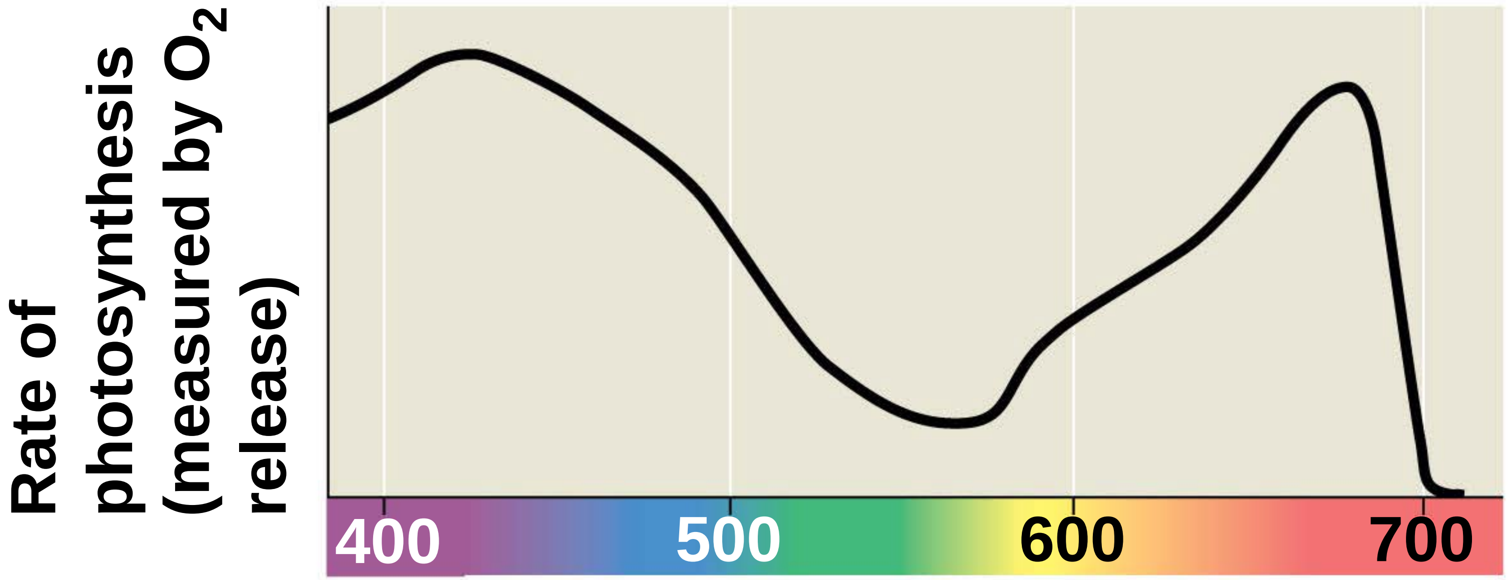
- An **absorption spectrum** is a graph plotting a pigment's light absorption versus wavelength
- The absorption spectrum of ***chlorophyll a*** suggests that violet-blue and red light work best for photosynthesis
- An **action spectrum** profiles the relative effectiveness of different wavelengths of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

Figure 11.10a



(a) Absorption spectra

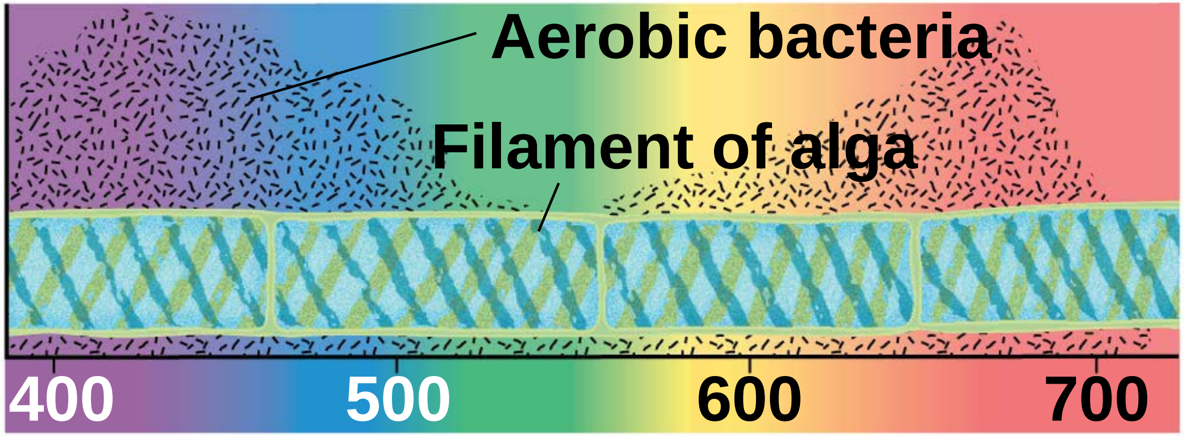
Figure 11.10b



(b) Action spectrum

- 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

oxygen seeking bacteria *B. termo*



(c) Engelmann's experiment

Why so many chlorophyll pigments?

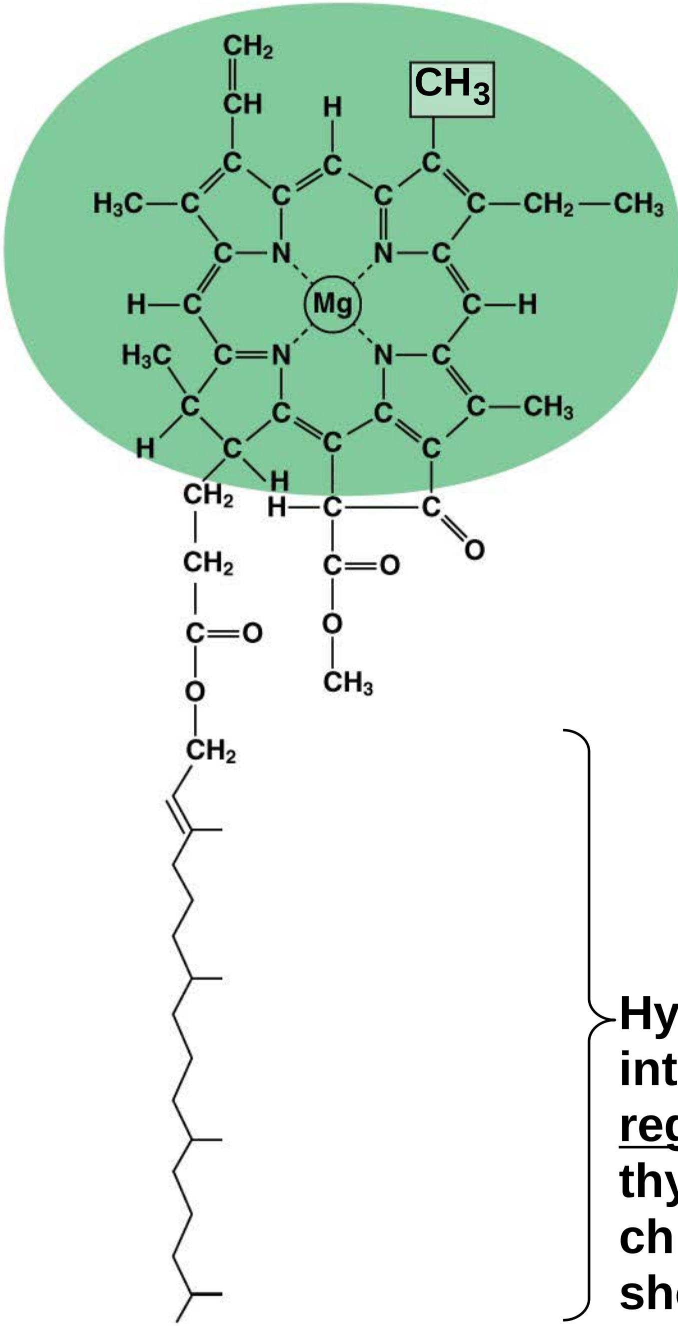
In response to different wavelength in the environment!

1. shading
2. under forest

Chl *b*/Chl *a* increases (Chl *b* content increases)

- **Chlorophyll *a*** is the **main photosynthetic pigment**
- **Chlorophyll *b***, broaden the spectrum used for photosynthesis
- The difference in the absorption spectrum between chlorophyll *a* and *b* is due to a slight structural difference between the pigment molecules
- **Accessory pigments** called **carotenoids** absorb excessive light that would damage chlorophyll

Figure 11.11

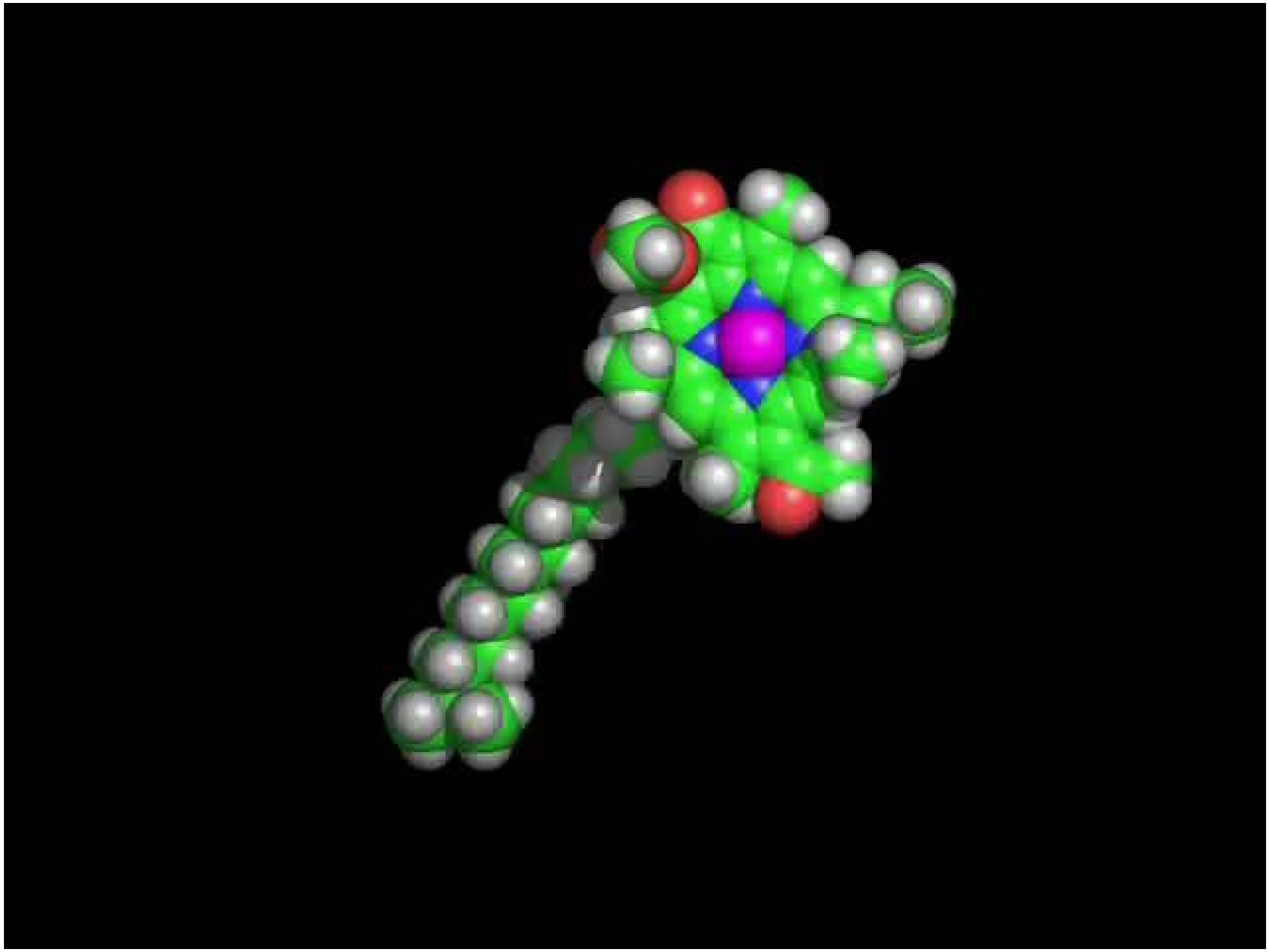


CH_3 in chlorophyll *a*
CHO in chlorophyll *b*

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

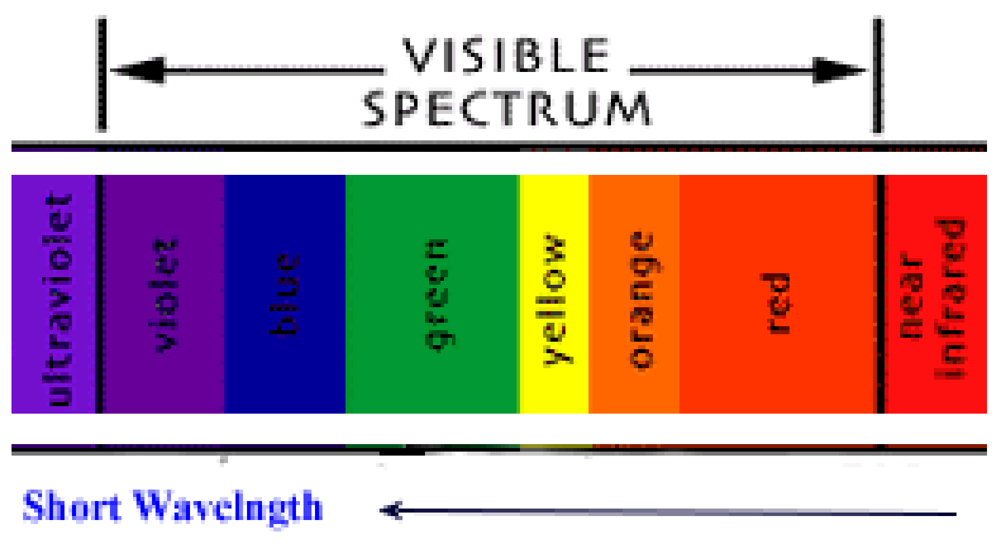
Hydrocarbon tail: interacts with hydrophobic regions of proteins inside thylakoid membranes of chloroplasts; H atoms not shown

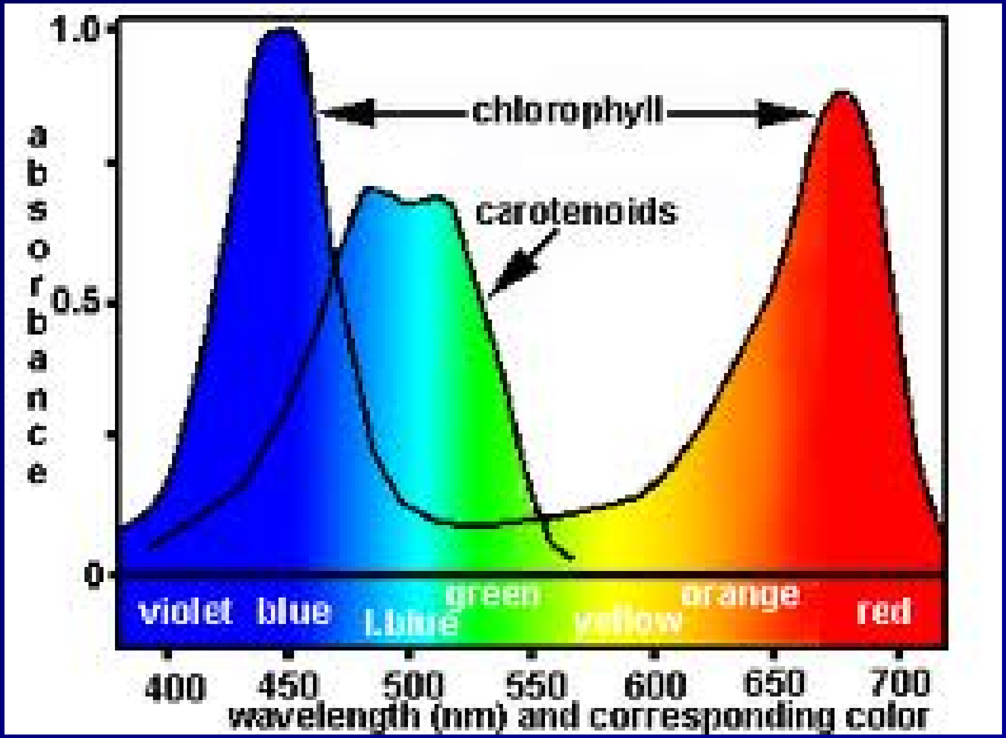
Video: Space-Filling Model of Chlorophyll *a*



- Accessory pigments called **carotenoids** function in photoprotection; they absorb excessive light that would damage chlorophyll

Sun Radiation

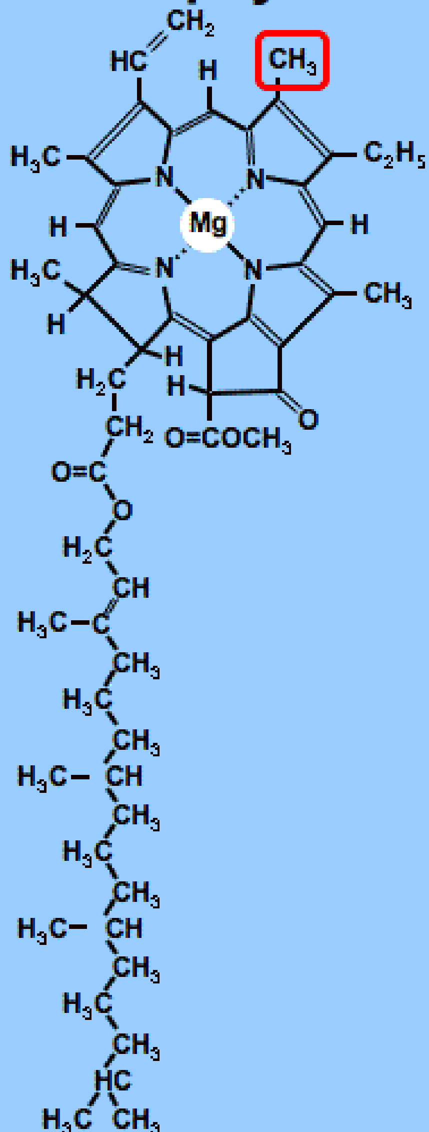




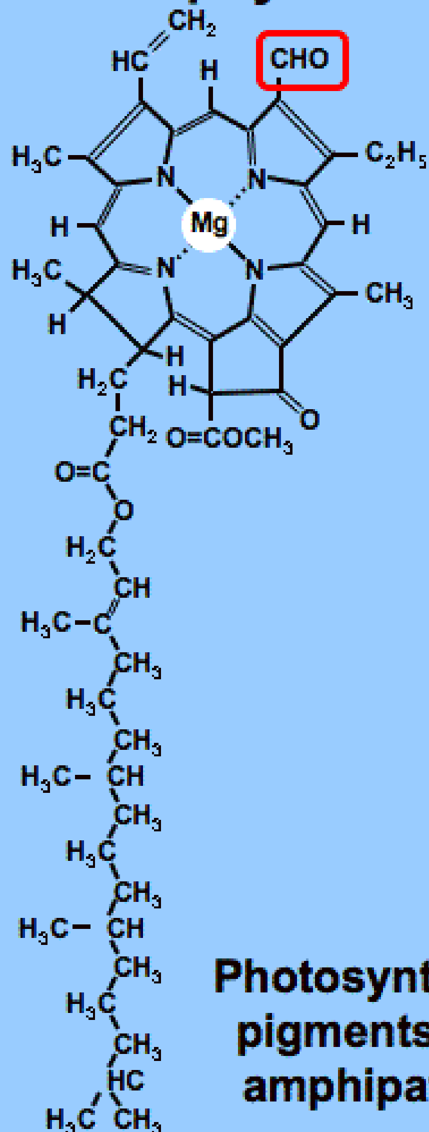
Chlorophyll is the main photosynthetic pigment

Photosynthetically active radiation, often abbreviated **PAR**, designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.

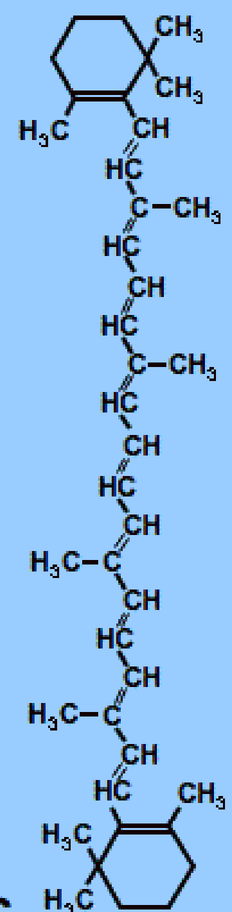
Chlorophyll a



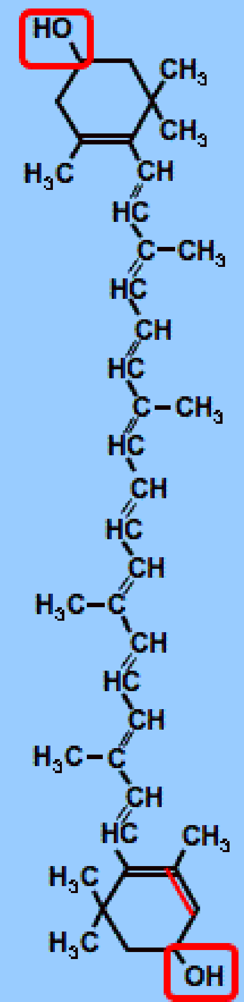
Chlorophyll b



ß-Carotene



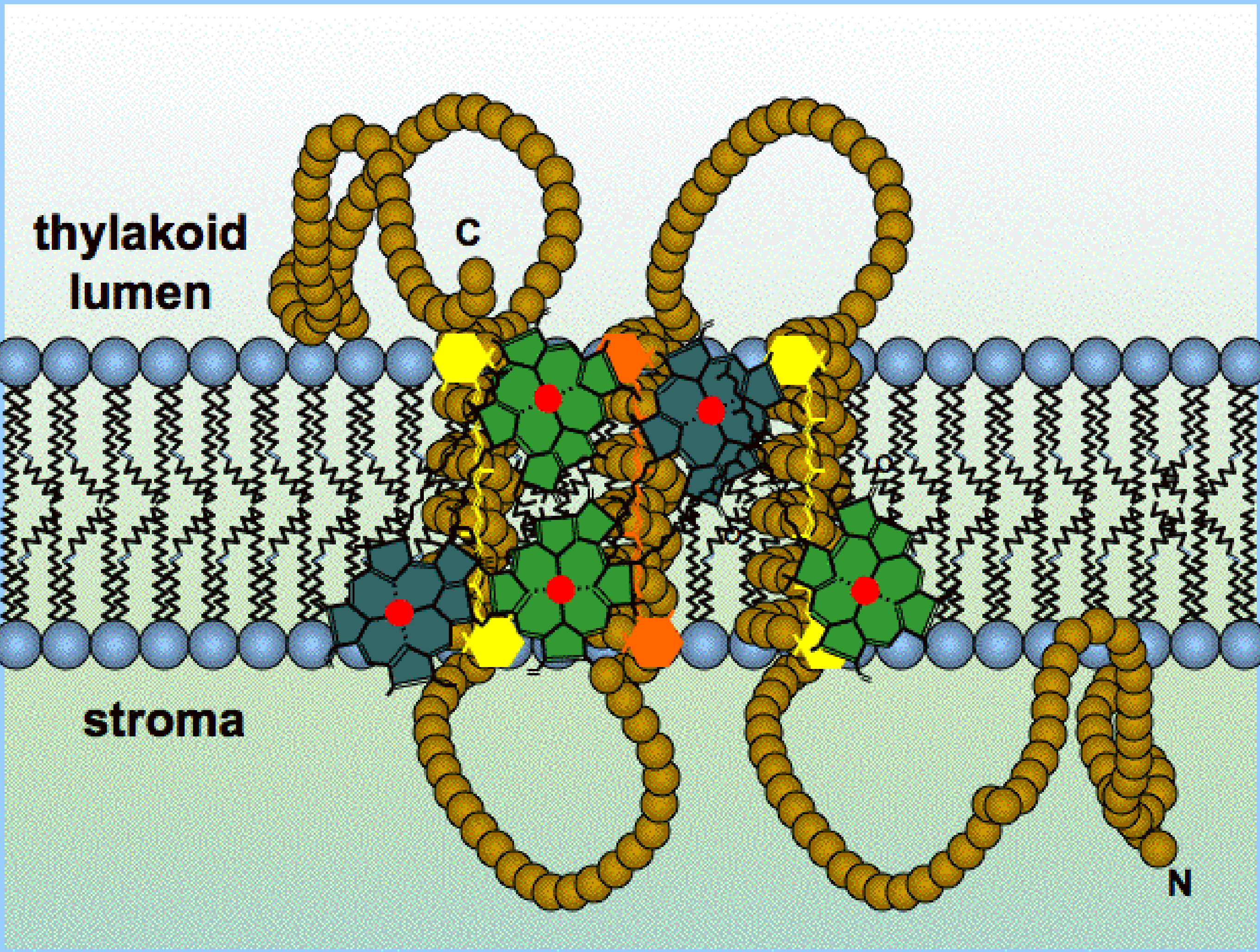
Zeaxanthin



Lutein

Photosynthetic pigments are amphipathic

Photosynthetic pigments are associated with membrane proteins



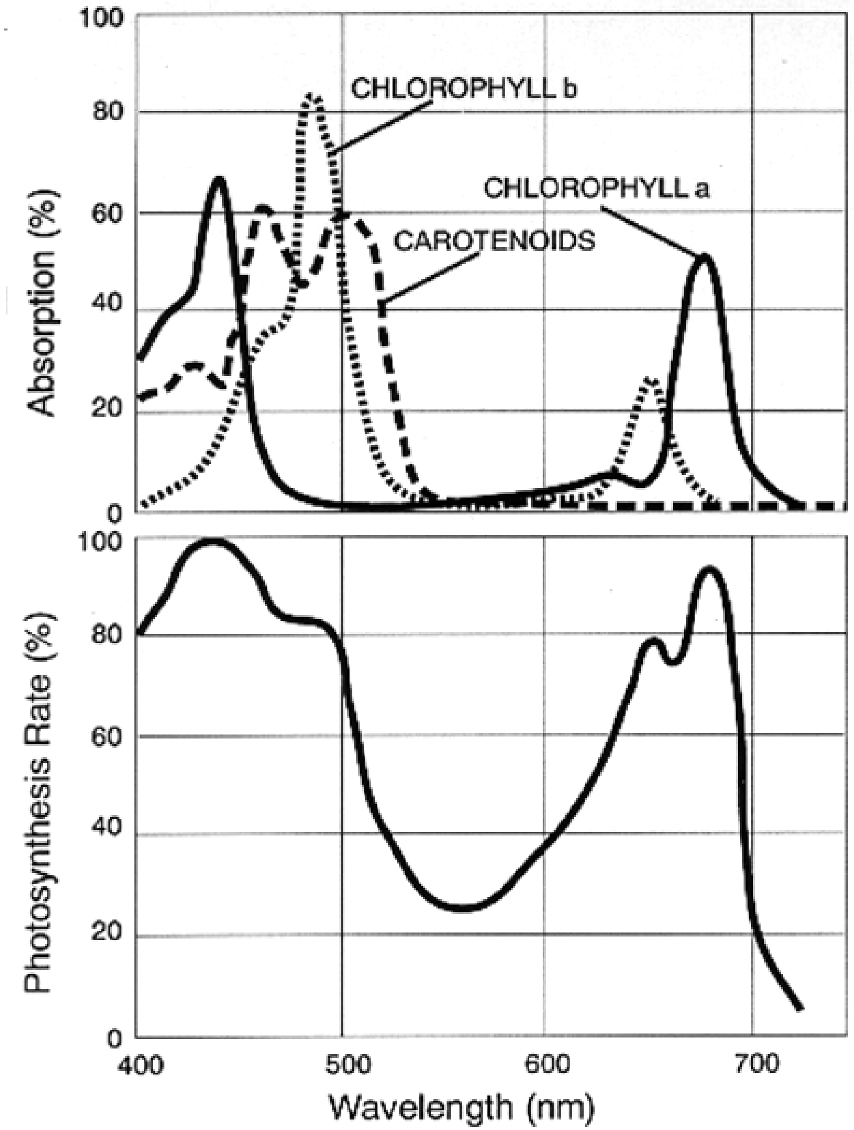
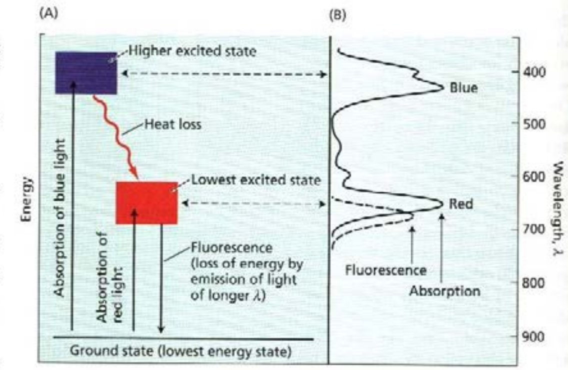
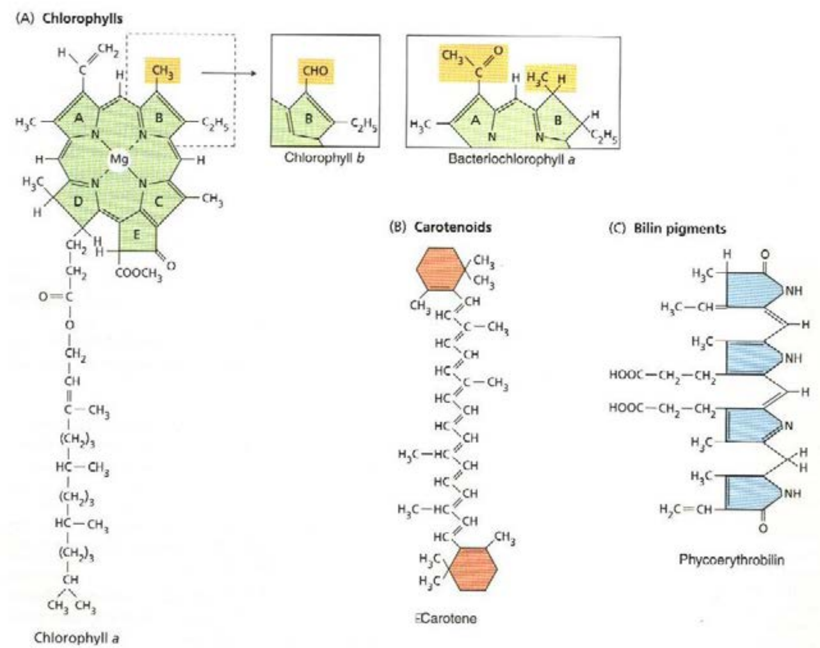


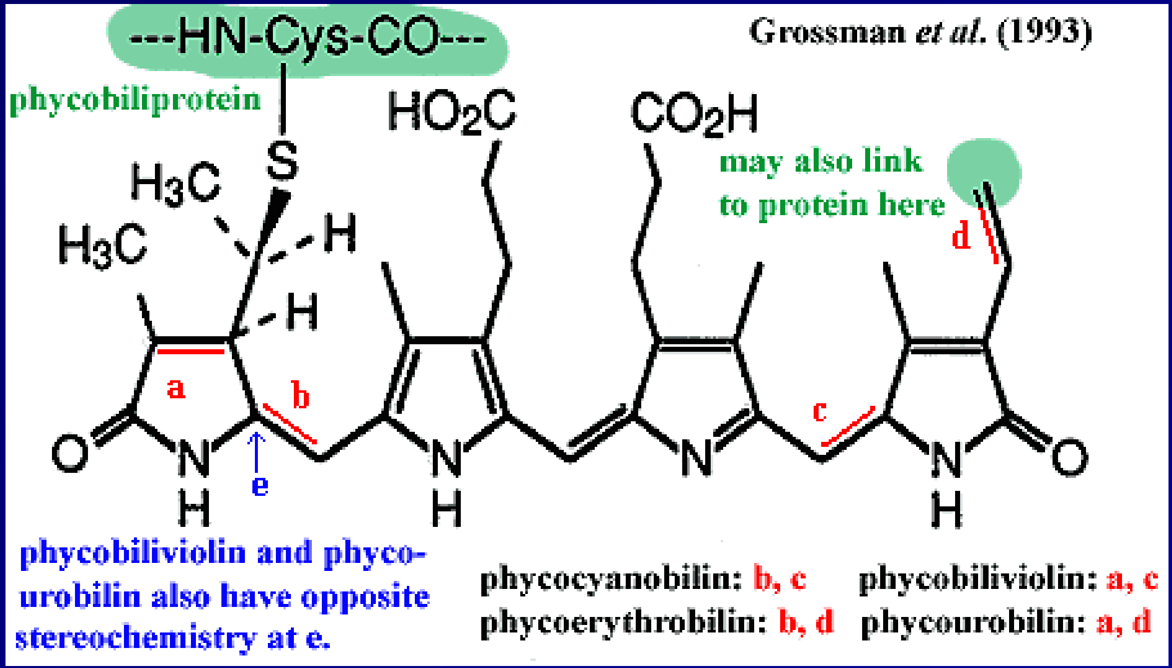
FIGURE 7.5 Light absorption and emission by chlorophyll. (A) Energy level diagram. Absorption or emission of light is indicated by vertical lines that connect the ground state with excited electron states. The blue and red absorption bands of chlorophyll (which absorb blue and red photons, respectively) correspond to the upward vertical arrows, signifying that energy absorbed from light causes the molecule to change from the ground state to an excited state. The downward-pointing arrow indicates fluorescence, in which the molecule goes from the lowest excited state to the ground state while re-emitting energy as a photon. (B) Spectra of absorption and fluorescence. The long-wavelength (red) absorption band of chlorophyll corresponds to light that has the energy required to cause the transition from the ground state to the first excited state. The short-wavelength (blue) absorption band corresponds to a transition to a higher excited state.

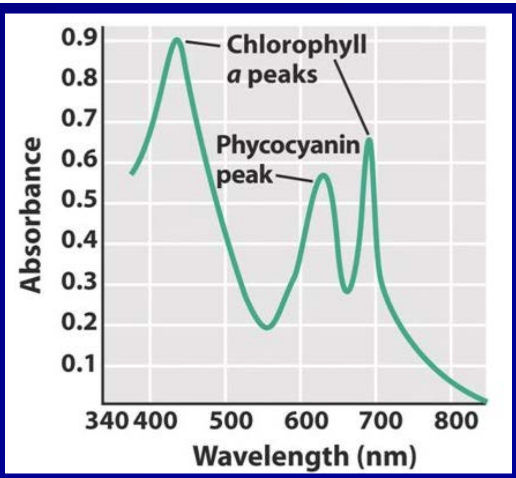




Phycobiliprotein: 藻膽蛋白

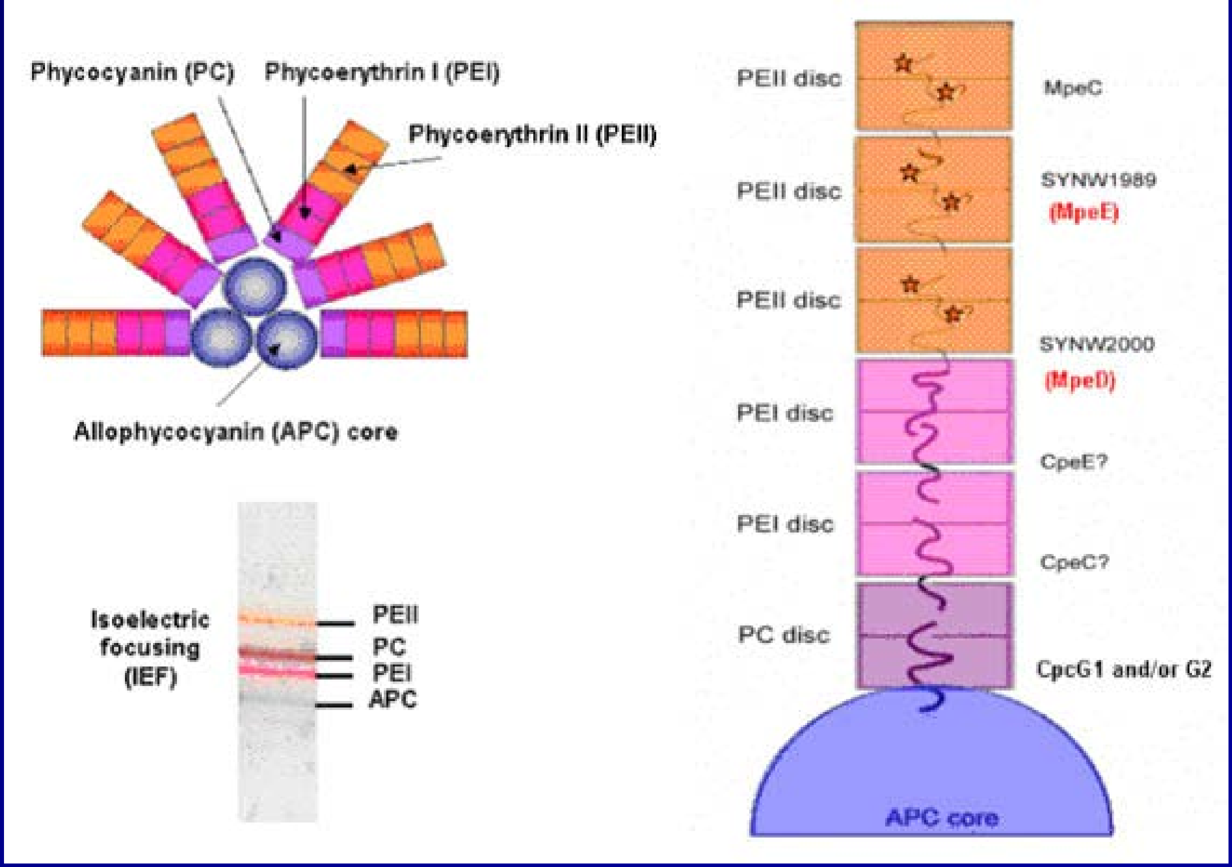
- 藍綠藻
- 紅藻
- 藻紅素 Phycoerthyrin
- 藻藍素 Phycocyanin
- 異藻藍素 Allophycocyanin

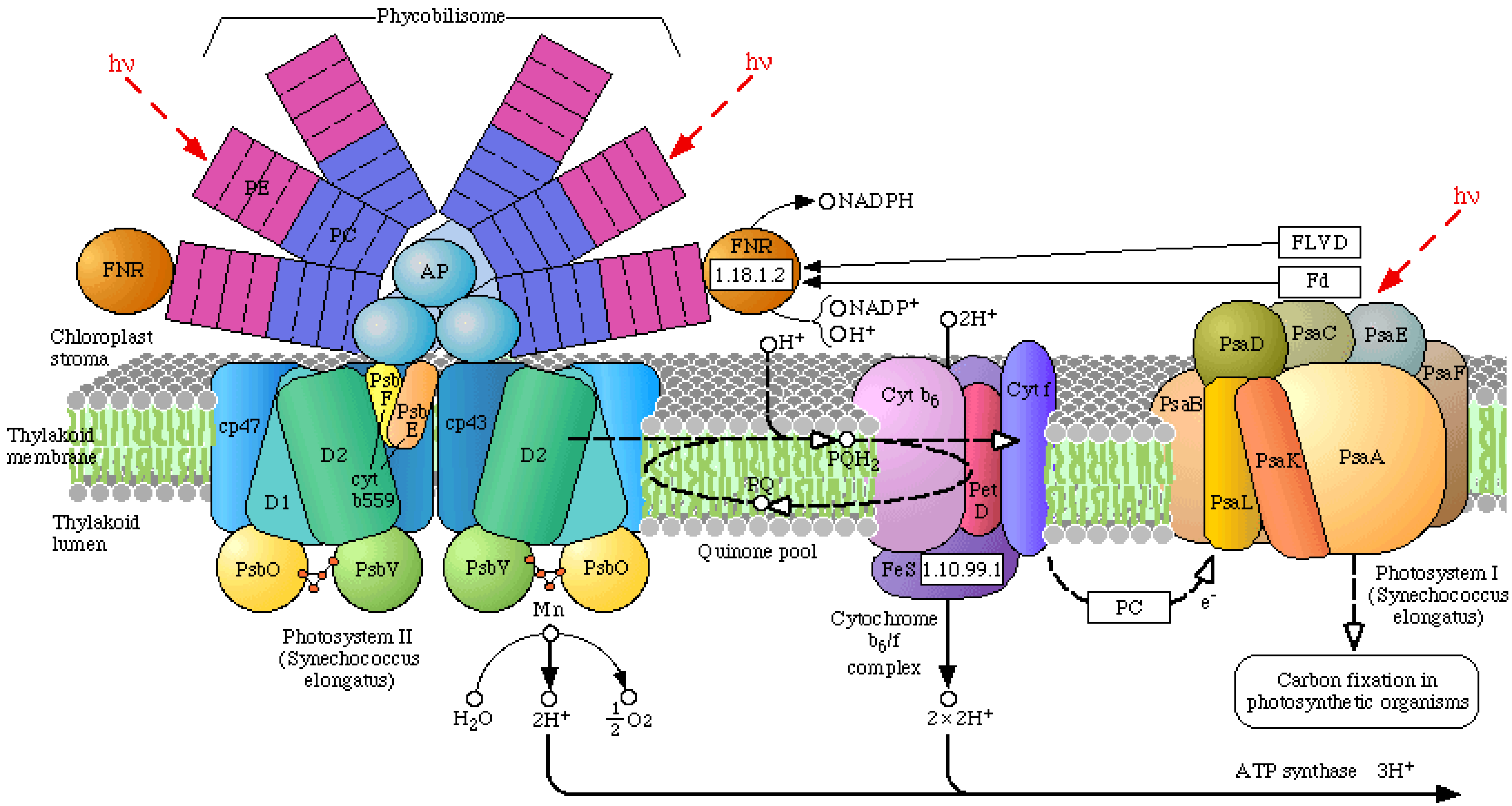


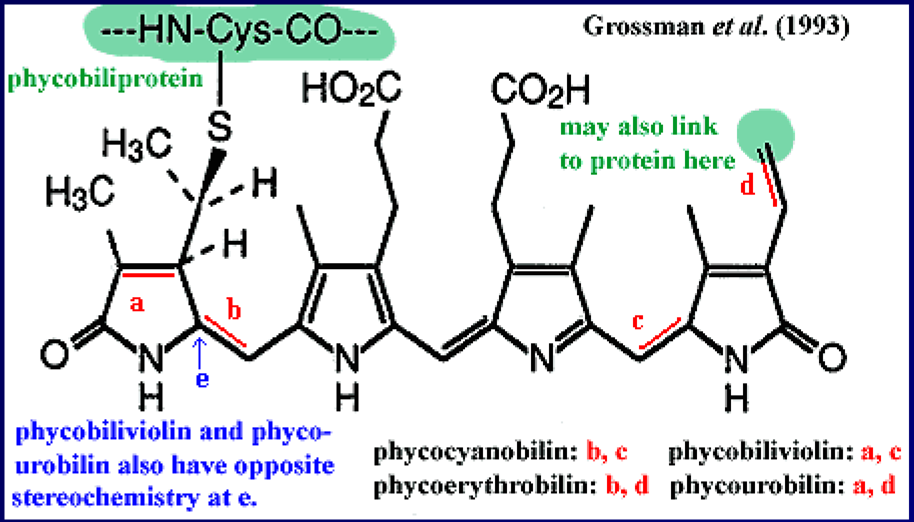


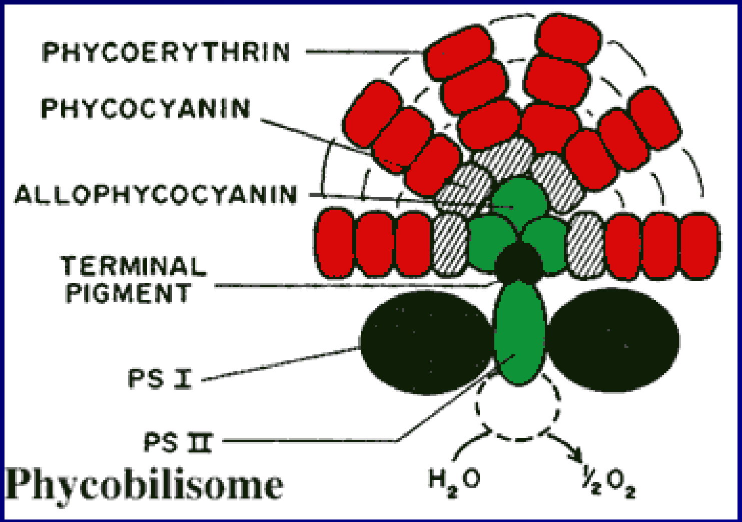
Phycobilisome藻膽蛋白體 in cyanobacteria

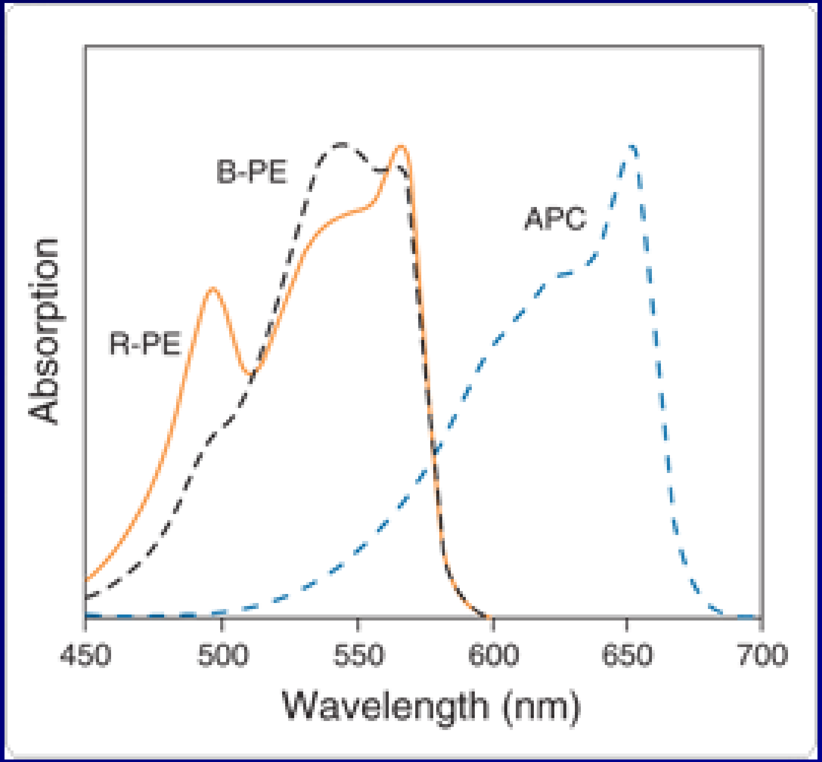
These antennae (called "**phycobilisomes**" in ***Synechococcus***) are composed of pigment-proteins complexes arranged in such a way to capture light with a high efficiency. Pigments that are bound to antenna systems may have very different colours (such as green, blue, pink or orange) and this will determine the wavelengths of the solar spectrum that cells can efficiently harvest in the oceanic waters.

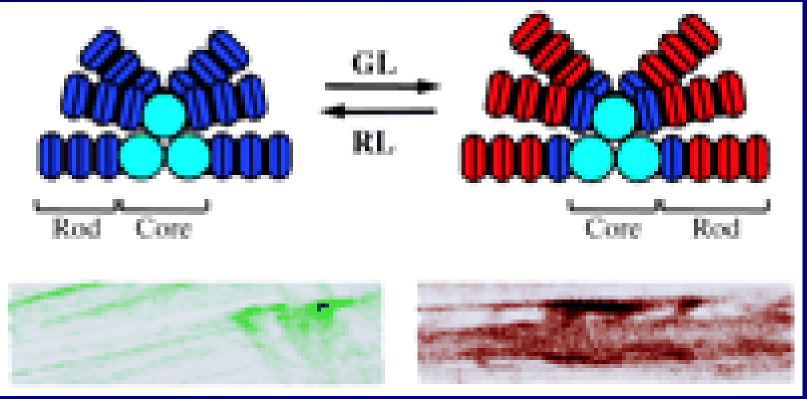



Phycobilisome
hν
hν
hν
PE
PC
AP
FNR
FNR
1.18.1.2
NADPH
NADP+
H+
FLVD
Fd
Chloroplast stroma
Thylakoid membrane
Thylakoid lumen
cp47
D1
D2
Psb F
Psb E
cyt b559
cp43
D2
PsbO
PsbV
PsbV
PsbO
Mn
H2O
2H+
1/2 O2
Photosystem II (Synechococcus elongatus)
H+
PQH2
PQ
Quinone pool
2H+
Cyt b6
Cyt f
Pet D
FeS
1.10.99.1
Cytochrome b6/f complex
2×2H+
PC
e-
PsaD
PsaC
PsaE
PsaF
PsaB
PsaL
PsaK
PsaA
Photosystem I (Synechococcus elongatus)
Carbon fixation in photosynthetic organisms
ATP synthase 3H+





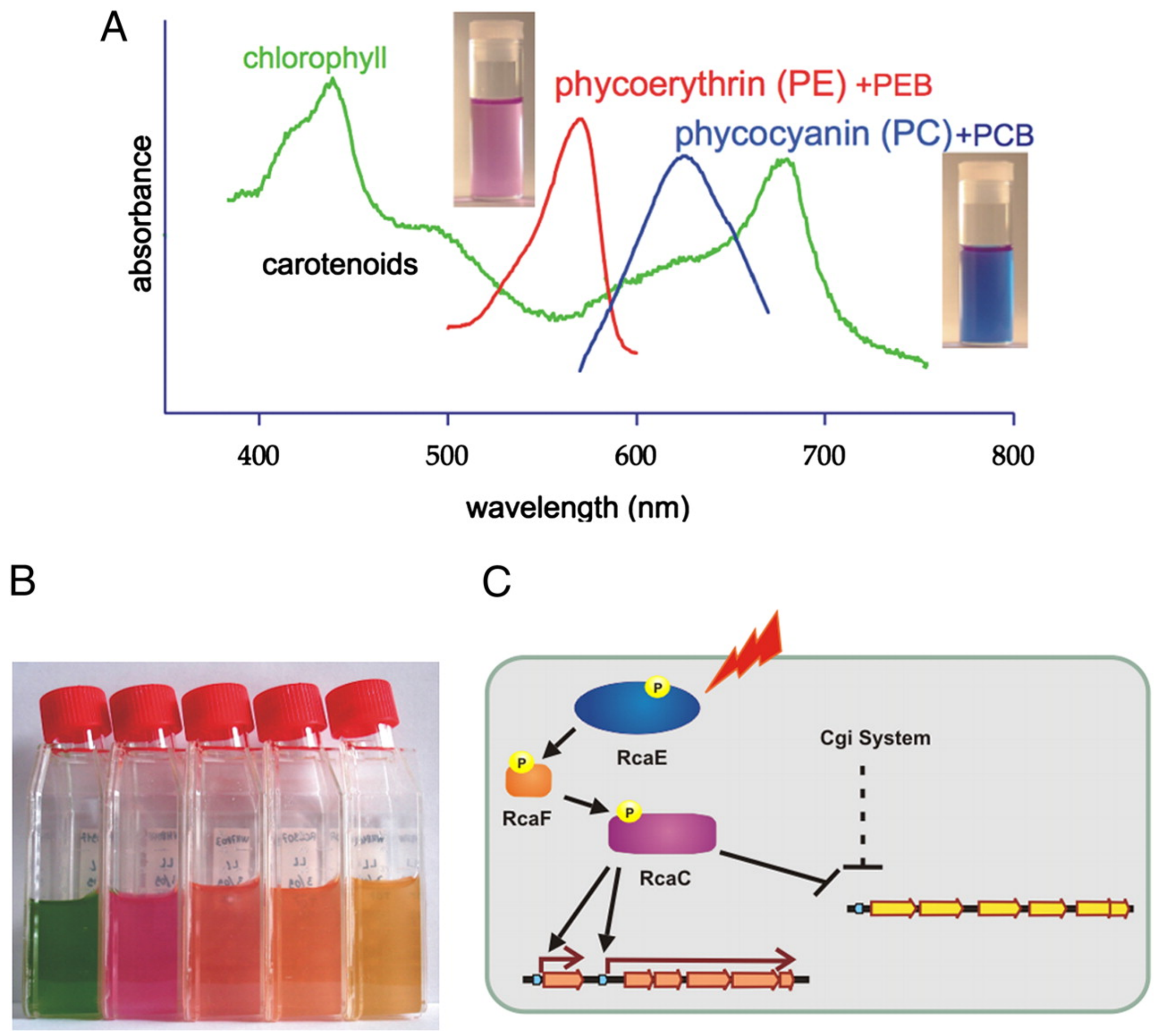




complementary chromatic adaptation (CCA)

The Journal of Biological Chemistry, 276, 11449-11452 (2001)

Phycobiliproteins, bilin variation, and group III CA regulation.



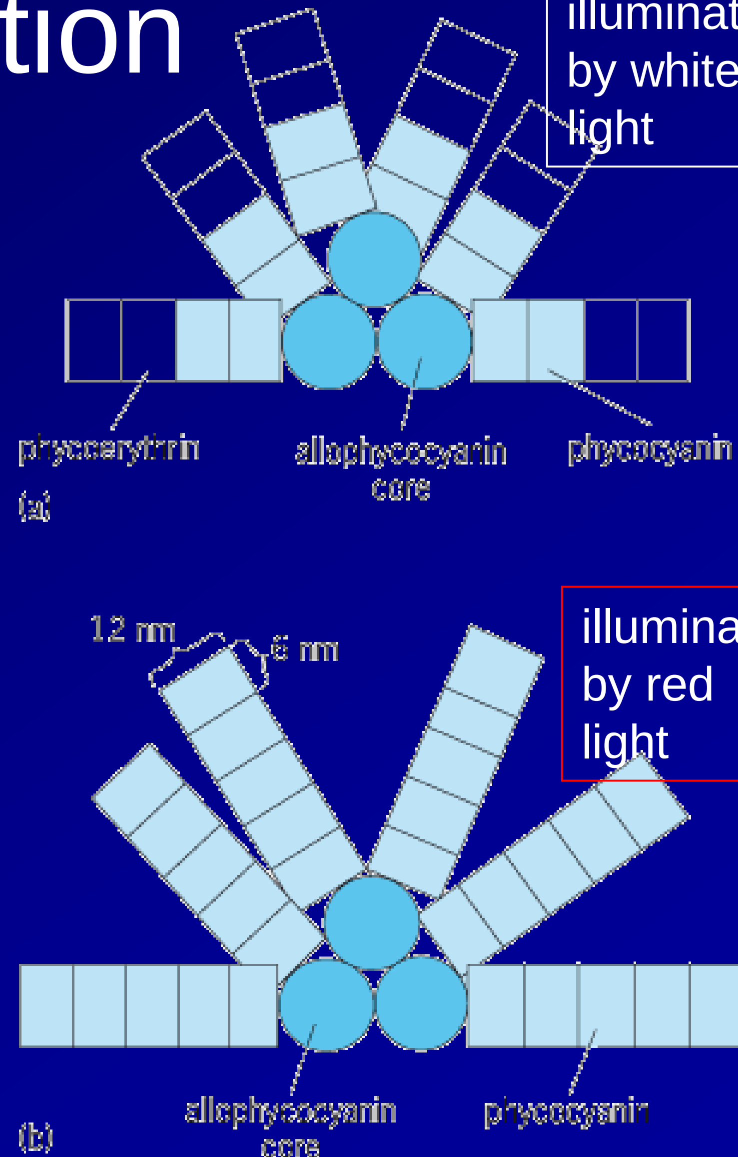
Kehoe D M PNAS 2010;107:9029-9030

PNAS

complementary chromatic adaptation

Structure of a hemidiscoidal phycobilisome of *Tolypothrix tenuis* under different light conditions. (*a*) When illuminated by white light, the phycobilisome contains phycoerythrin, phycocyanin, and allophycocyanin. Energy absorbed by phycoerythrin is transferred to phycocyanin and allophycocyanin. The allophycocyanin core proteins are attached, via a linker protein, to the photosynthetic membrane, which is not shown. (*b*) When illuminated by red light, the phycobilisome undergoes complementary chromatic adaptation, in which phycoerythrin is no longer produced but additional phycocyanin is produced. (*After R. MacColl and D. Guard-Friar*, *Phycobiliproteins*, *CRC Press*, *Boca Raton*, *FL*, *1987*)

illuminated by white light

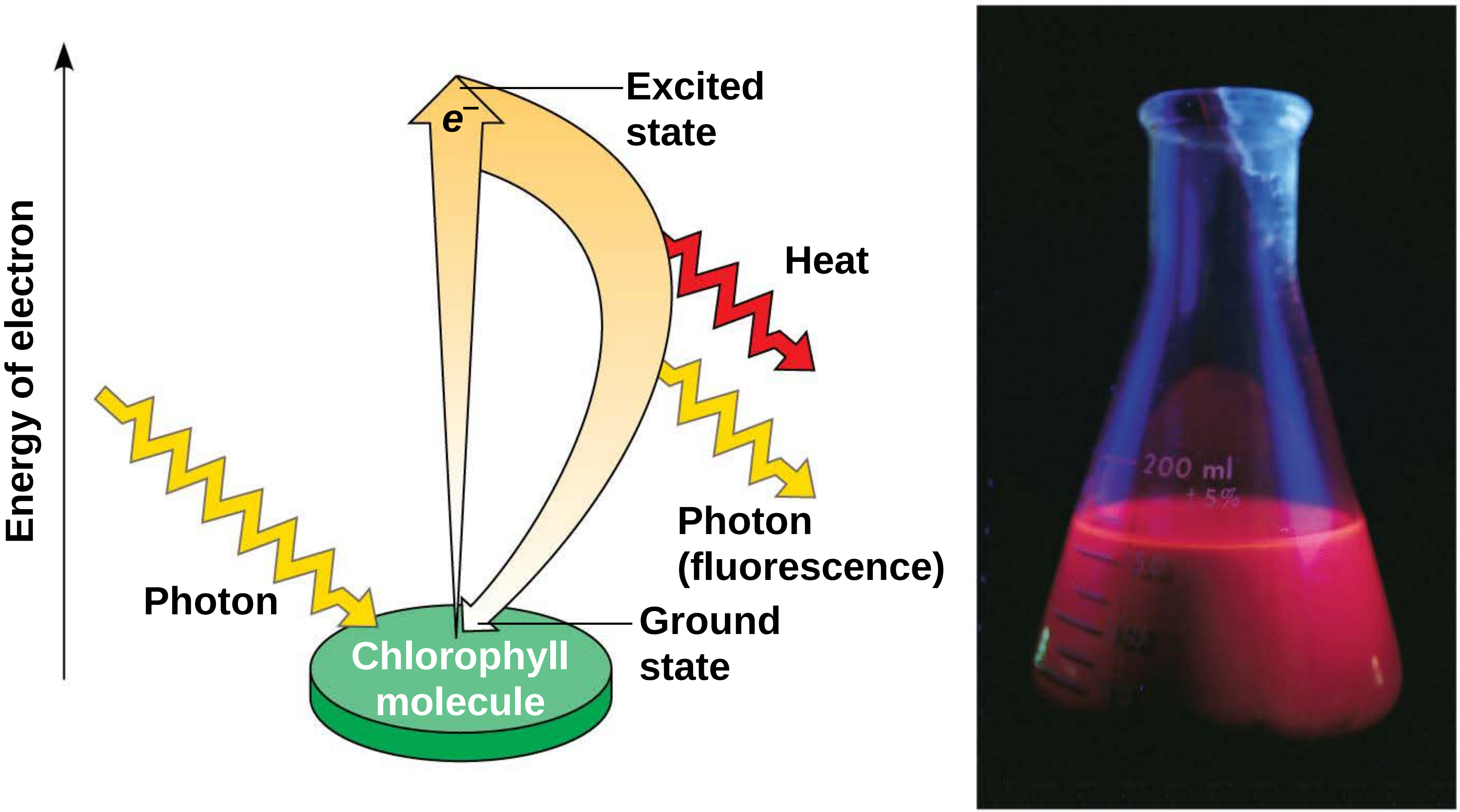


illuminated by red light

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 11.12



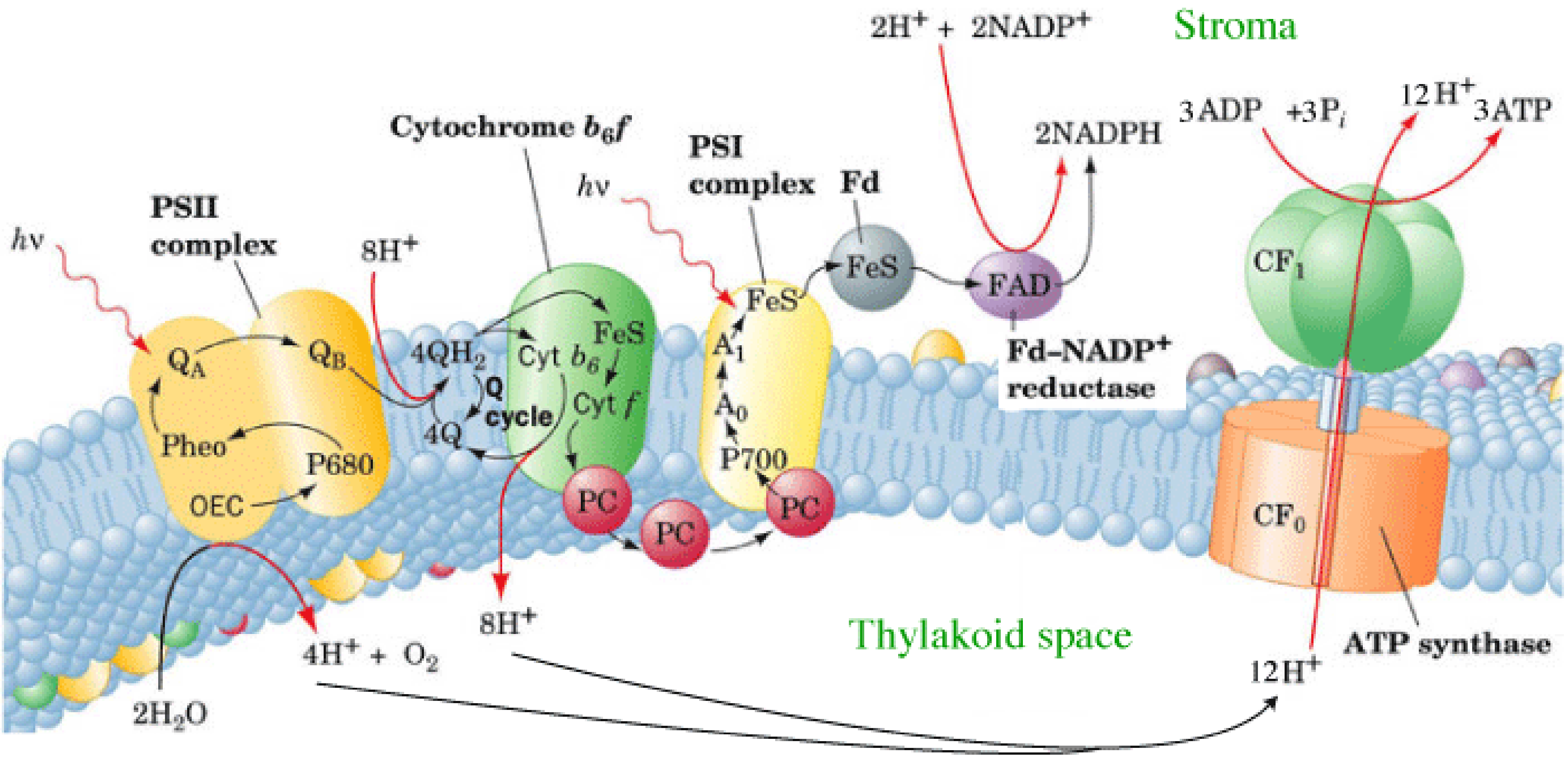
(a) Excitation of isolated chlorophyll molecule

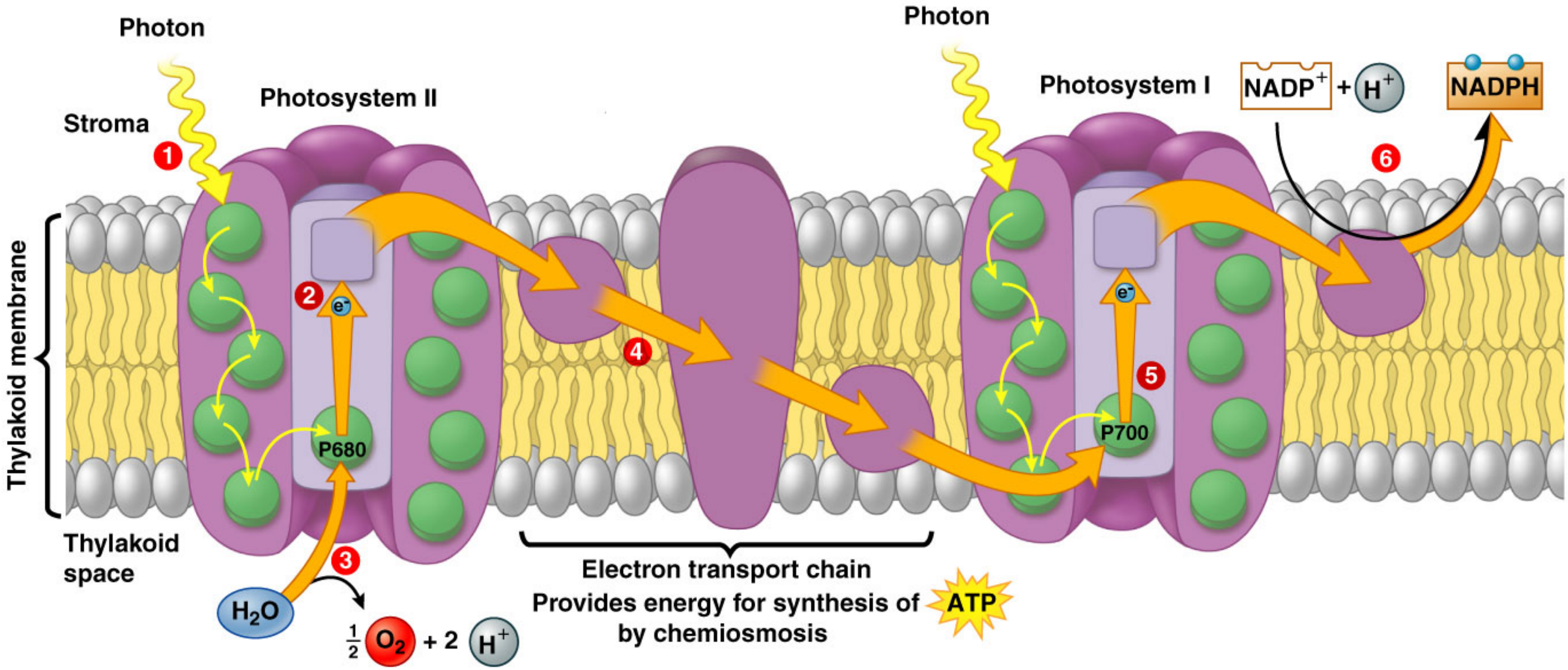
(b) Fluorescence

Figure 11.12a

(b) Fluorescence

Electron transport chain (ETC)



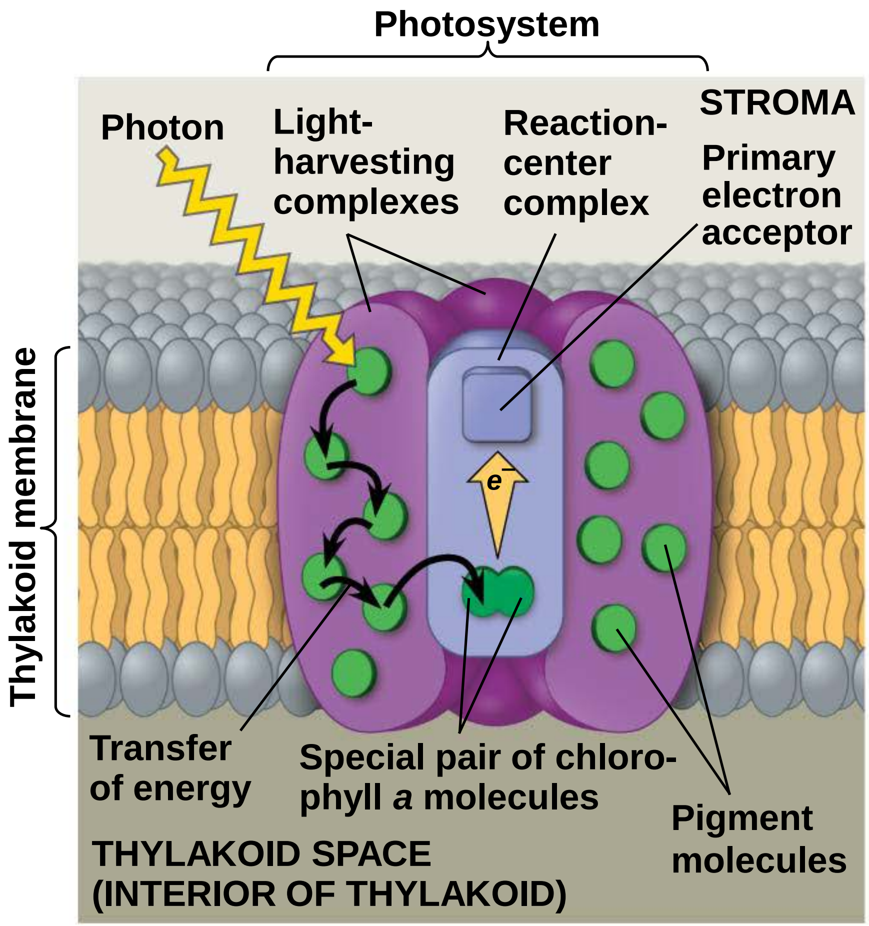


Photon
Photosystem II
Stroma
1
Thylakoid membrane
2
e⁻
P680
Thylakoid space
3
H_2O
$\frac{1}{2}$ O_2 + 2 H^+
4
Electron transport chain
Provides energy for synthesis of
ATP
by chemiosmosis
Photon
Photosystem I
$NADP^+$ + H^+
NADPH
6
e⁻
5
P700

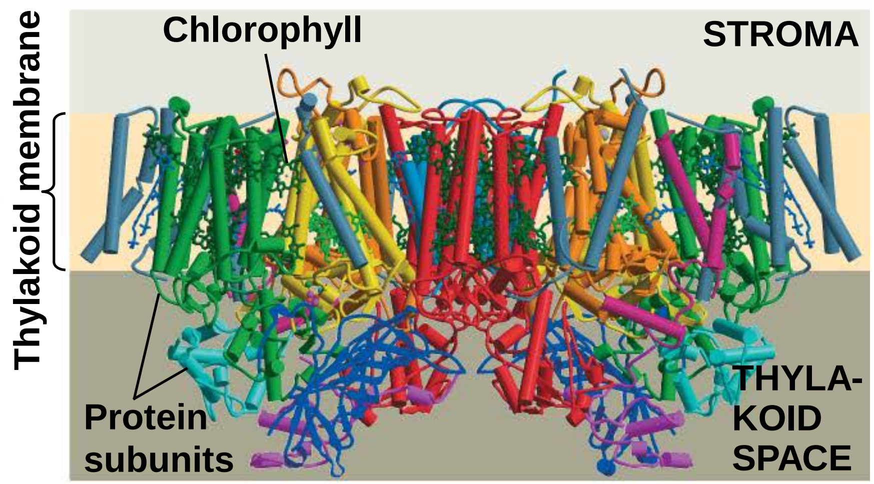
A Photosystem: A Reaction-Center Complex Associated with Light-Harvesting Complexes

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

Figure 11.13

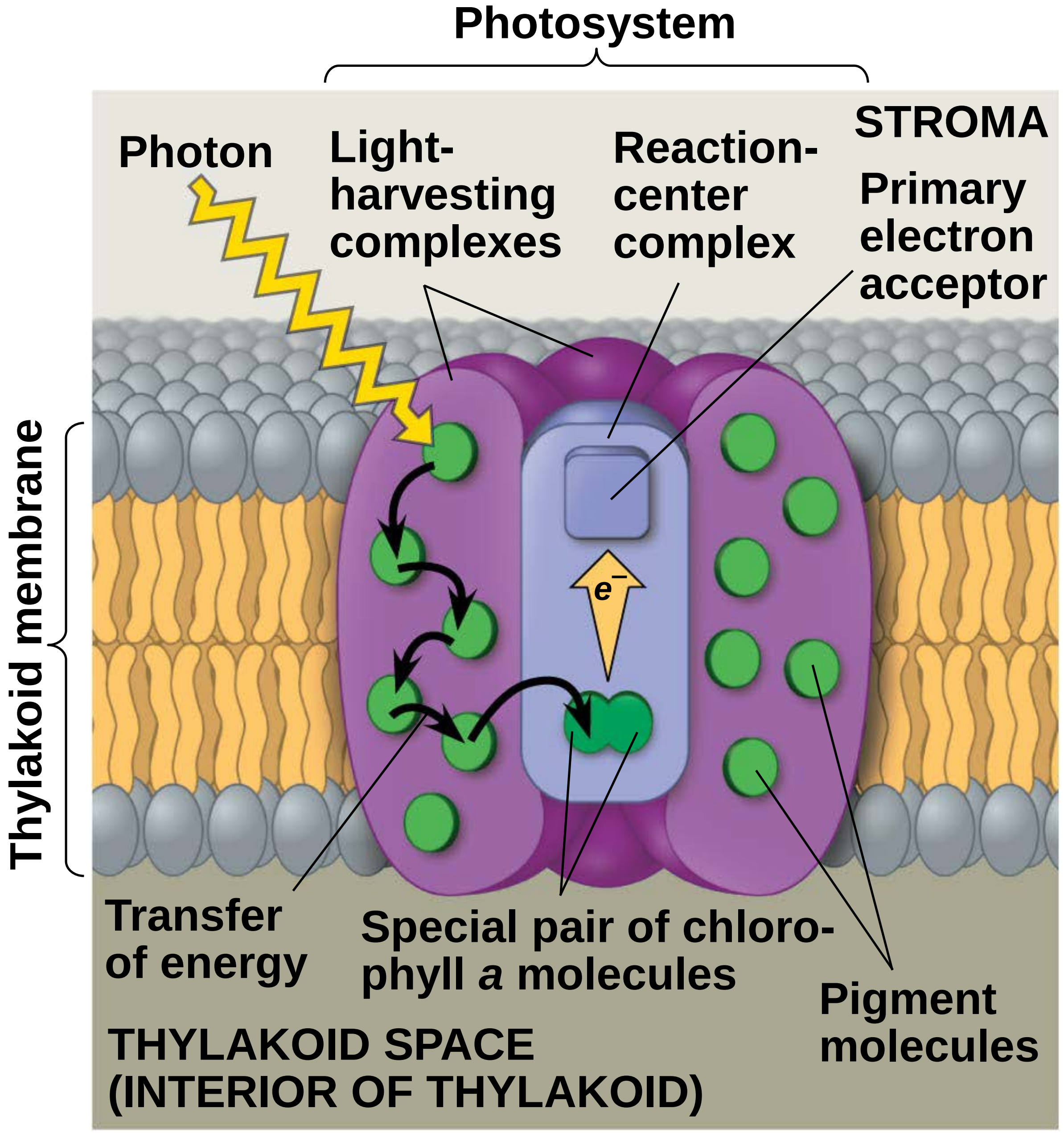


(a) How a photosystem harvests light



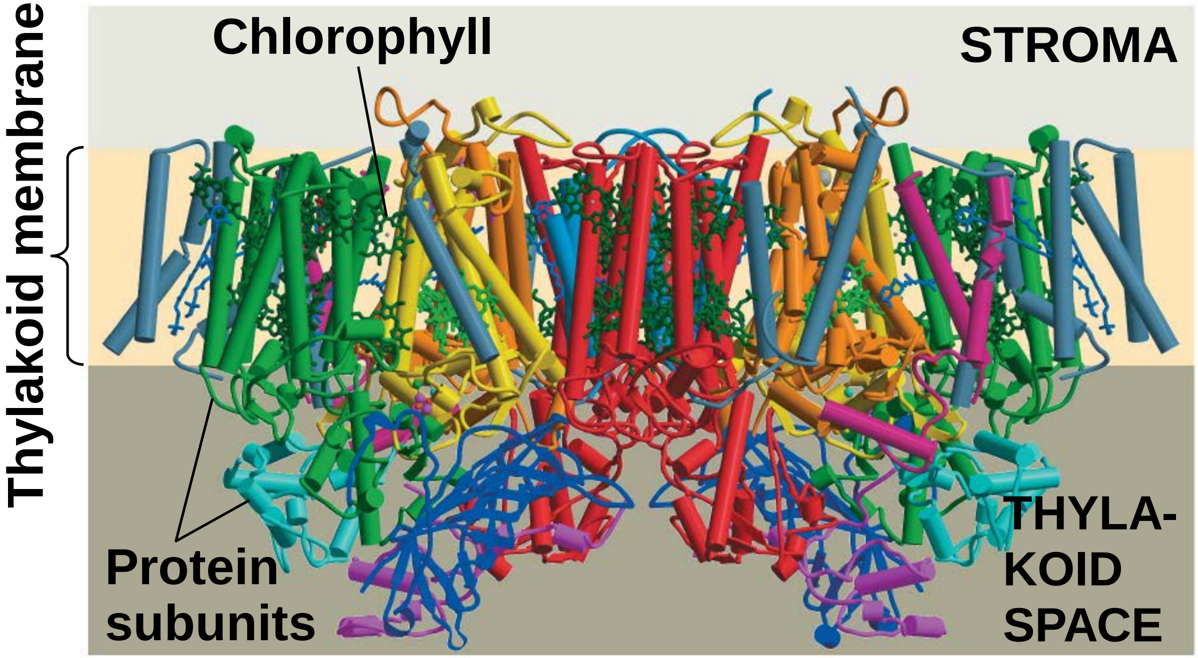
(b) Structure of a photosystem

Figure 11.13a



(a) How a photosystem harvests light

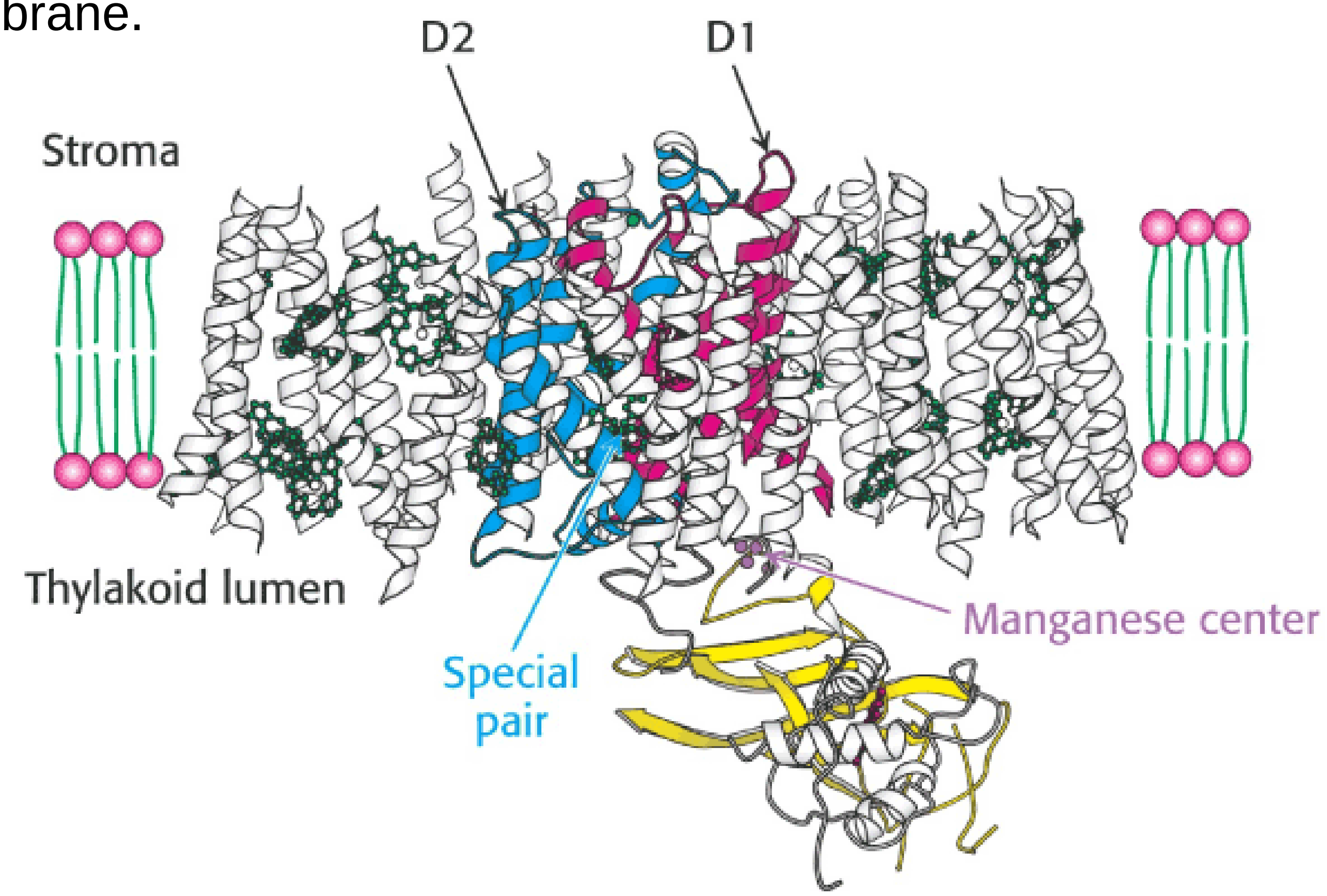
Figure 11.13b



(b) Structure of a photosystem

Photosystem II (PSII)

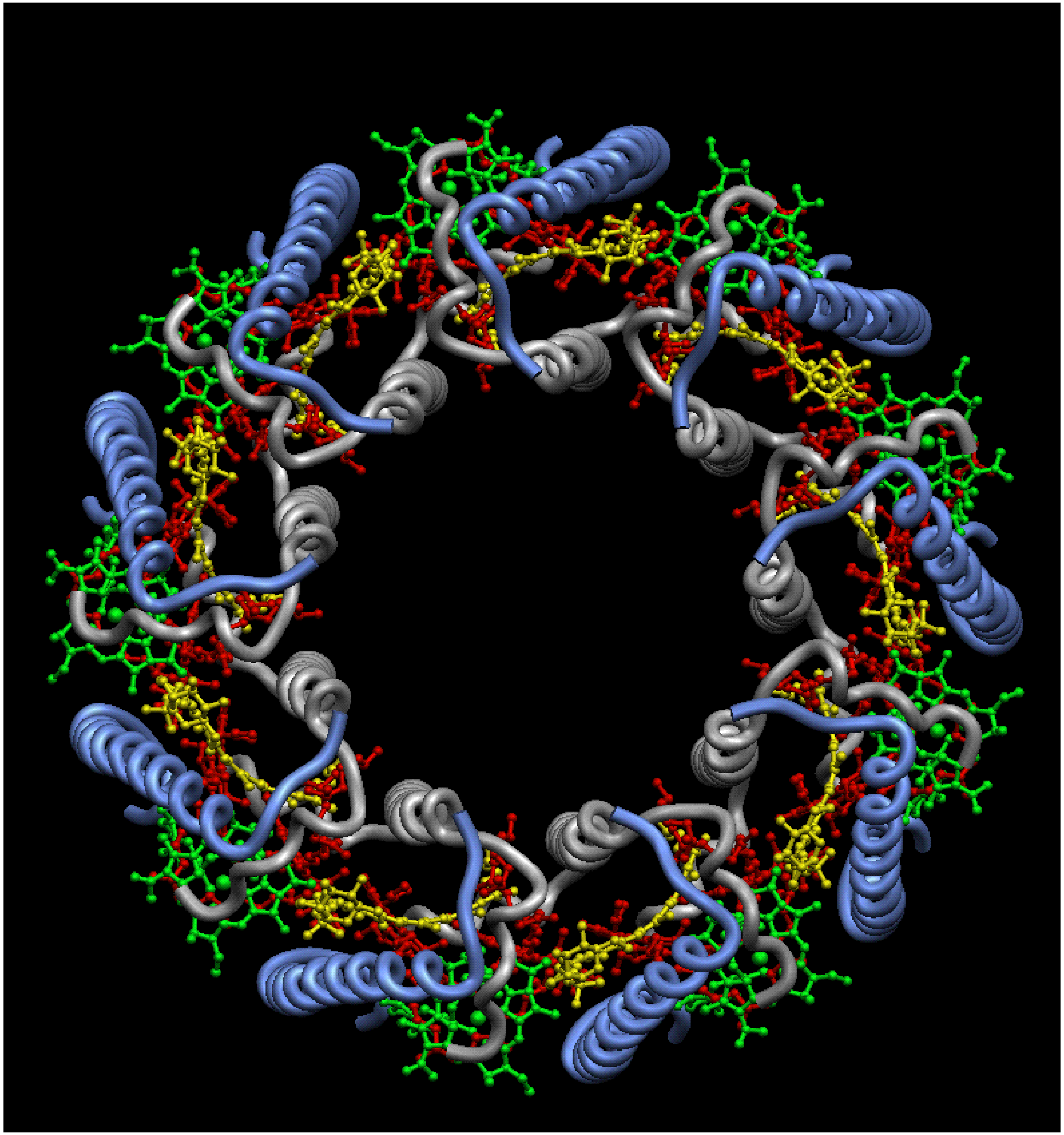
Photosystem II contains chlorophylls a and b and absorbs light at 680nm. This is a large protein complex that is located in the thylakoid membrane.

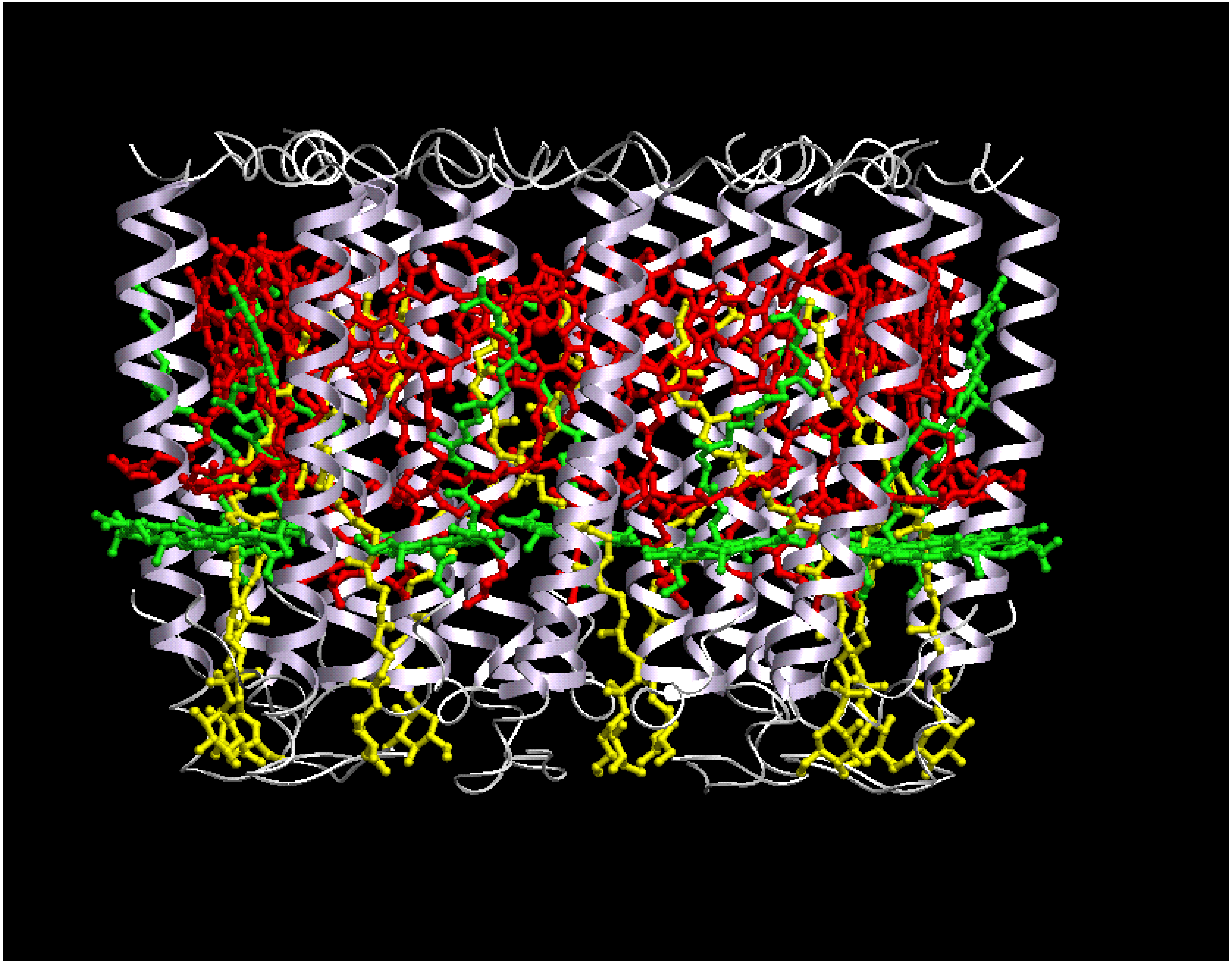


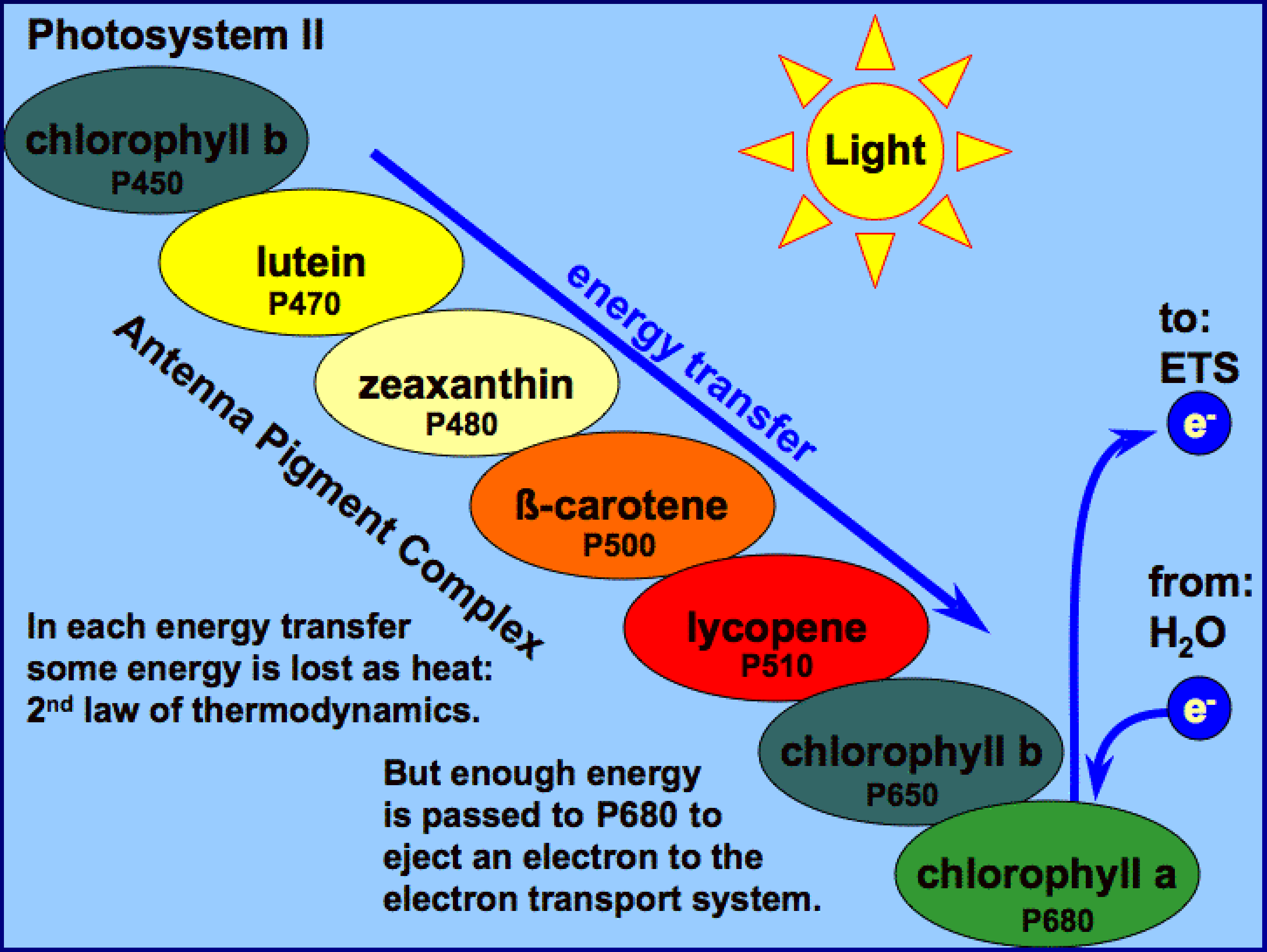
LHC-II

- MOST ABUNDANT MEMBRANE PROTEIN IN CHLOROPLASTS OF GREEN PLANTS
- A TRANSMEMBRANE PROTEIN
- BINDS
  - ~ 7 CHLOROPHYLL a MOLECULES
  - ~ 5 CHLOROPHYLL b MOLECULES
  - TWO CAROTENOIDS
- COMPRISES ABOUT 50% OF ALL CHLOROPHYLL IN BIOSPHERE

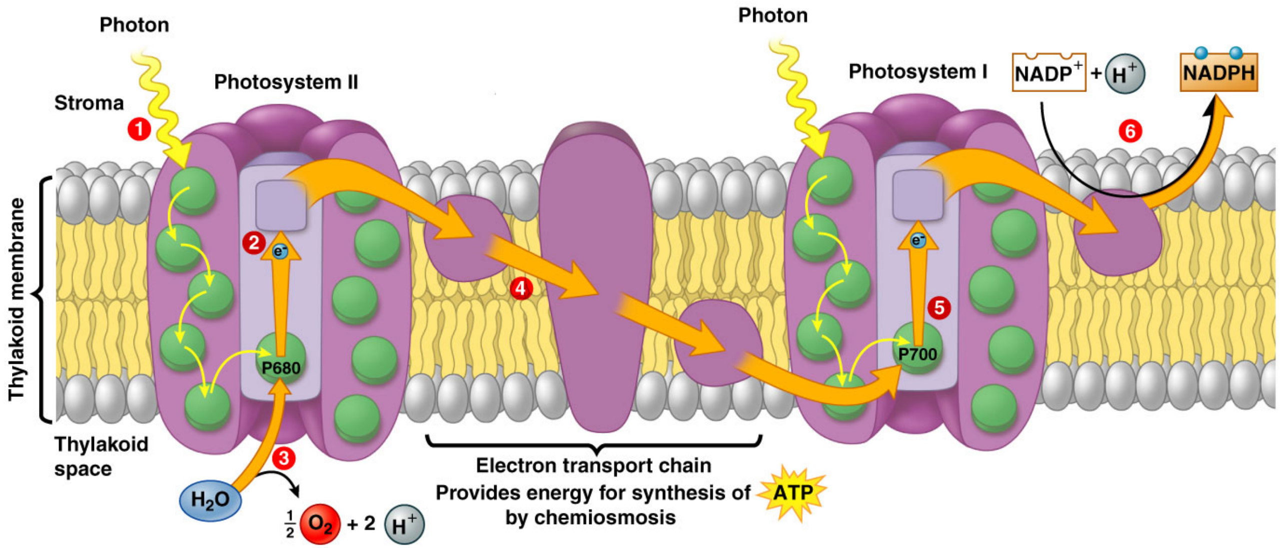
LH2 FROM *Rs. acidophhilus*



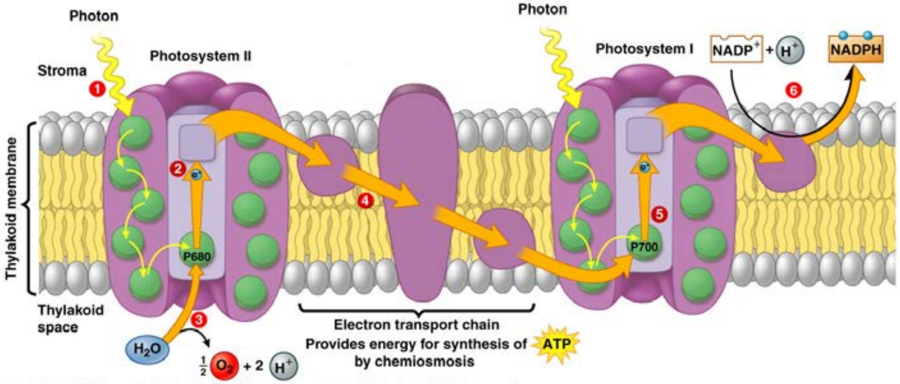



Photosystem II
chlorophyll b
P450
lutein
P470
zeaxanthin
P480
ß-carotene
P500
lycopene
P510
chlorophyll b
P650
chlorophyll a
P680
Light
energy transfer
Antenna Pigment Complex
to:
ETS
e-
from:
H_2O
e-
In each energy transfer
some energy is lost as heat:
2nd law of thermodynamics.
But enough energy
is passed to P680 to
eject an electron to the
electron transport system.

- 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



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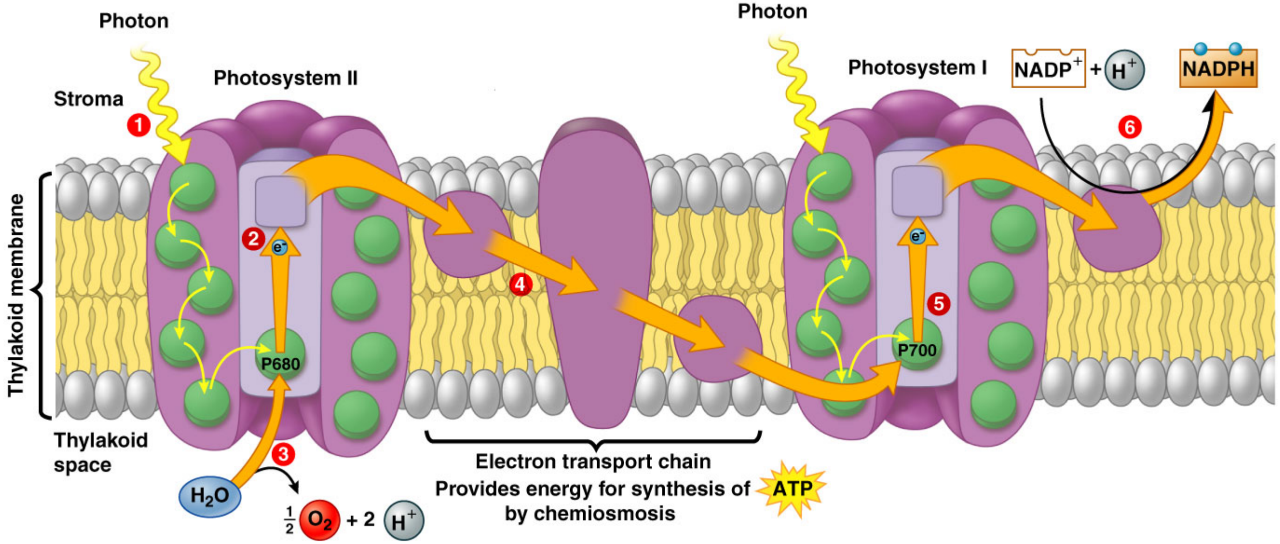
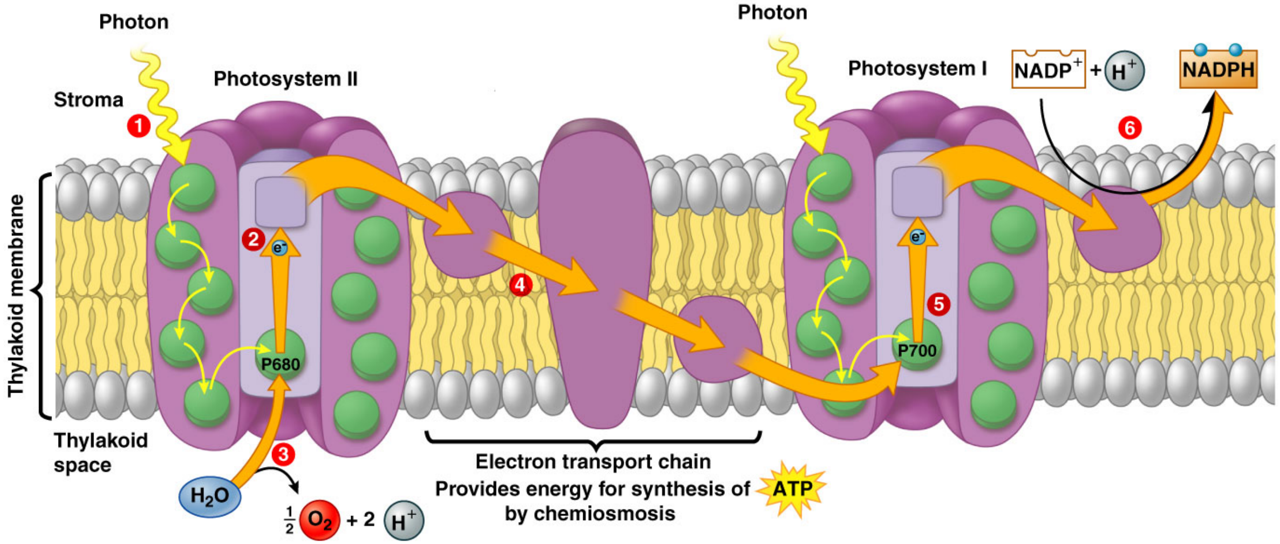
- **Photosystem I (PS I)** is best at absorbing a wavelength of 700 nm
- The reaction-center chlorophyll a of PS I is called P700



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



- There are 8 steps in linear electron flow:

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

Figure 11.UN02

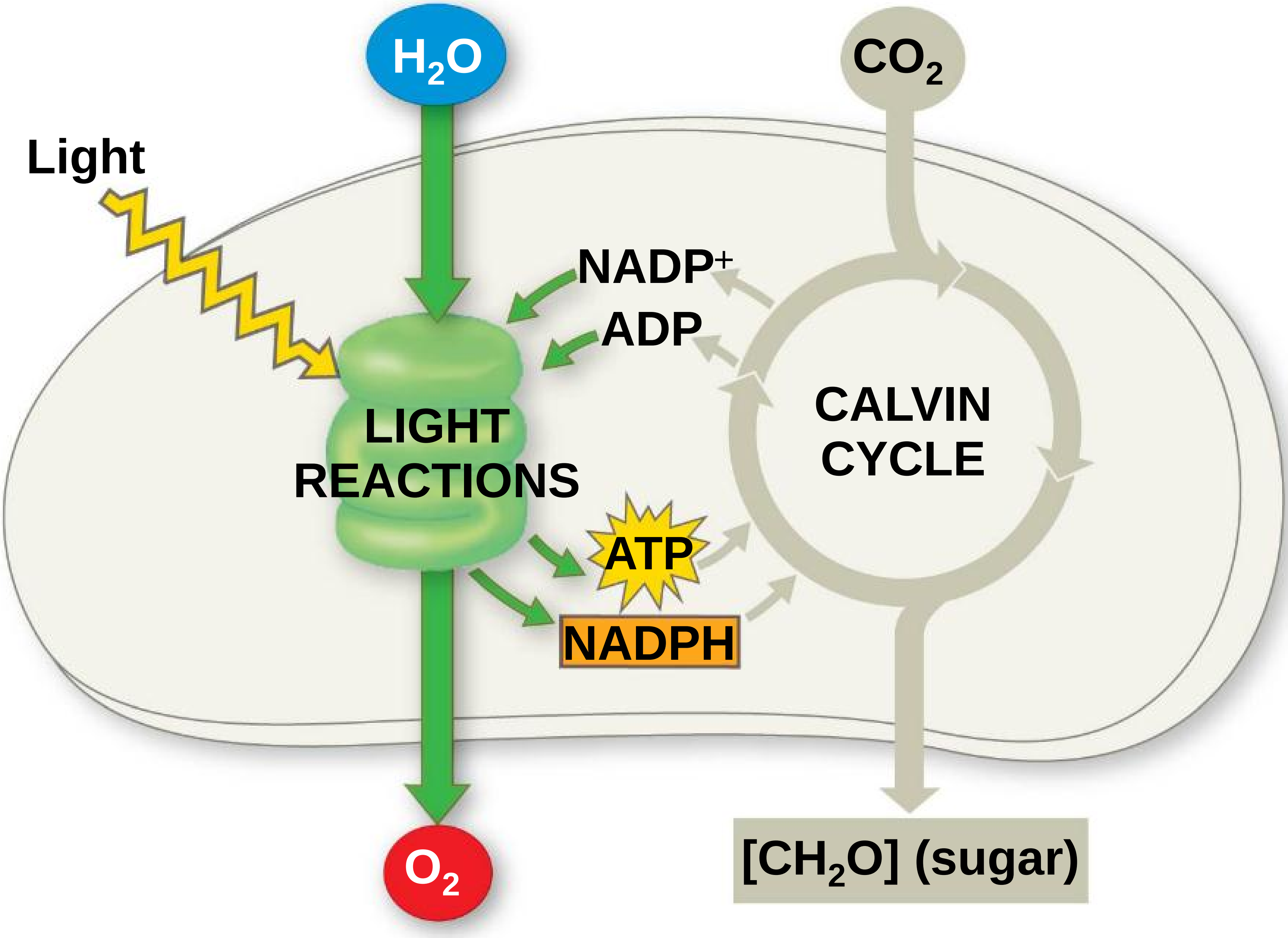


Figure 11.14-1

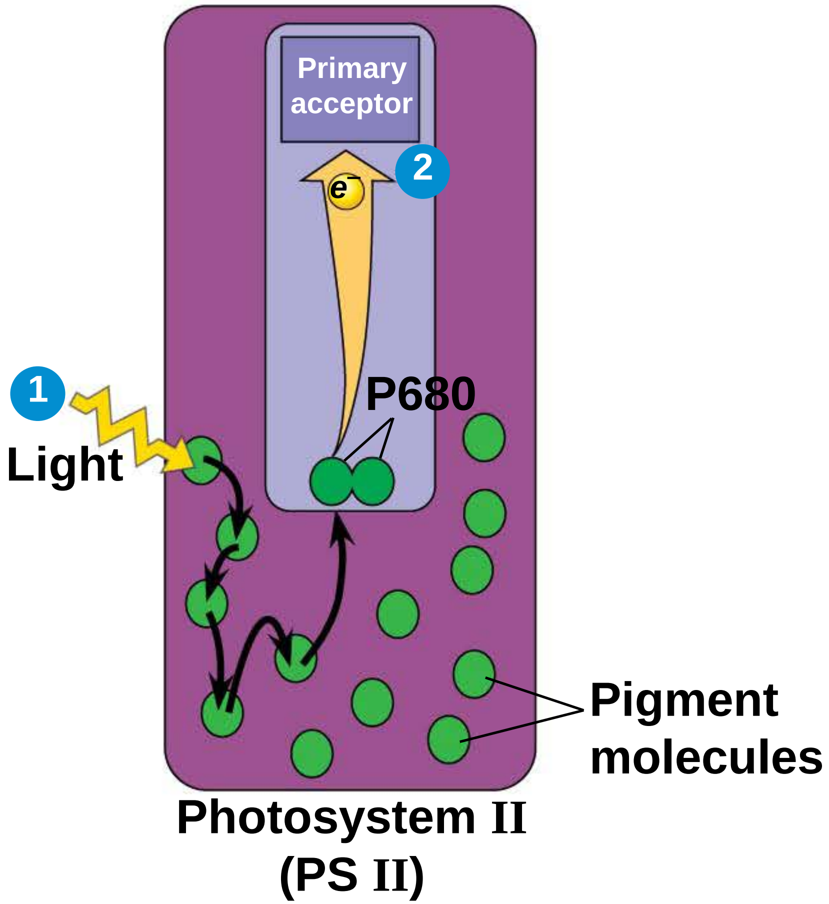


Figure 11.14-2

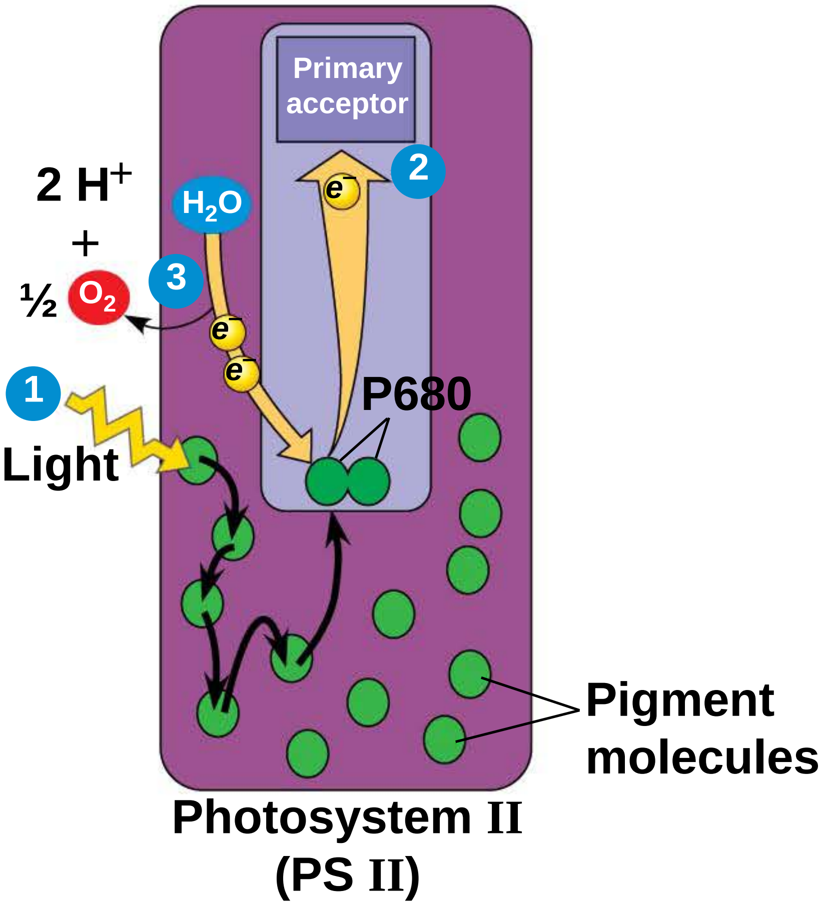


Figure 11.14-3

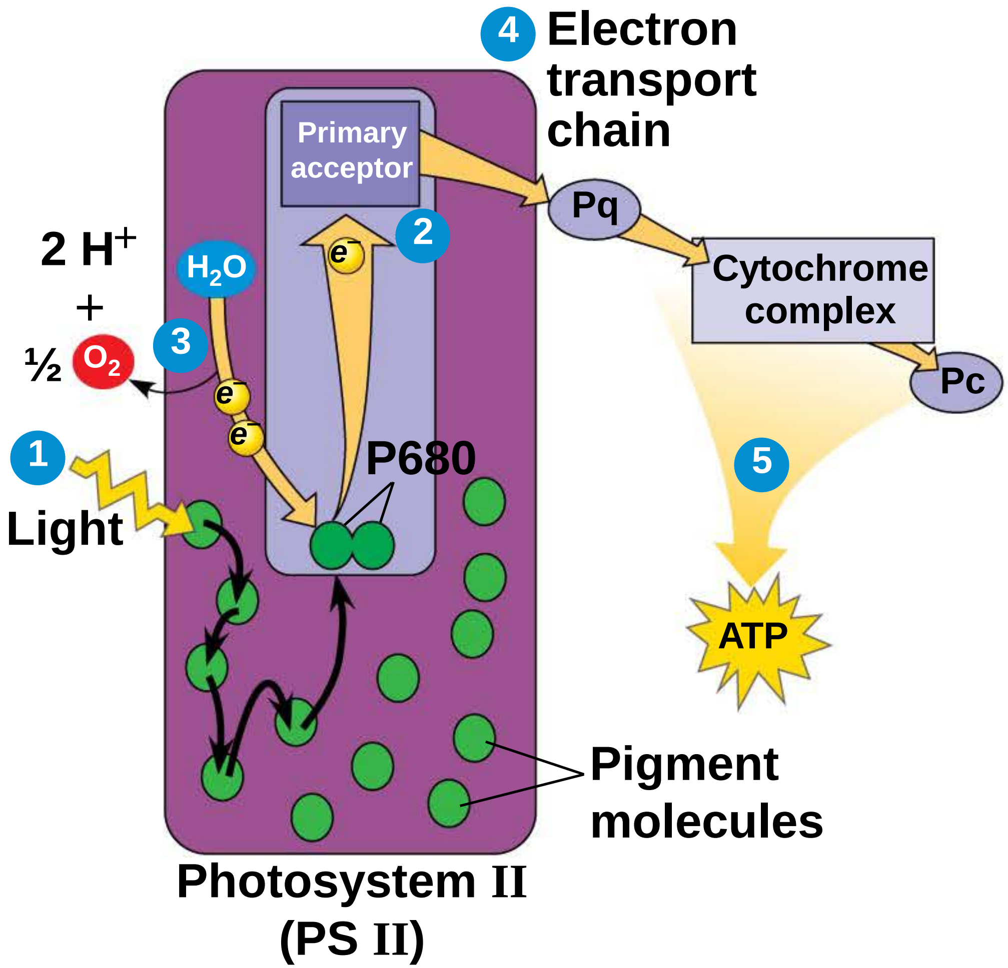


Figure 11.14-4

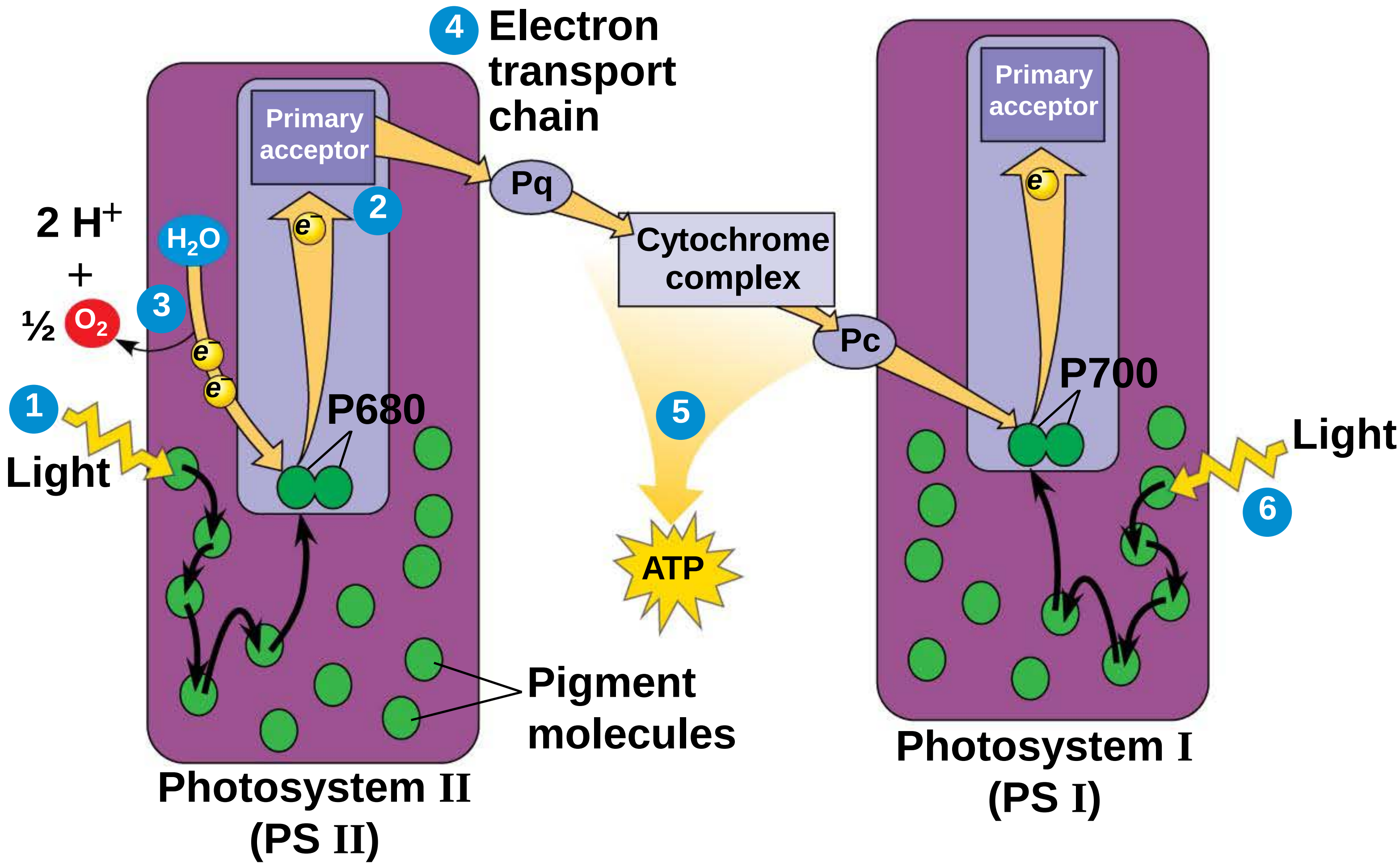
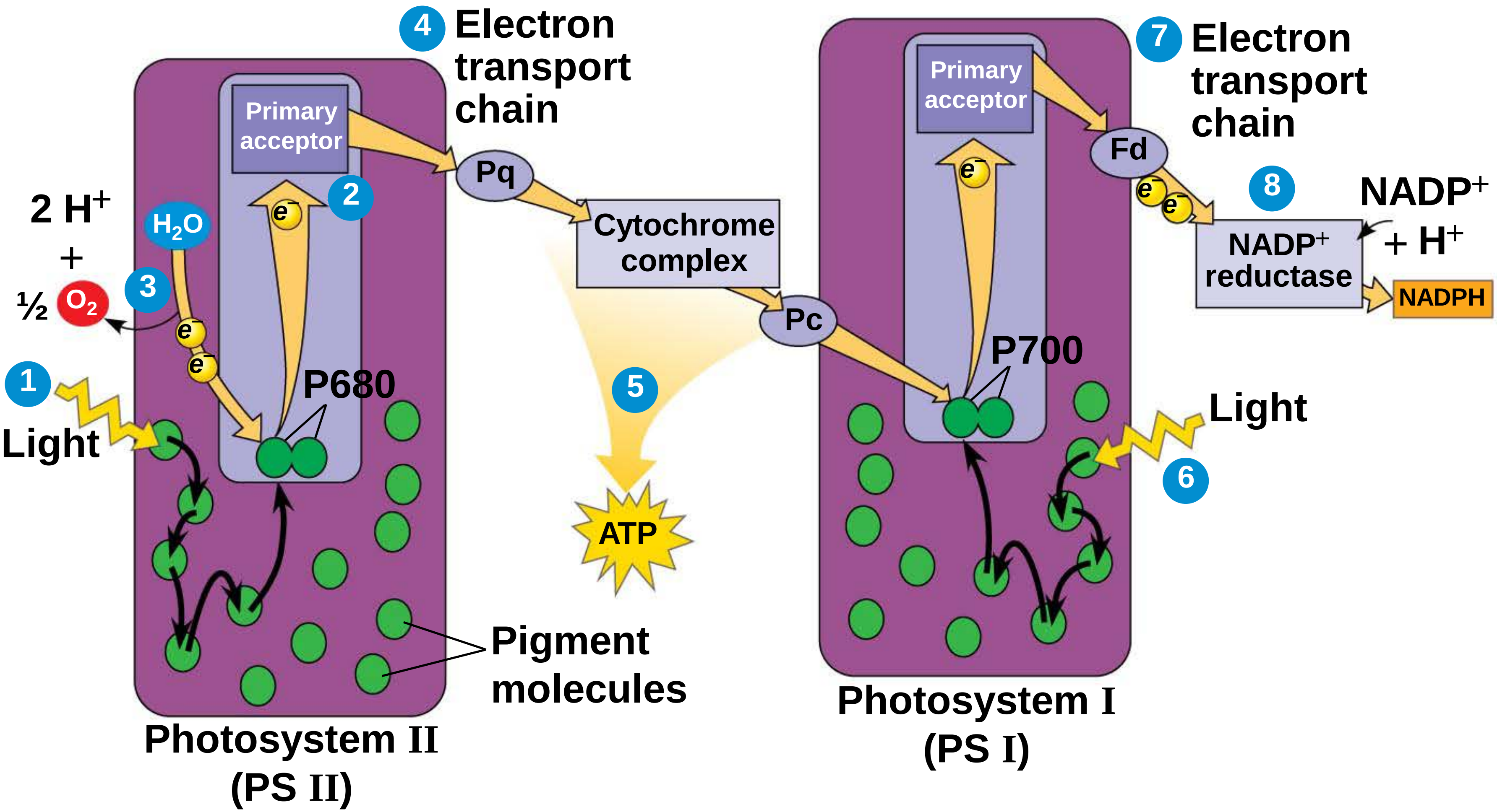
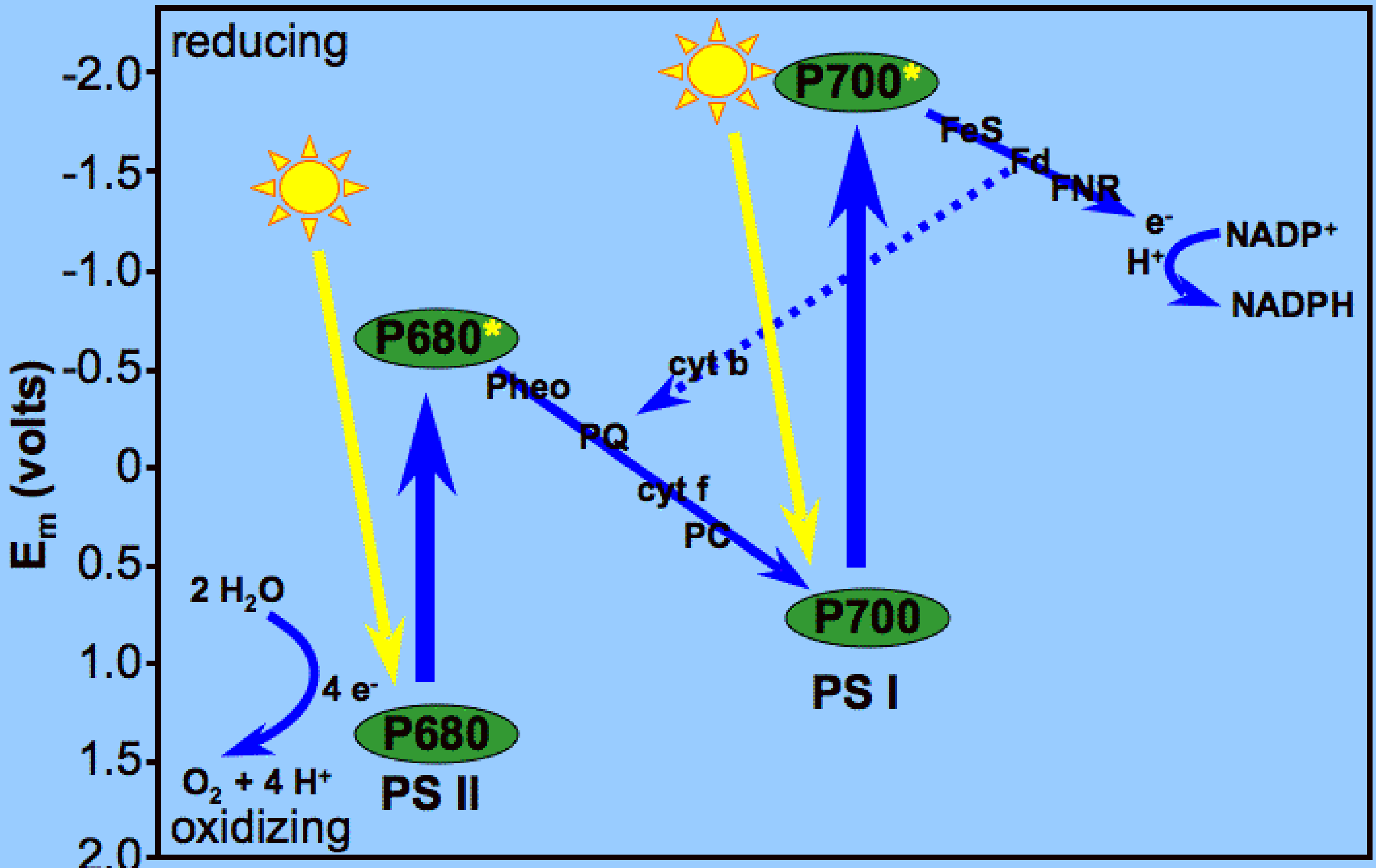


Figure 11.14-5



The Z-scheme of the Light Reactions: An Energy Diagram



3. H_2O is split by enzymes, and the electrons are transferred from the hydrogen atoms to $P680^+$, thus reducing it to P680

- $P680^+$ is the strongest known biological oxidizing agent
- O_2 is released as a by-product of this reaction

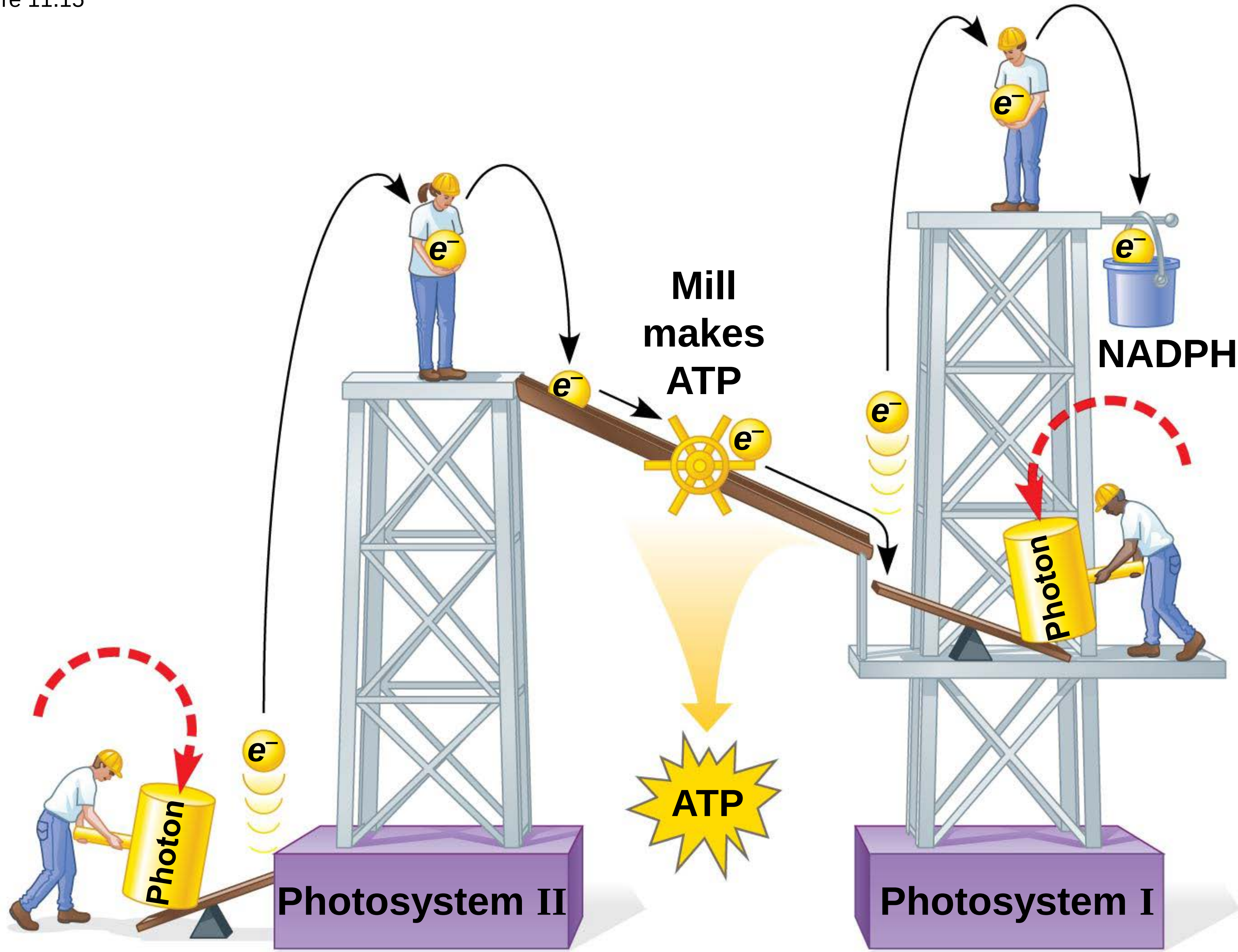
4. Each electron "falls" down an electron transport chain from the primary electron acceptor of PS II to PS I
5. Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
   - Diffusion of H^+ (protons) across the membrane drives ATP synthesis

6. 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

7. Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
8. 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

- The energy changes of electrons during linear flow through the light reactions can be shown in a mechanical analogy

Figure 11.15

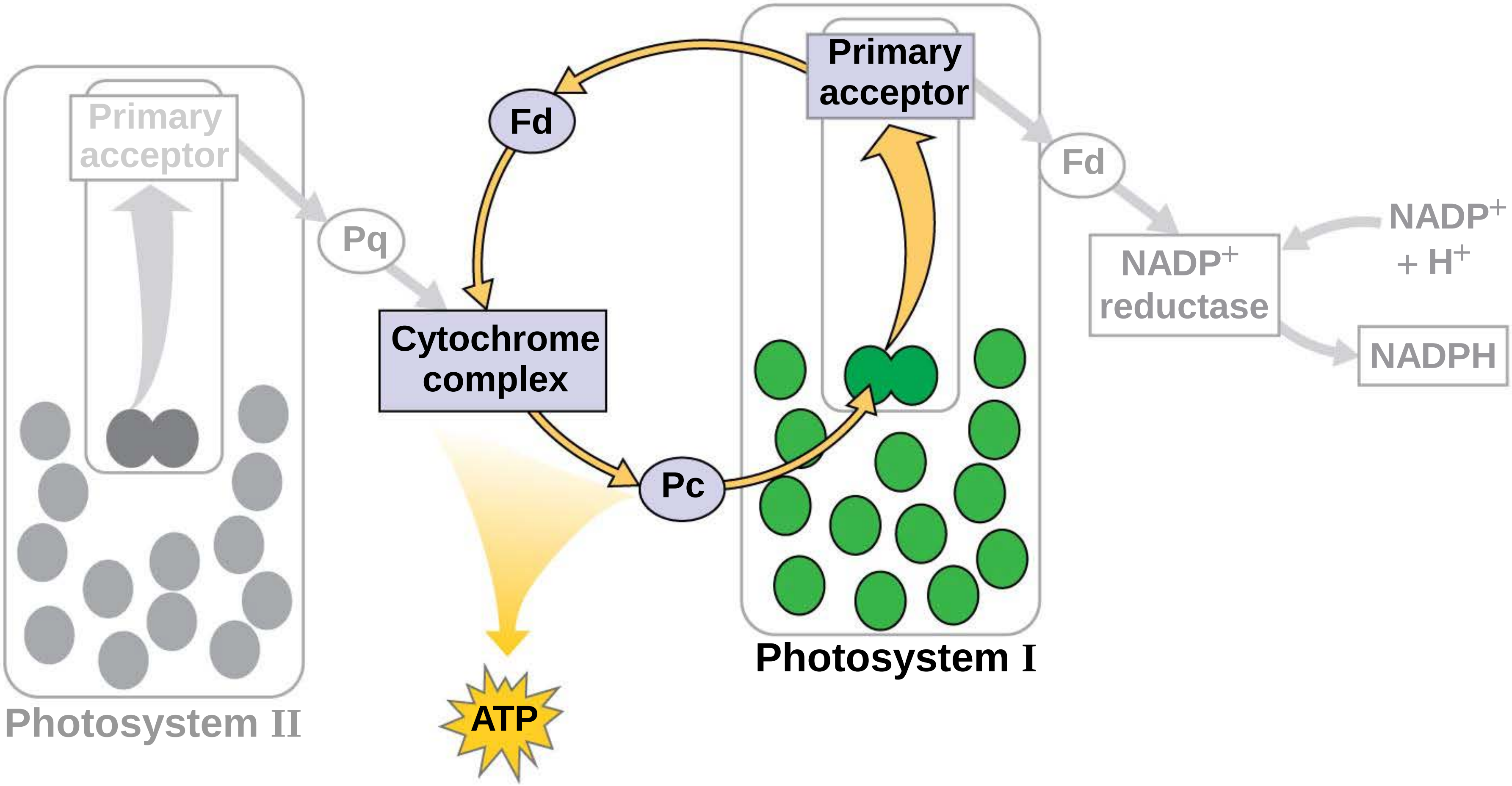


e⁻
Mill makes ATP
NADPH
Photon
ATP
Photosystem II
Photosystem I

Cyclic Electron Flow

- In **cyclic electron flow**, electrons cycle back from Fd to the PS I reaction center
- Cyclic electron flow uses only photosystem I and produces ATP, but not NADPH
- No oxygen is released

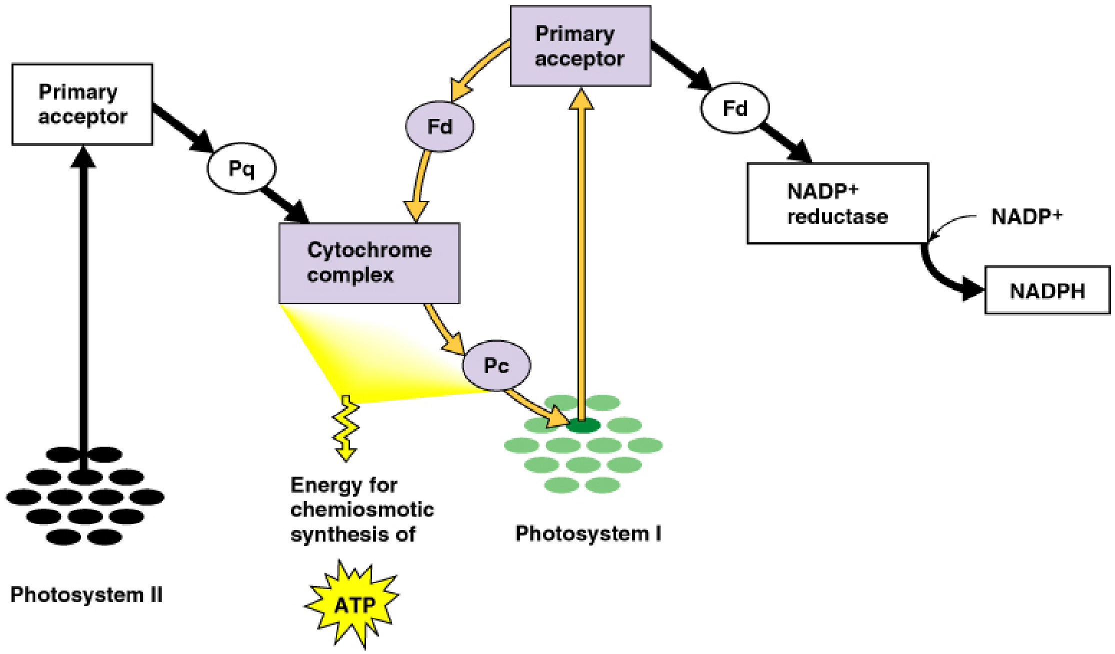
Figure 11.16



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

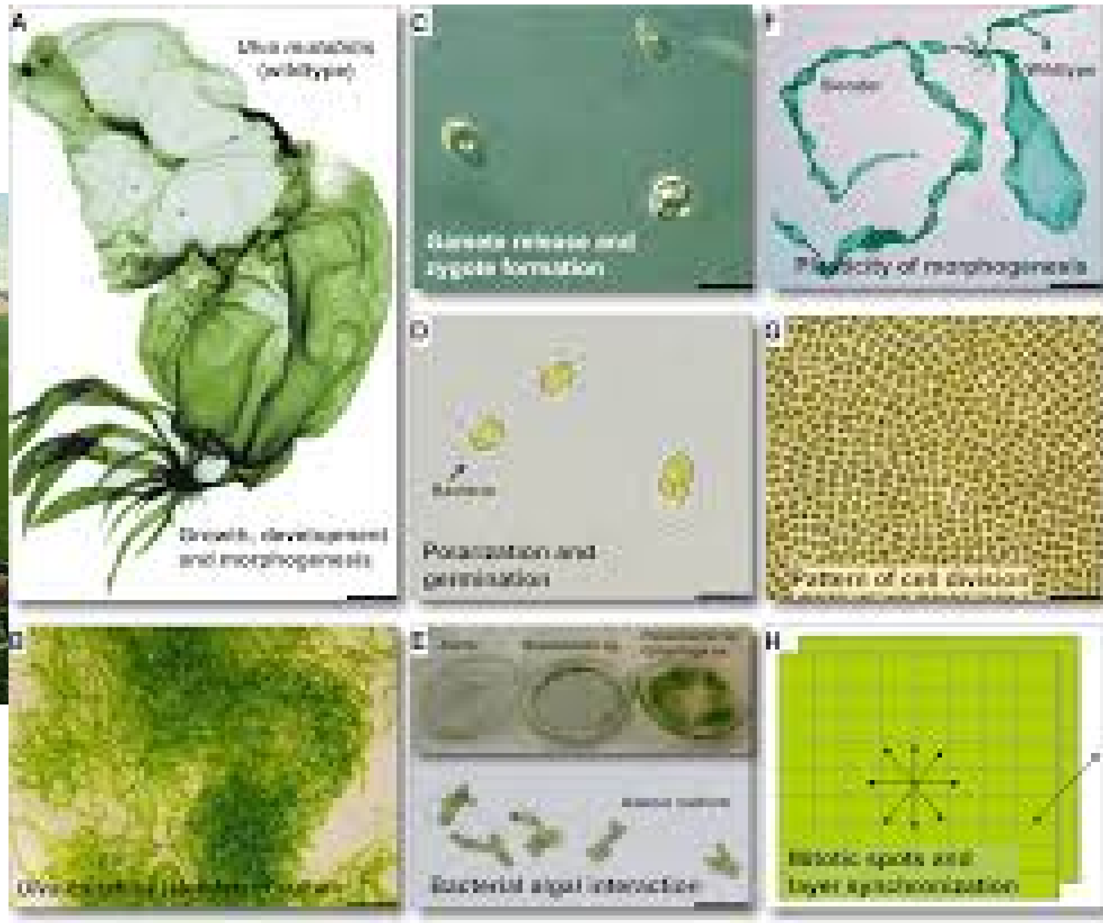
- Some organisms such as purple sulfur bacteria have PS I but not PS II
- Cyclic electron flow is thought to have evolved before linear electron flow
- Cyclic electron flow may protect cells from light-induced damage

Cyclic Electron Flow



- Electron in Photosystem I is excited and transferred to ferredoxin that shuttles the electron to the cytochrome complex.
- The electron then travels down the electron chain and re-enters photosystem I

Green tide

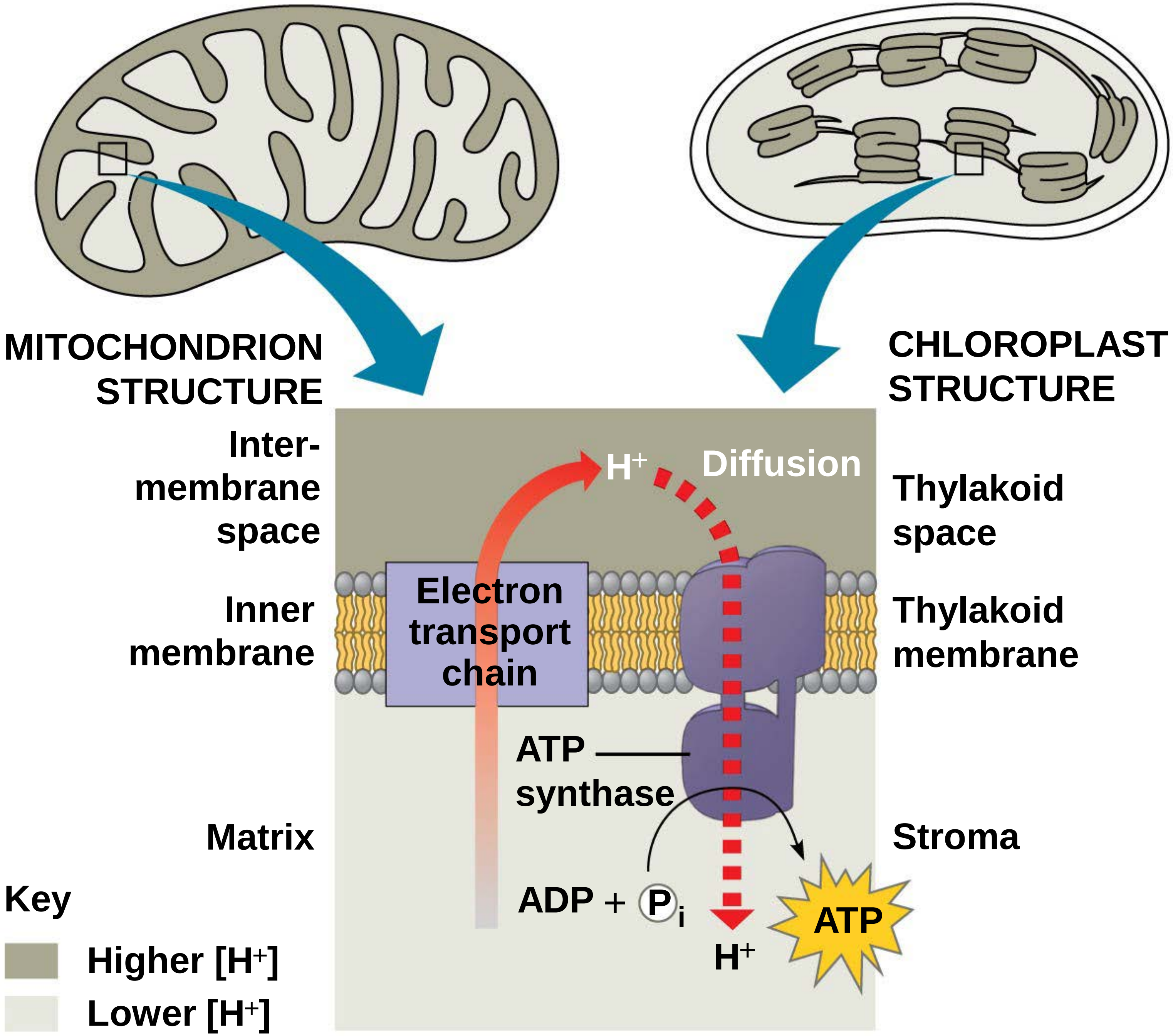

Gamete release and zygote formation
Growth, development and morphogenesis
Polarization and germination
Pattern of cell division
Bacterial algal interaction
Mitotic spots and layer synchronization

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

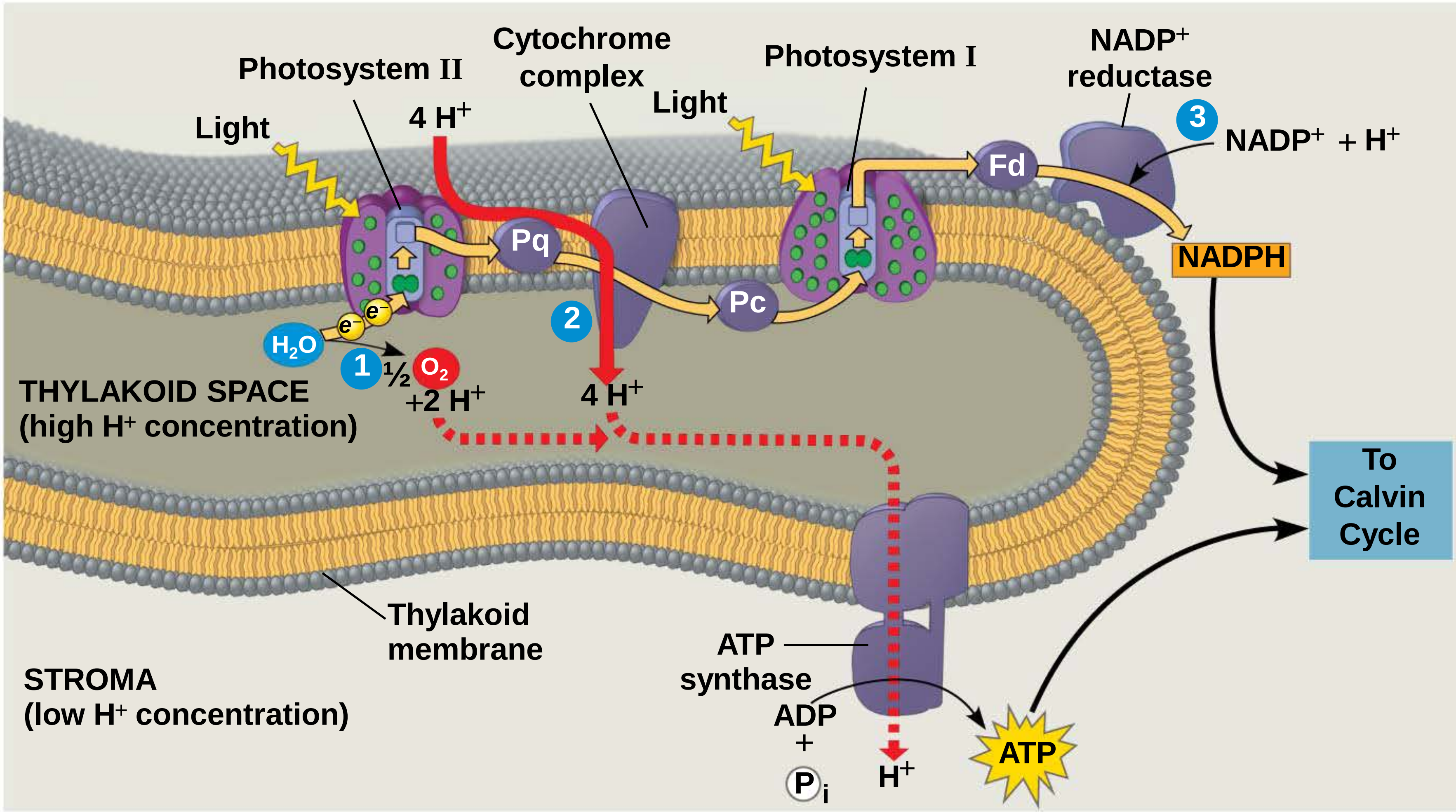
Figure 11.17



MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Inter-membrane space
Inner membrane
Matrix
H+
Diffusion
Electron transport chain
ATP synthase
ADP + P i
H+
ATP
Thylakoid space
Thylakoid membrane
Stroma
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 11.18



Cytochrome complex
Photosystem II
Photosystem I
NADP+ reductase
Light
4 H+
Light
3
NADP+ + H+
Fd
Pq
NADPH
Pc
2
H2O
e−
e−
1
½ O2
+2 H+
4 H+
THYLAKOID SPACE (high H+ concentration)
To Calvin Cycle
Thylakoid membrane
ATP synthase
STROMA (low H+ concentration)
ADP
+
Pi
H+
ATP

Figure 11.18a

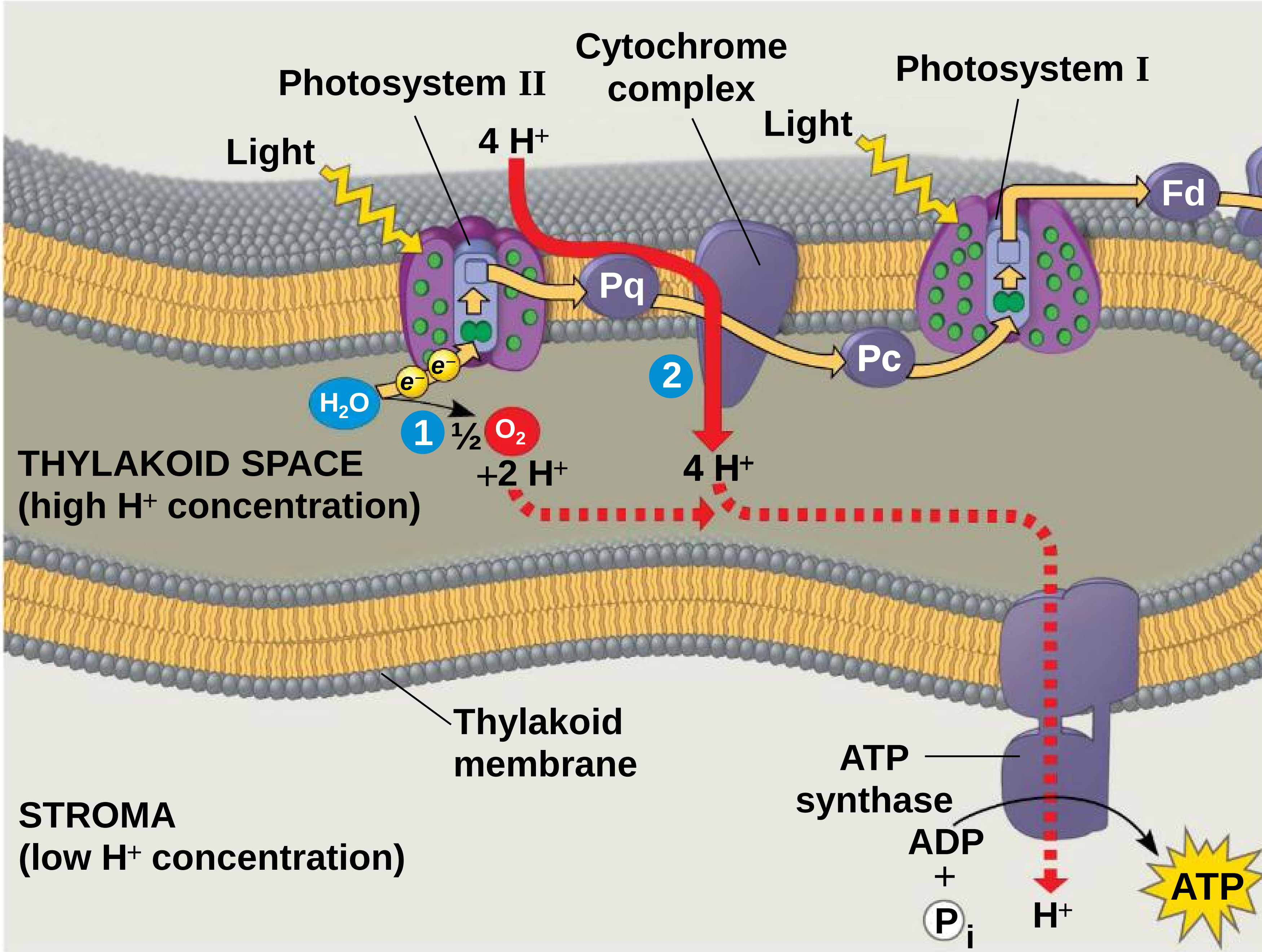
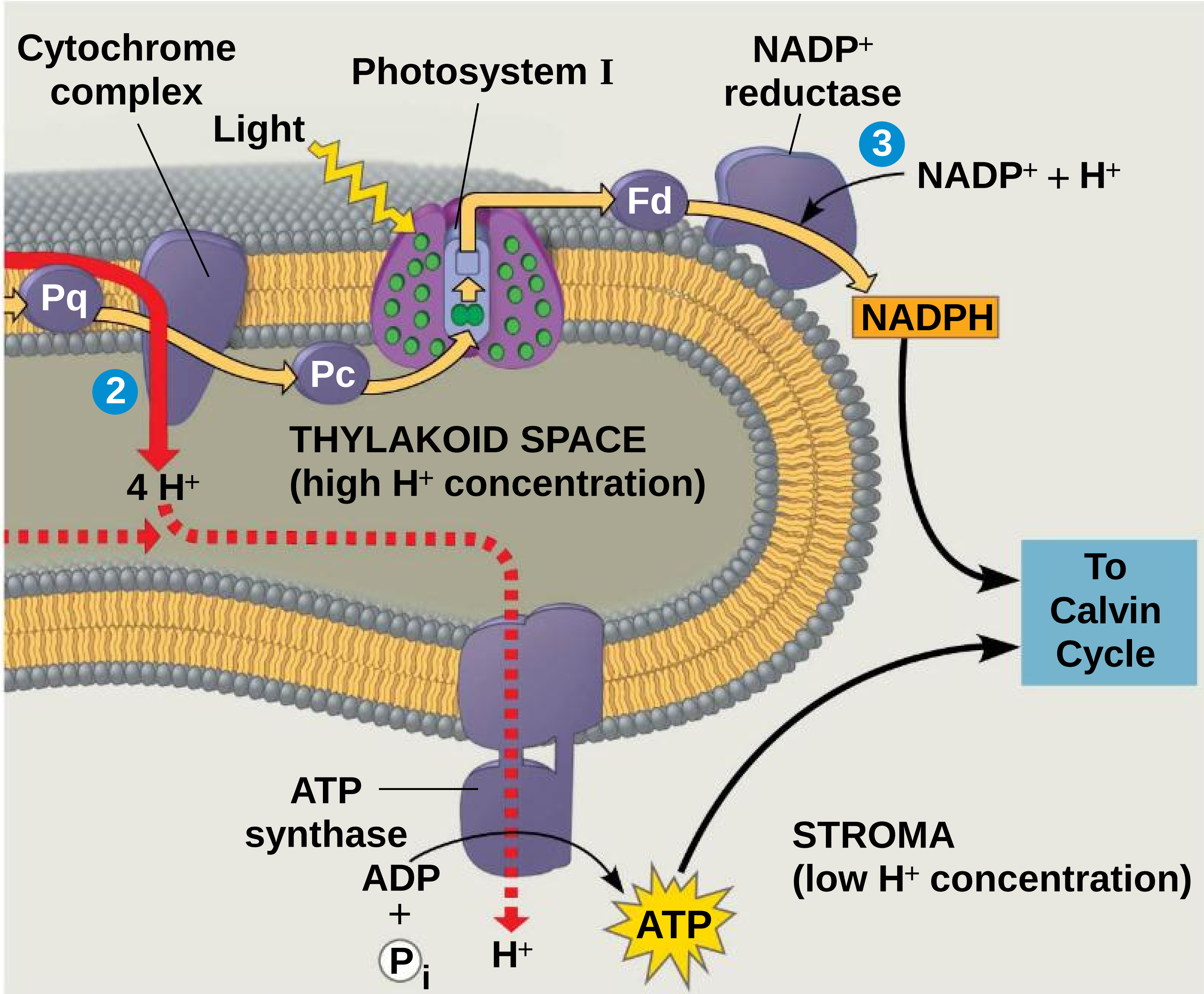


Figure 11.18b



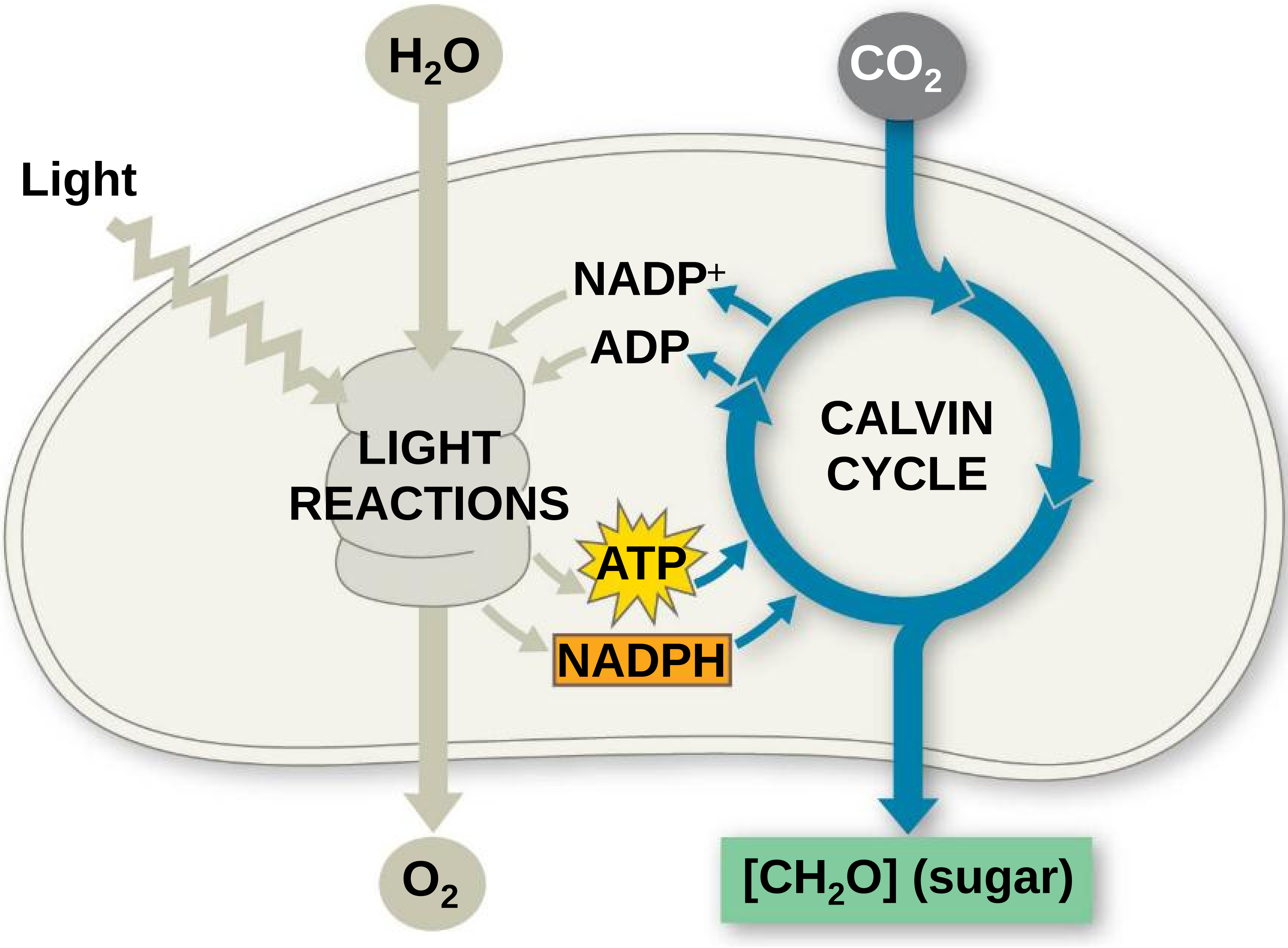
Concept 11.3: The Calvin cycle uses the chemical energy of ATP and NADPH to reduce CO_2 to sugar

- 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
  1. **Carbon fixation** (catalyzed by **rubisco**)
  2. **Reduction**
  3. **Regeneration of the CO_2 acceptor (RuBP)**

Figure 11.UN03



C3 cycle

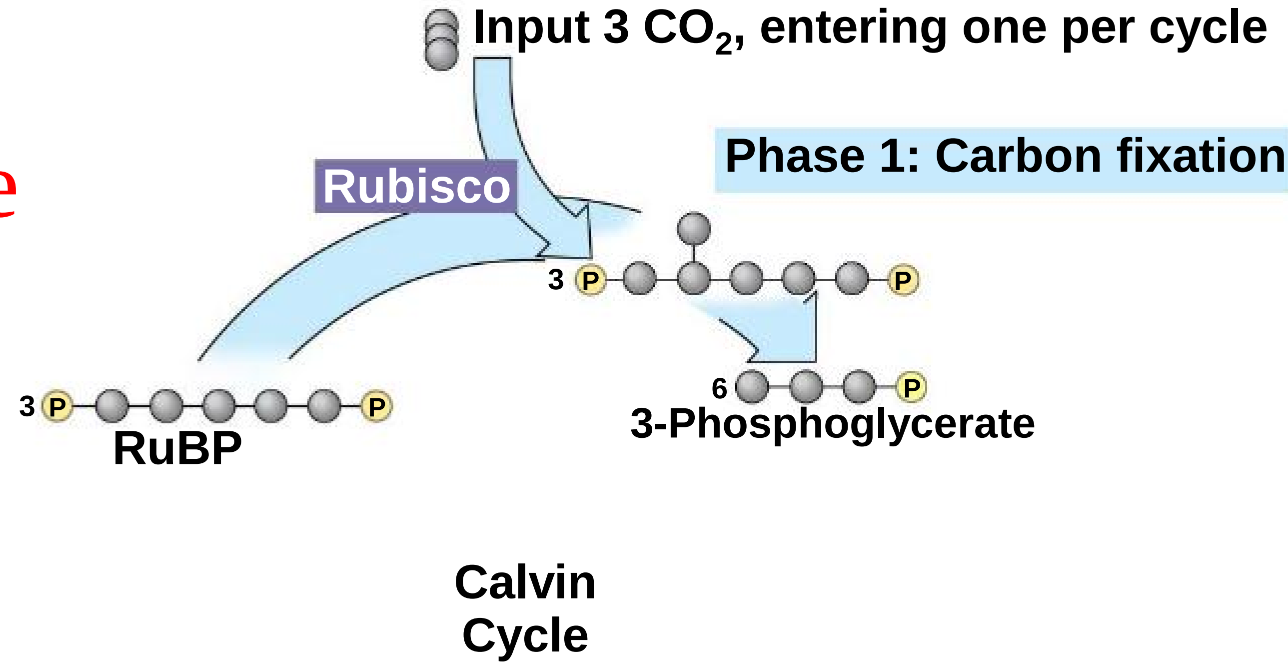

Input 3 CO_2, entering one per cycle
Phase 1: Carbon fixation
Rubisco
3 P P
3 P P
RuBP
6 P
3-Phosphoglycerate
Calvin
Cycle

Figure 11.19-2

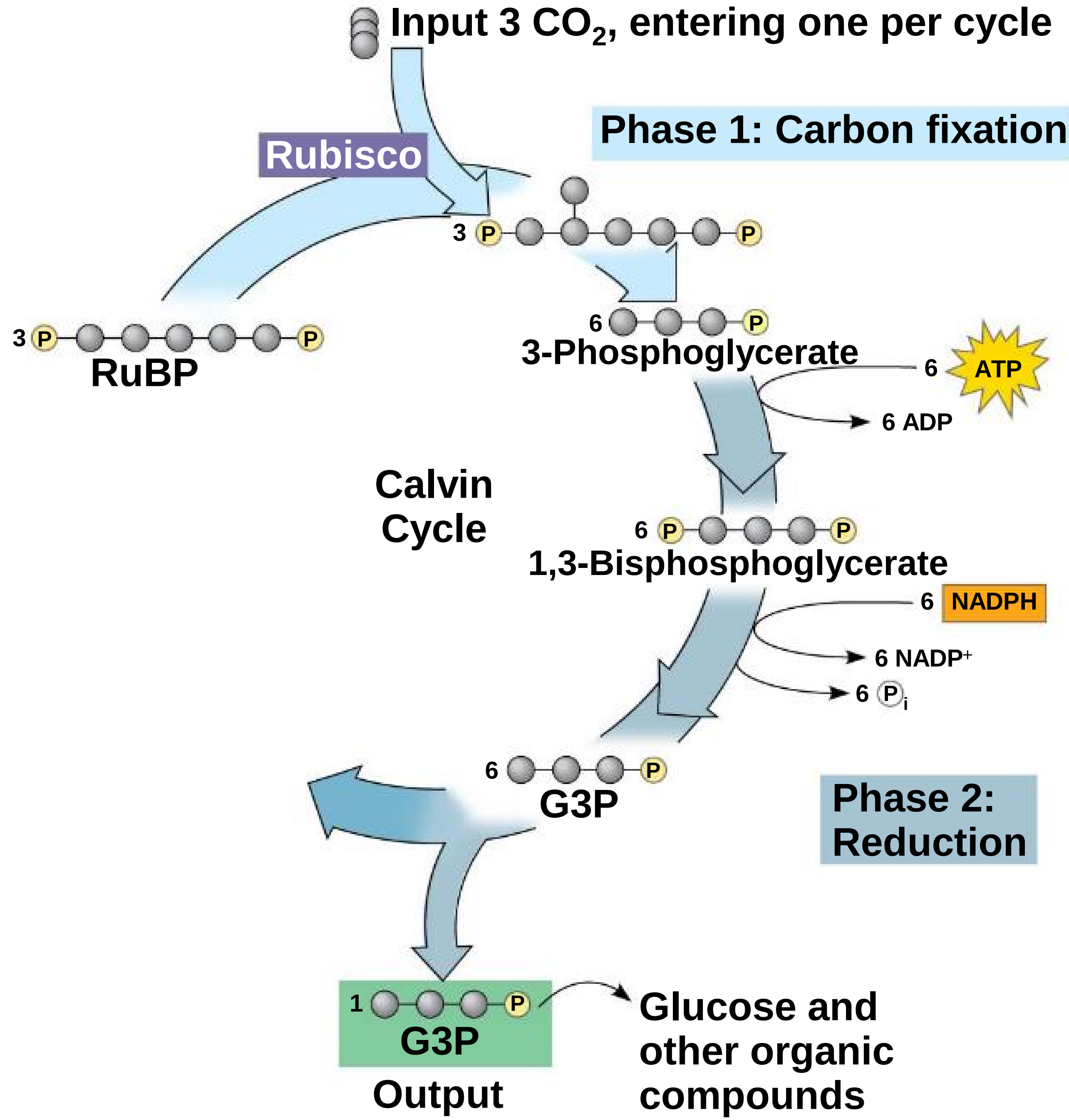
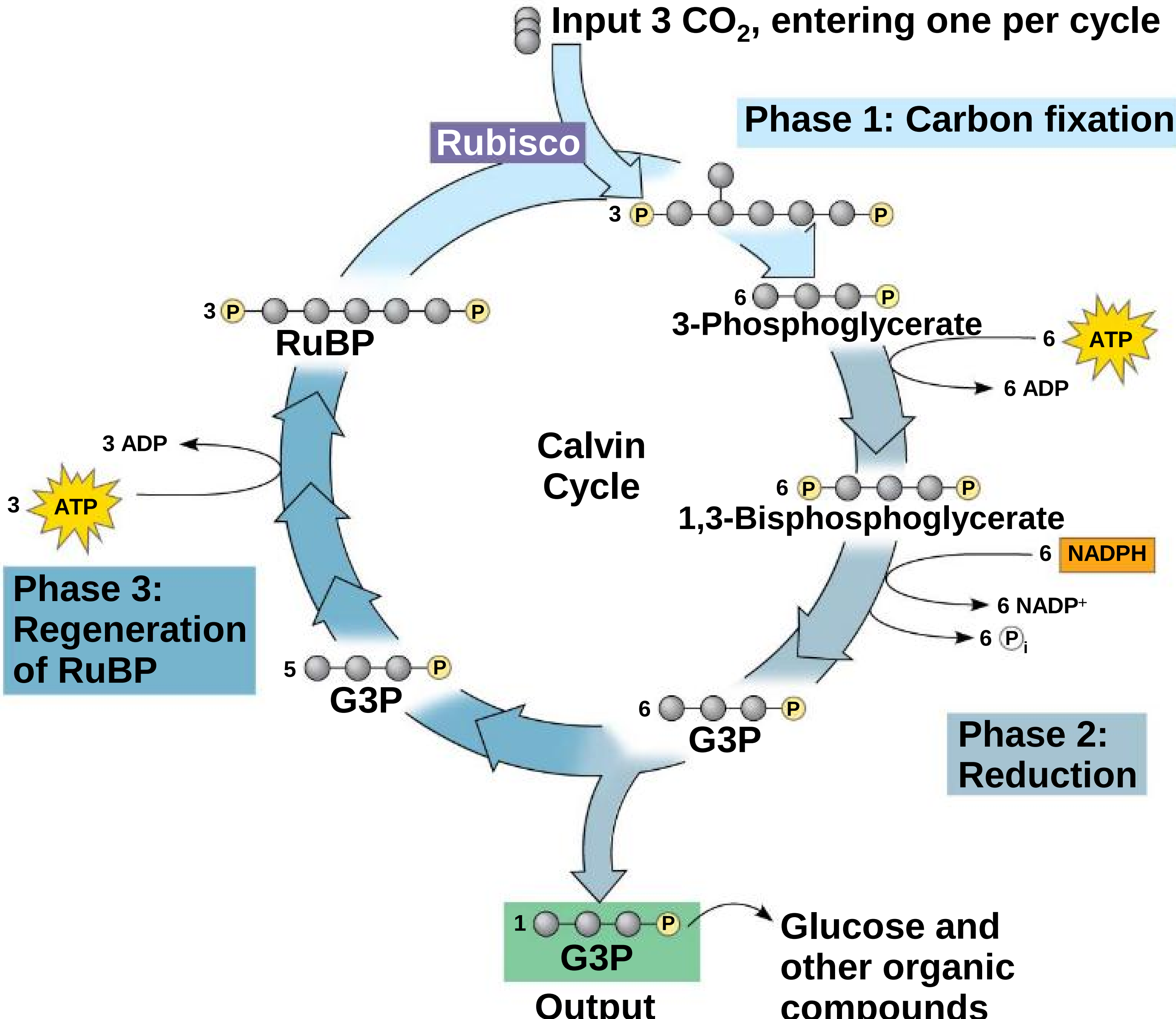


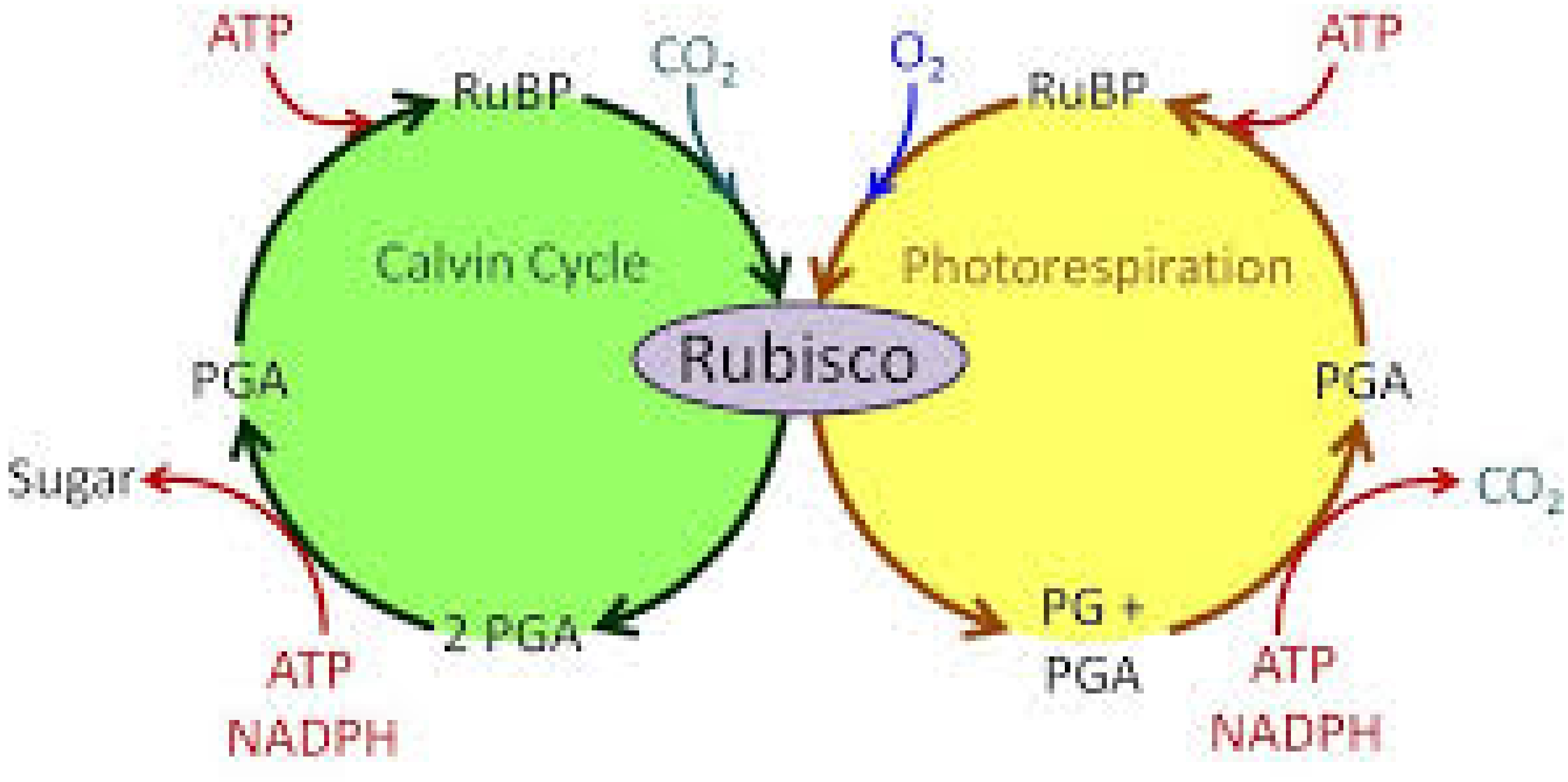
Figure 11.19-3



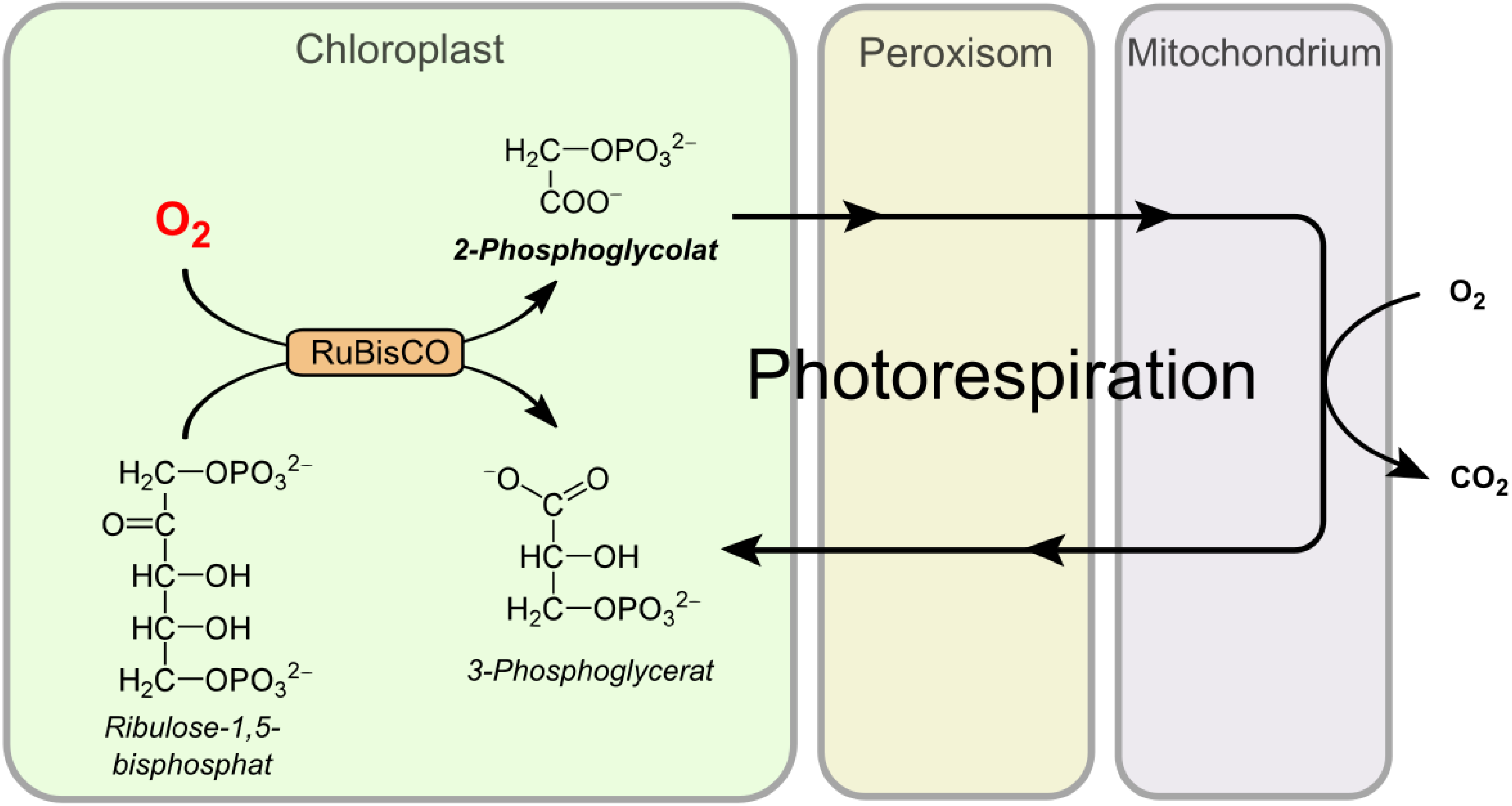
Concept 11.4: Alternative mechanisms of carbon fixation have evolved in hot, arid climates

- 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 an apparently wasteful process called photorespiration

Rubisco: Ribulose-1,5-bisphosphate carboxylase/oxygenase



Photorespiration: C2 cycle



- 胺基酸代謝

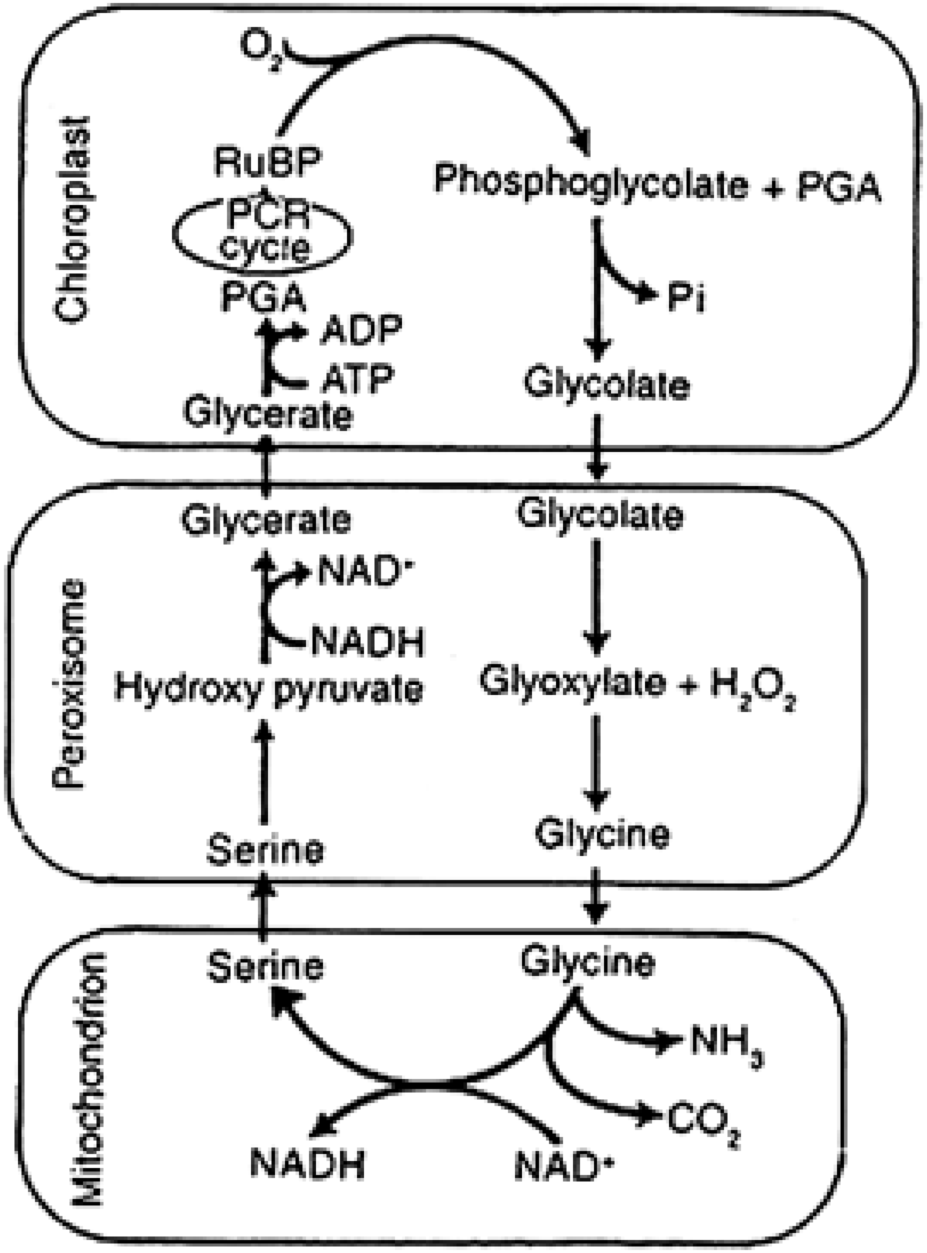


Fig. 5.10. Photorespiration.

Photorespiration: An Evolutionary Relic?

- In most plants (**C_3 plants**), initial fixation of CO_2, via rubisco, forms a three-carbon compound (3-phosphoglycerate)
- In **photorespiration**, rubisco adds O_2 instead of CO_2 in the Calvin cycle, producing a two-carbon compound
- 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
- There are two distinct types of cells in the leaves of C_4 plants:
  - **Bundle-sheath cells** are arranged in tightly packed sheaths around the veins of the leaf
  - Mesophyll cells are loosely packed between the bundle sheath and the leaf surface

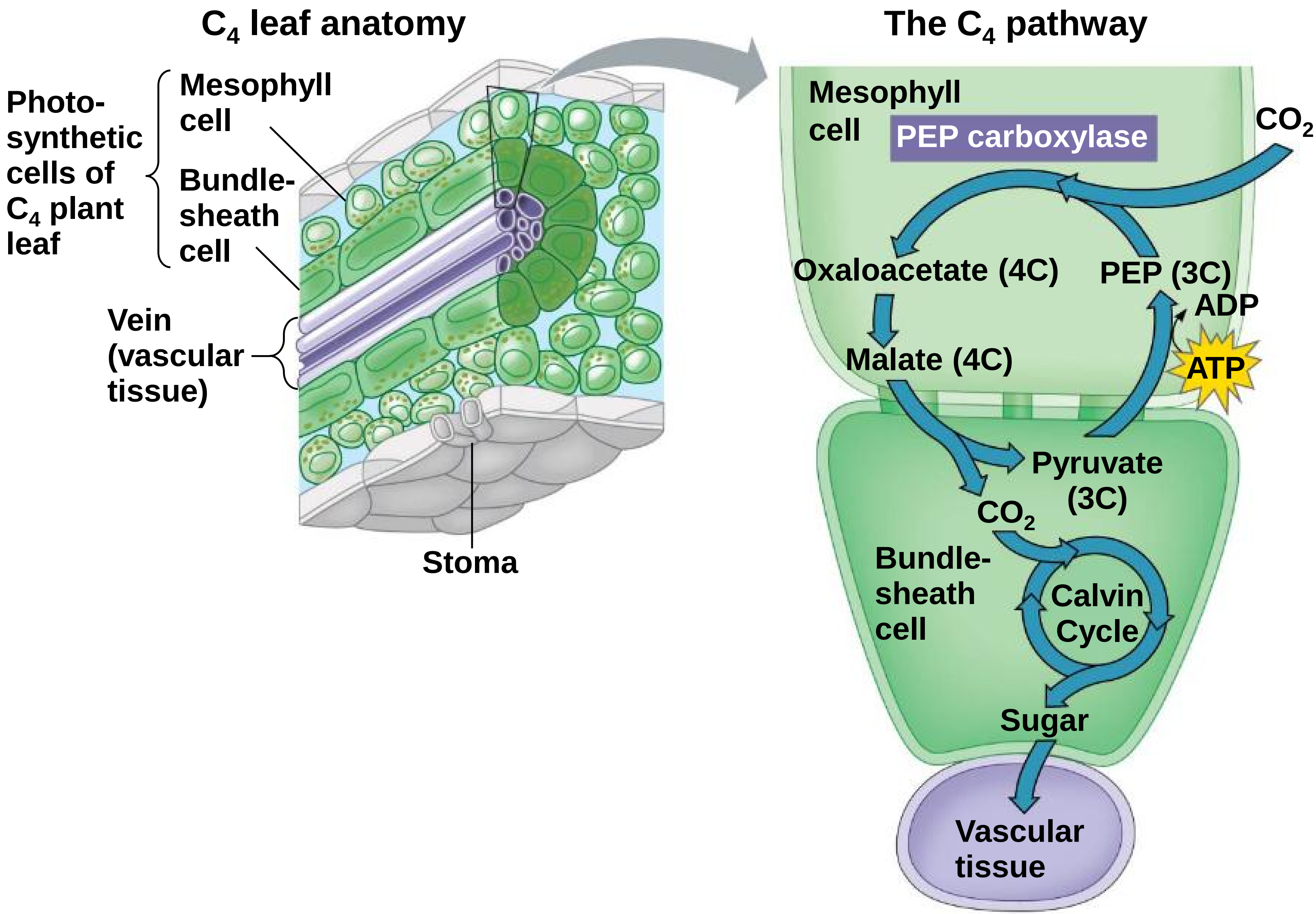
- Sugar production in C_4 plants occurs in a three-step process:

  1. The production of the four carbon precursors is catalyzed by the enzyme **PEP carboxylase** in the mesophyll cells

     - PEP carboxylase has a higher affinity for CO_2 than rubisco does; it can fix CO_2 even when CO_2 concentrations are low

2. These four-carbon compounds are exported to bundle-sheath cells
3. Within the bundle-sheath cells, they release CO_2 that is then used in the Calvin cycle

Figure 11.20



C4 leaf anatomy
Photo-synthetic cells of C4 plant leaf
Mesophyll cell
Bundle-sheath cell
Vein (vascular tissue)
Stoma
The C4 pathway
Mesophyll cell
PEP carboxylase
CO2
Oxaloacetate (4C)
PEP (3C)
ADP
ATP
Malate (4C)
Pyruvate (3C)
CO2
Bundle-sheath cell
Calvin Cycle
Sugar
Vascular tissue

Figure 11.20a

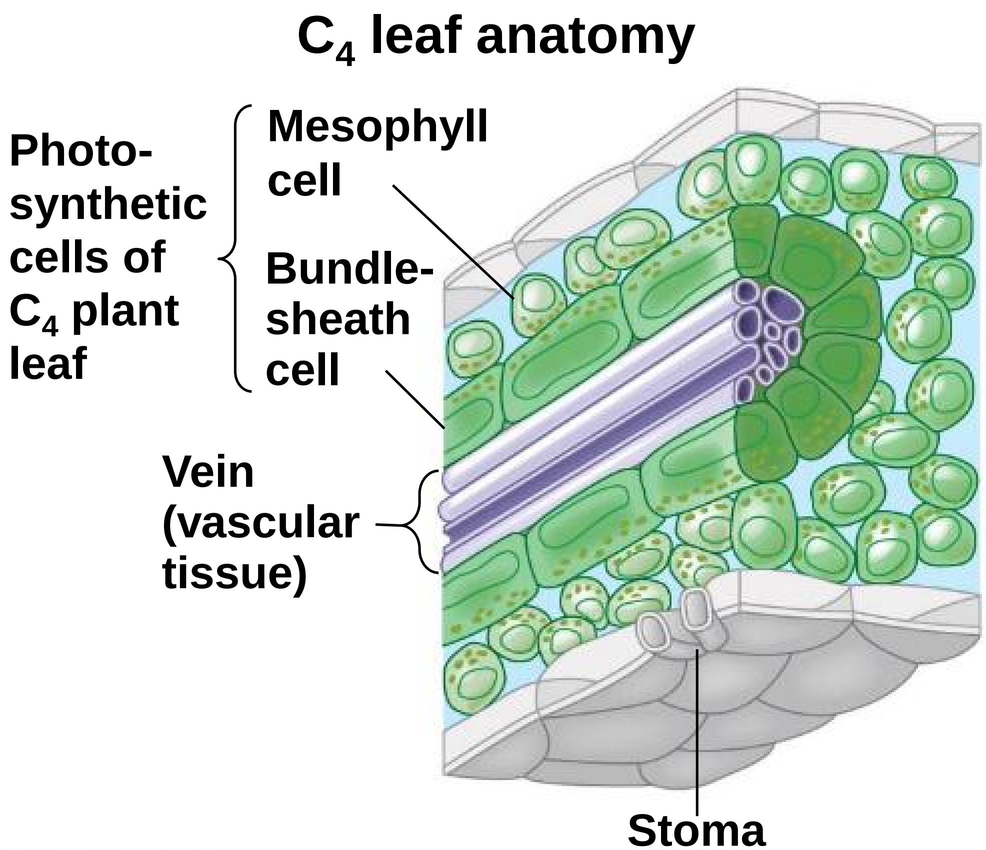
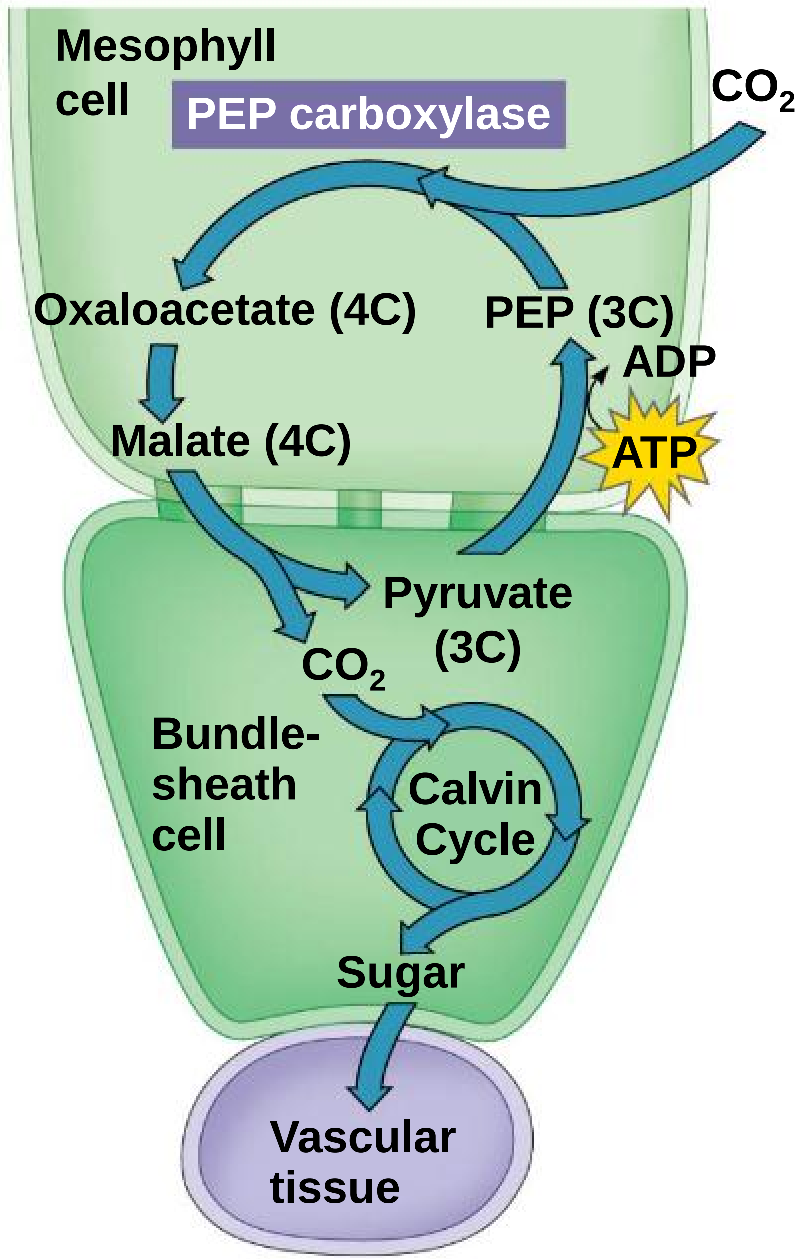


Figure 11.20b

The C_4 pathway

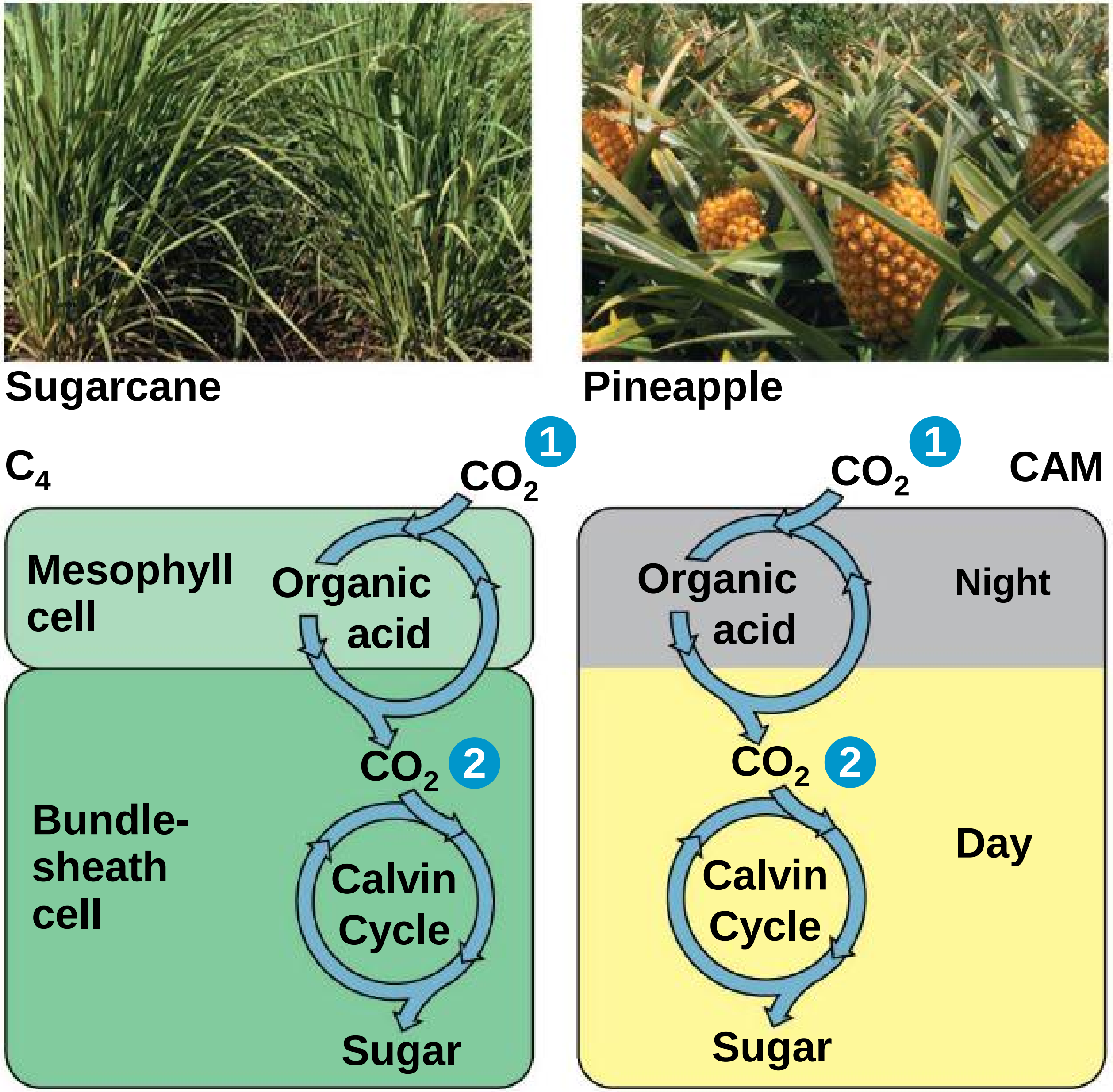


- Since the Industrial Revolution in the 1800s, CO_2 levels have risen greatly
- Increasing levels of CO_2 may affect C_3 and C_4 plants differently, perhaps changing the relative abundance of these species
- The effects of such changes are unpredictable and a cause for concern

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

Figure 11.21



(a) Spatial separation of steps

(b) Temporal separation of steps

Figure 11.21a

Sugarcane

Figure 11.21b

Pineapple

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

Figure 11.22a

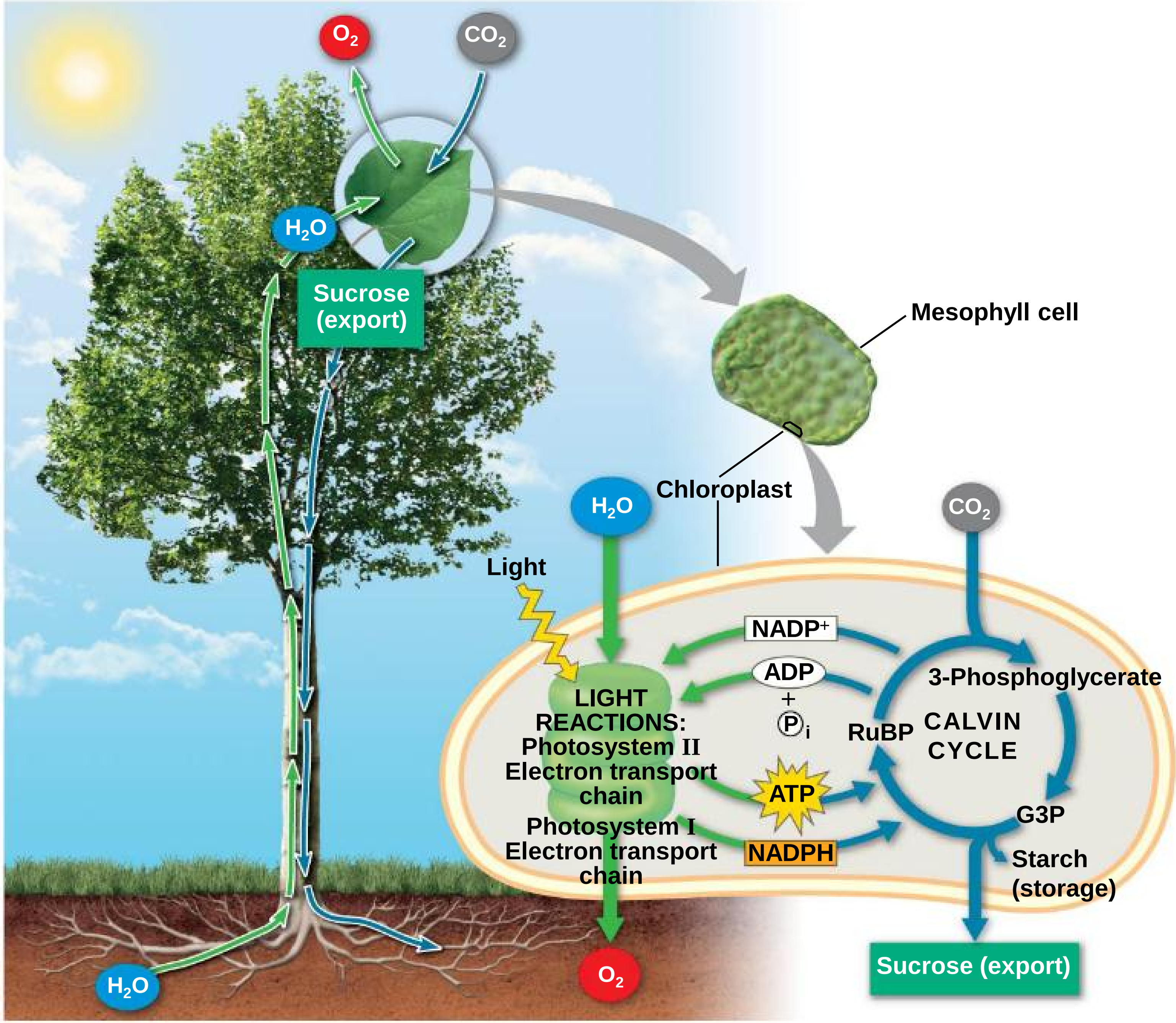


Figure 11.22b

LIGHT REACTIONS	CALVIN CYCLE REACTIONS
• Are carried out by molecules in the thylakoid membranes • Convert light energy to the chemical energy of ATP and NADPH • Split H_2O and release O_2 to the atmosphere	• Take place in the stroma • Use ATP and NADPH to convert CO_2 to the sugar G3P • Return ADP, inorganic phosphate, and $NADP^+$ to the light reactions

Figure 11.23

MAKE CONNECTIONS
The Working Cell

Flow of Genetic Information in the Cell: DNA → RNA → Protein (Chapters 5–7)

Movement Across Cell Membranes (Chapter 7)

Energy Transformations in the Cell: Photosynthesis and Cellular Respiration (Chapters 8–11)

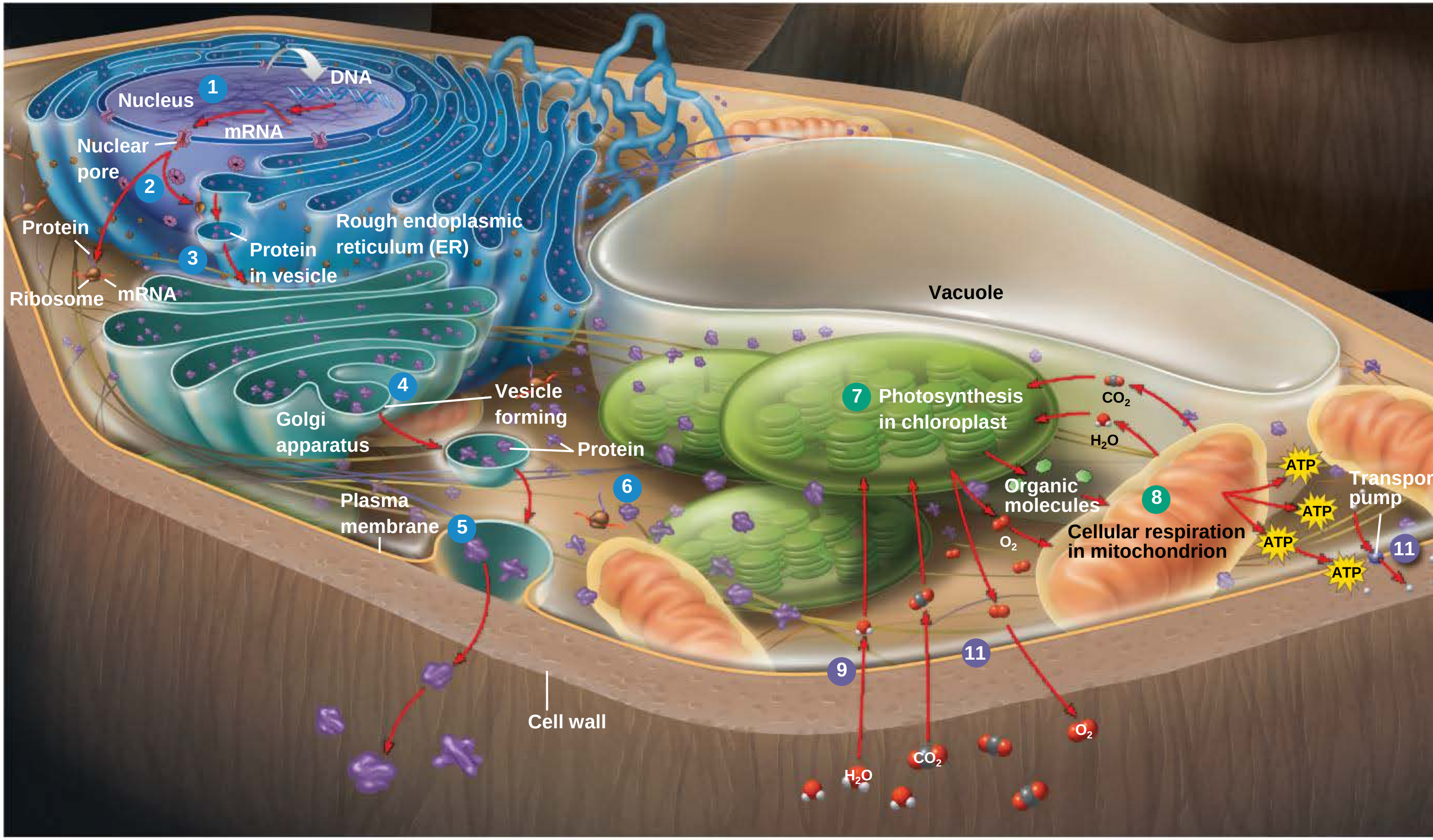


Figure 11.23a

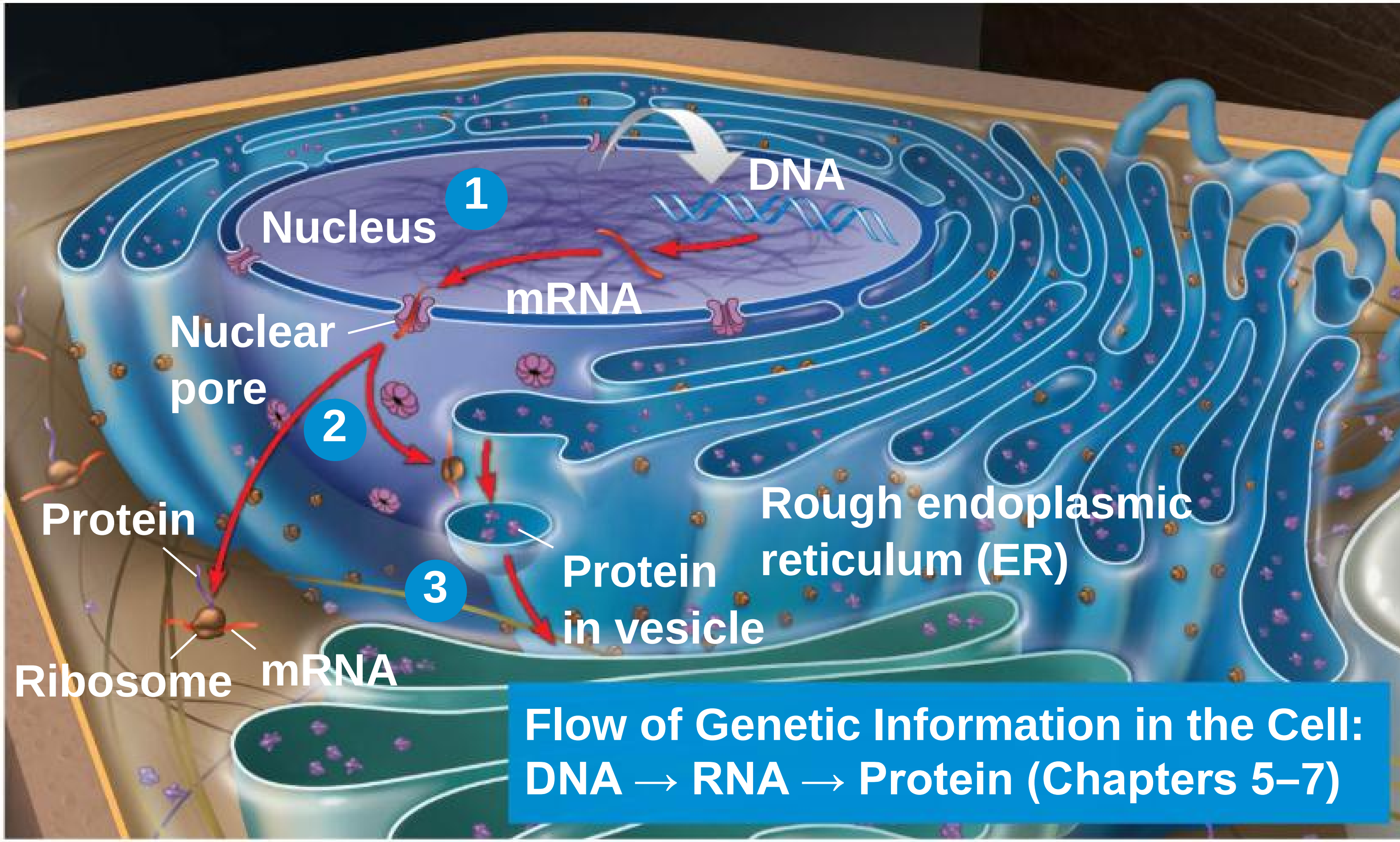


Figure 11.23b

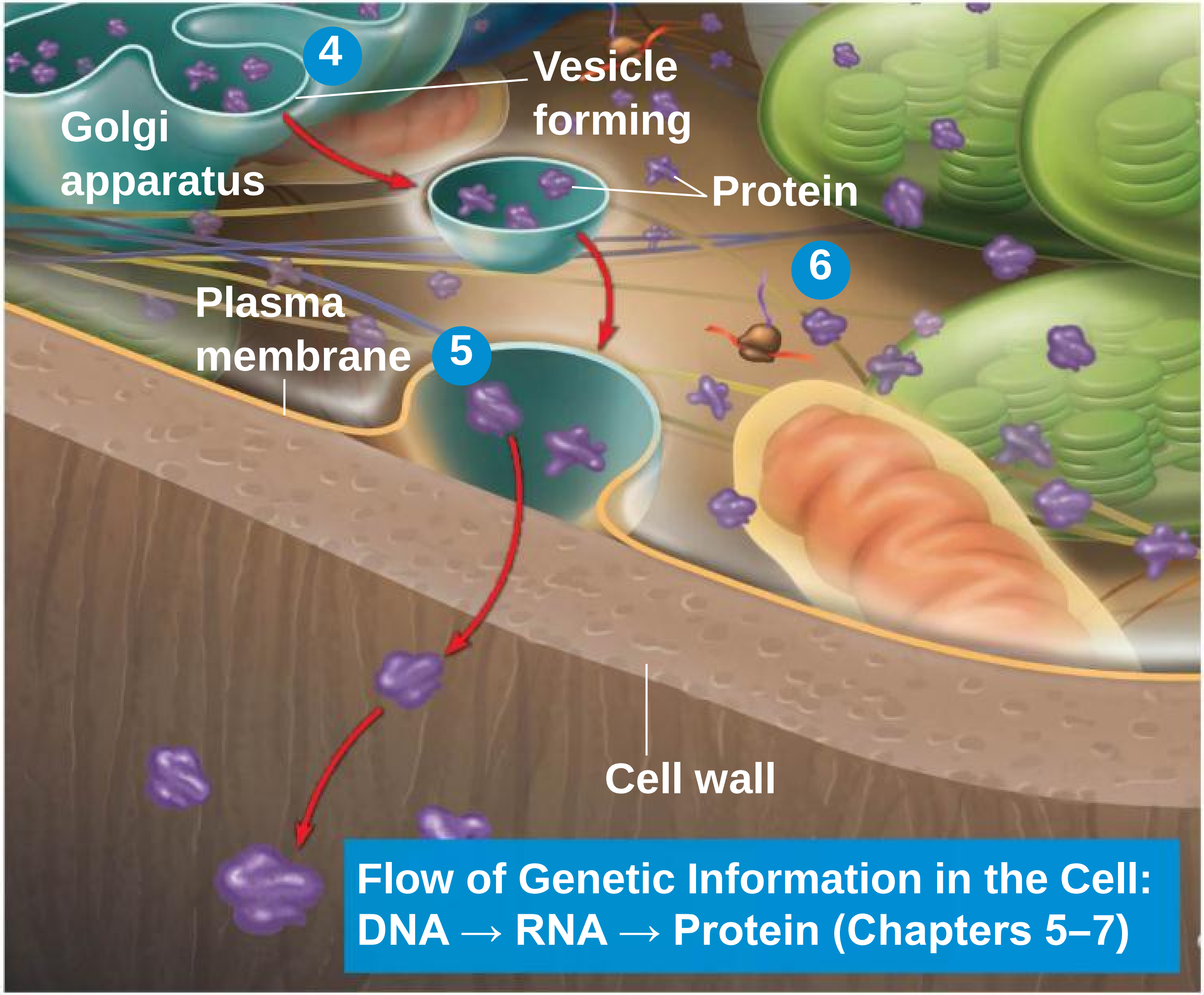


Figure 11.23c

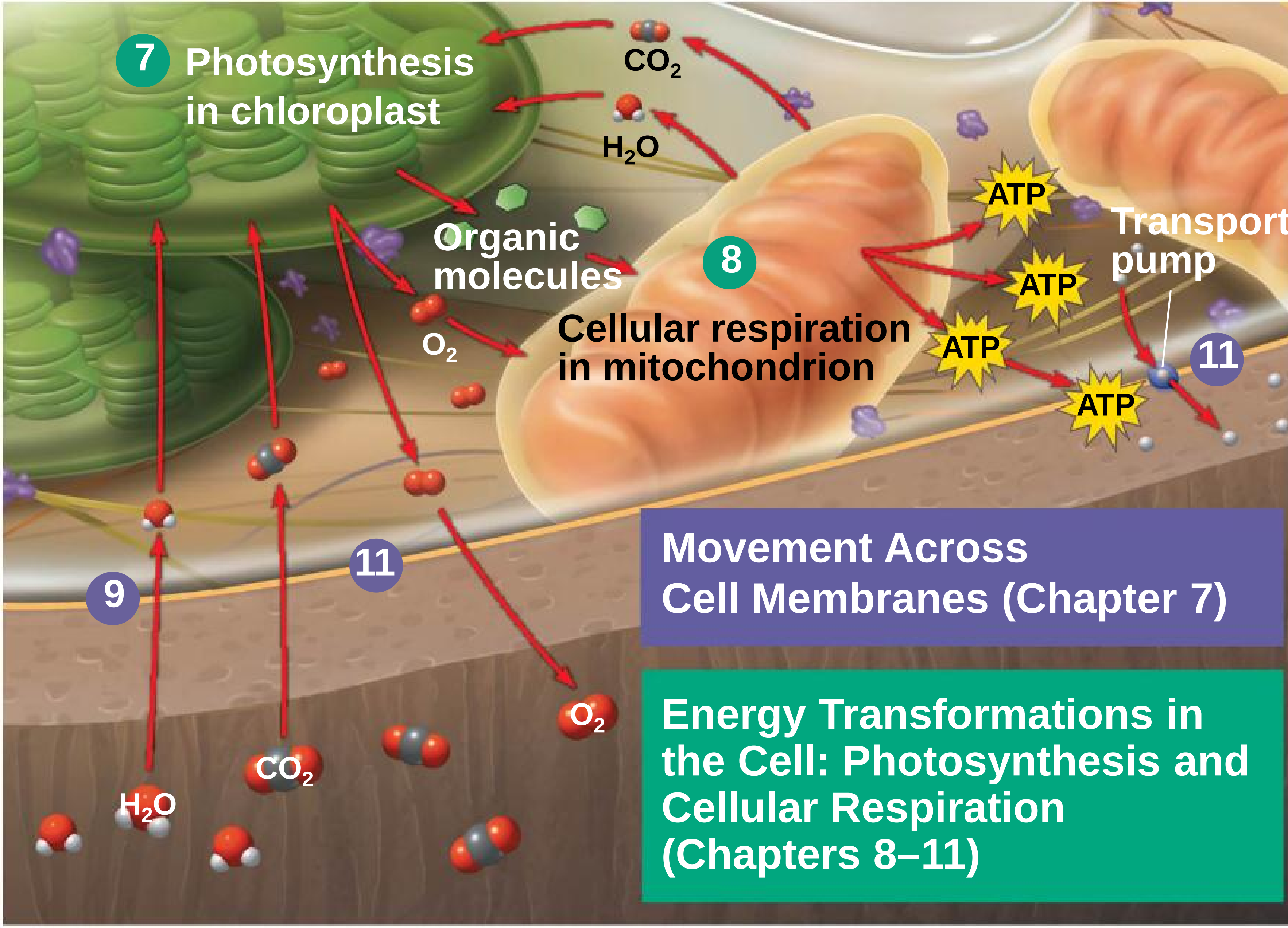


Figure 11.UN04a

	350 ppm CO_2	600 ppm CO_2	1,000 ppm CO_2
Average dry mass of one corn plant (g)	91	89	80
Average dry mass of one velvetleaf plant (g)	35	48	54

Figure 11.UN04b

Corn plant surrounded by invasive velvetleaf plants

Figure 11.UN05

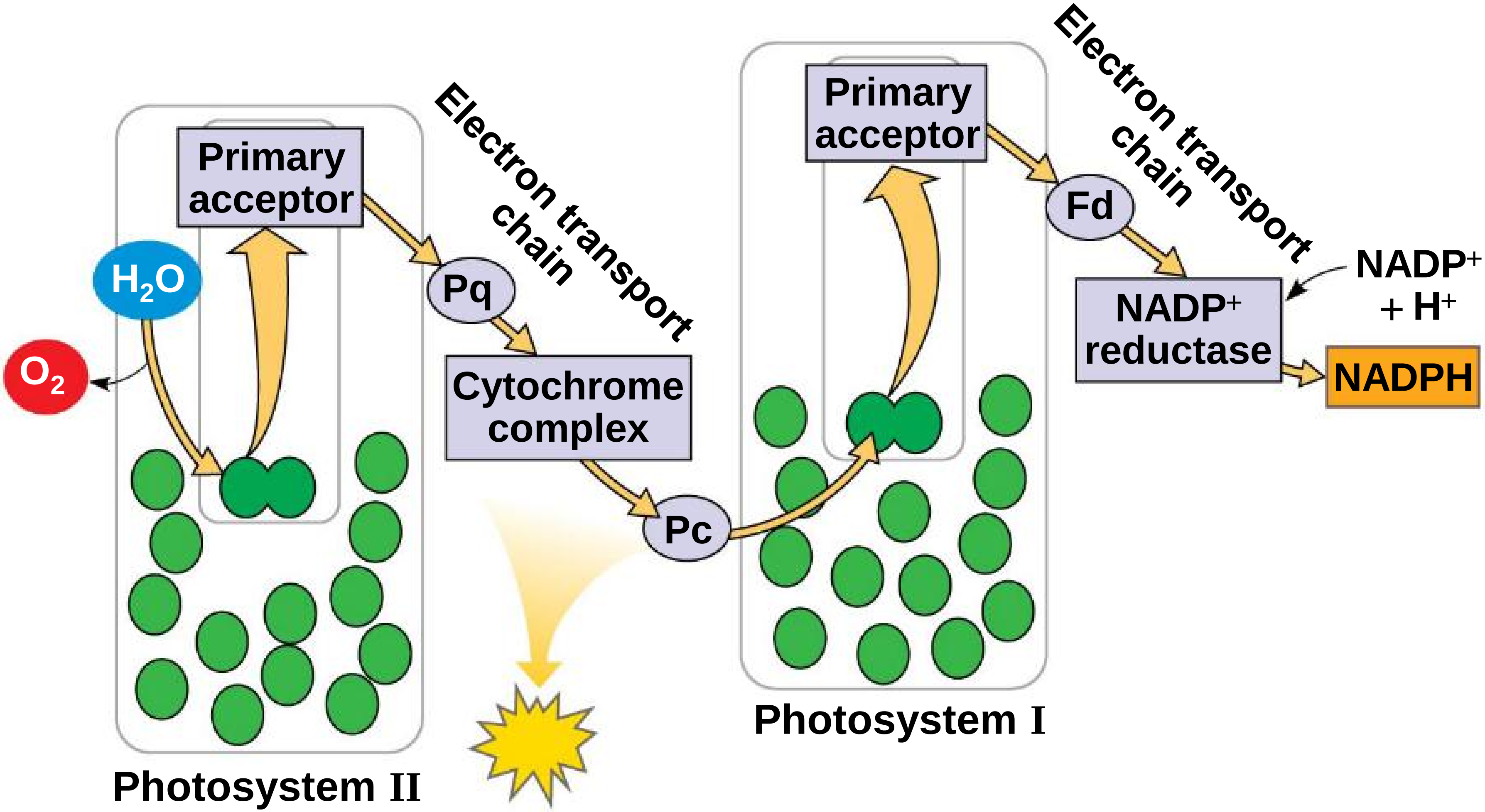


Figure 11.UN06

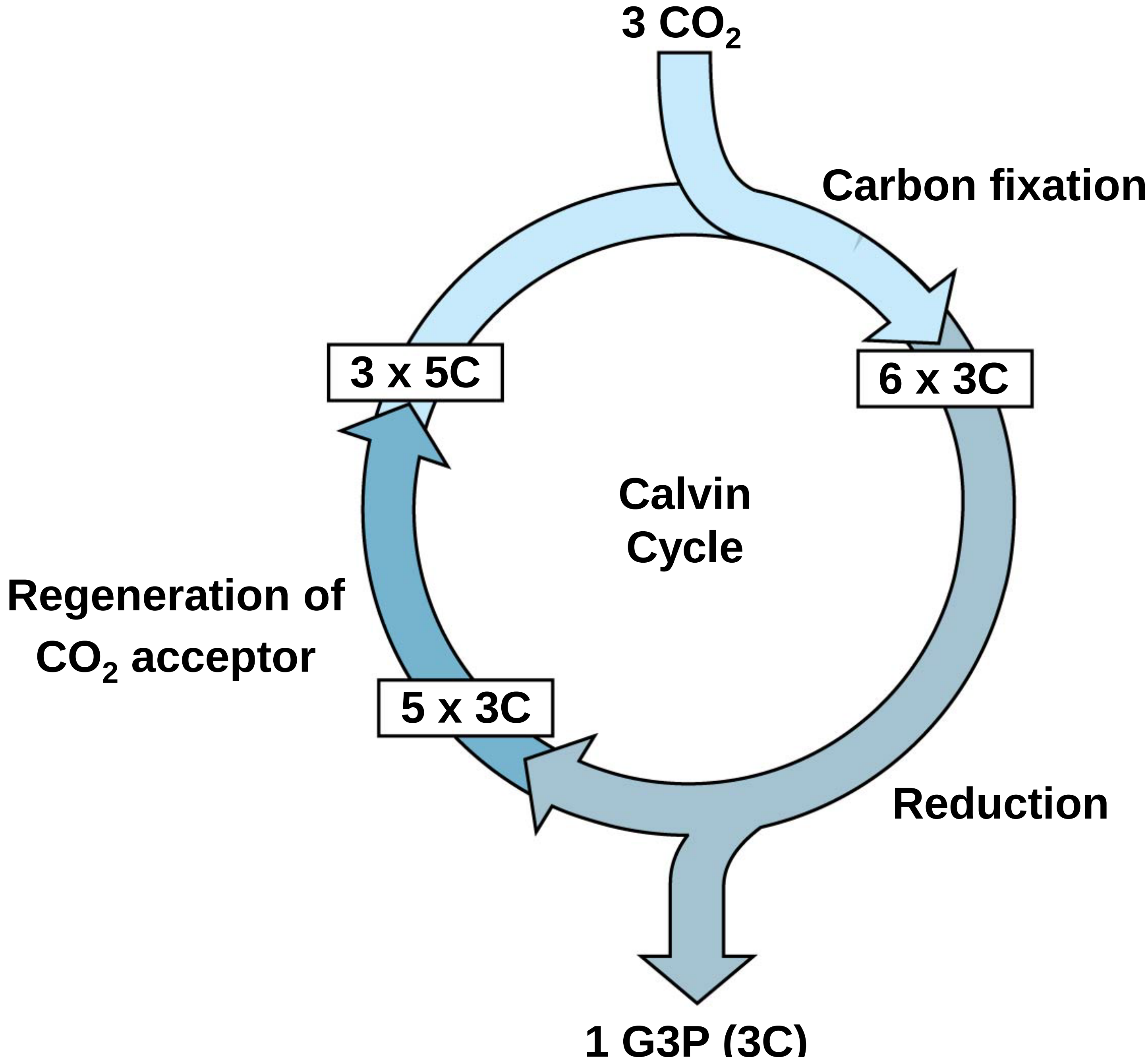


Figure 11.UN07

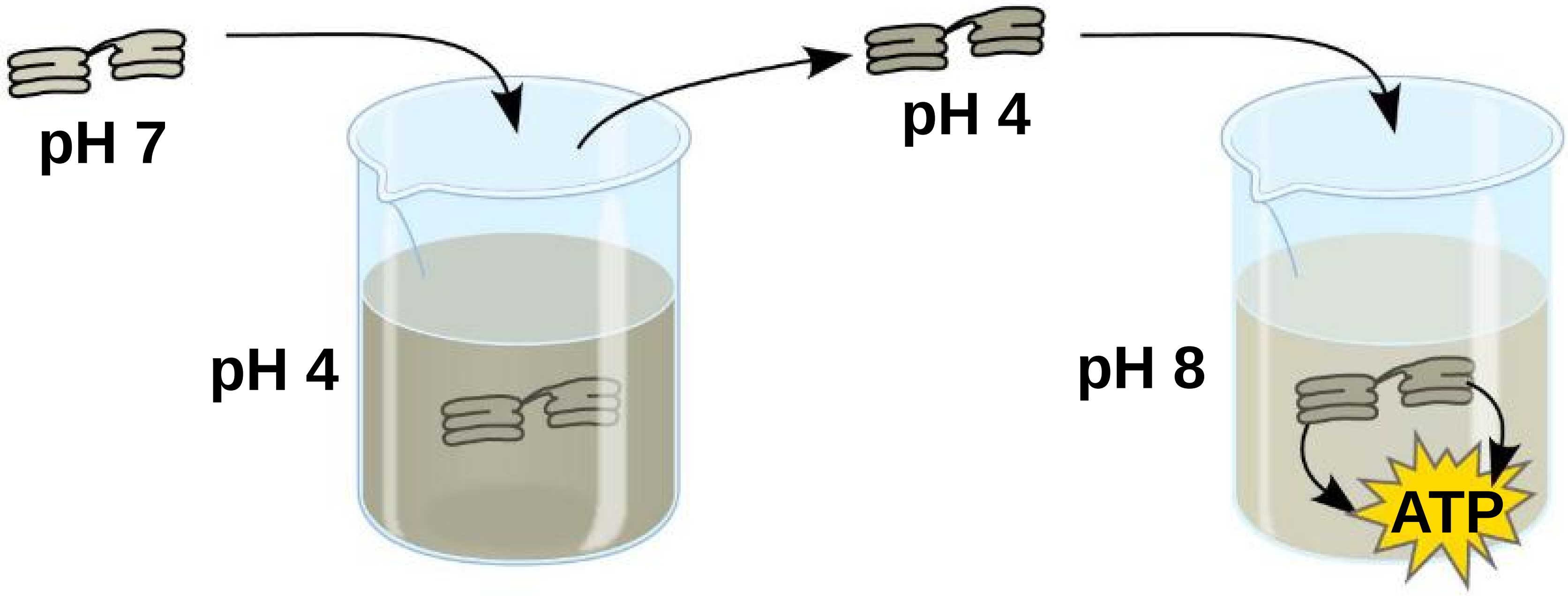
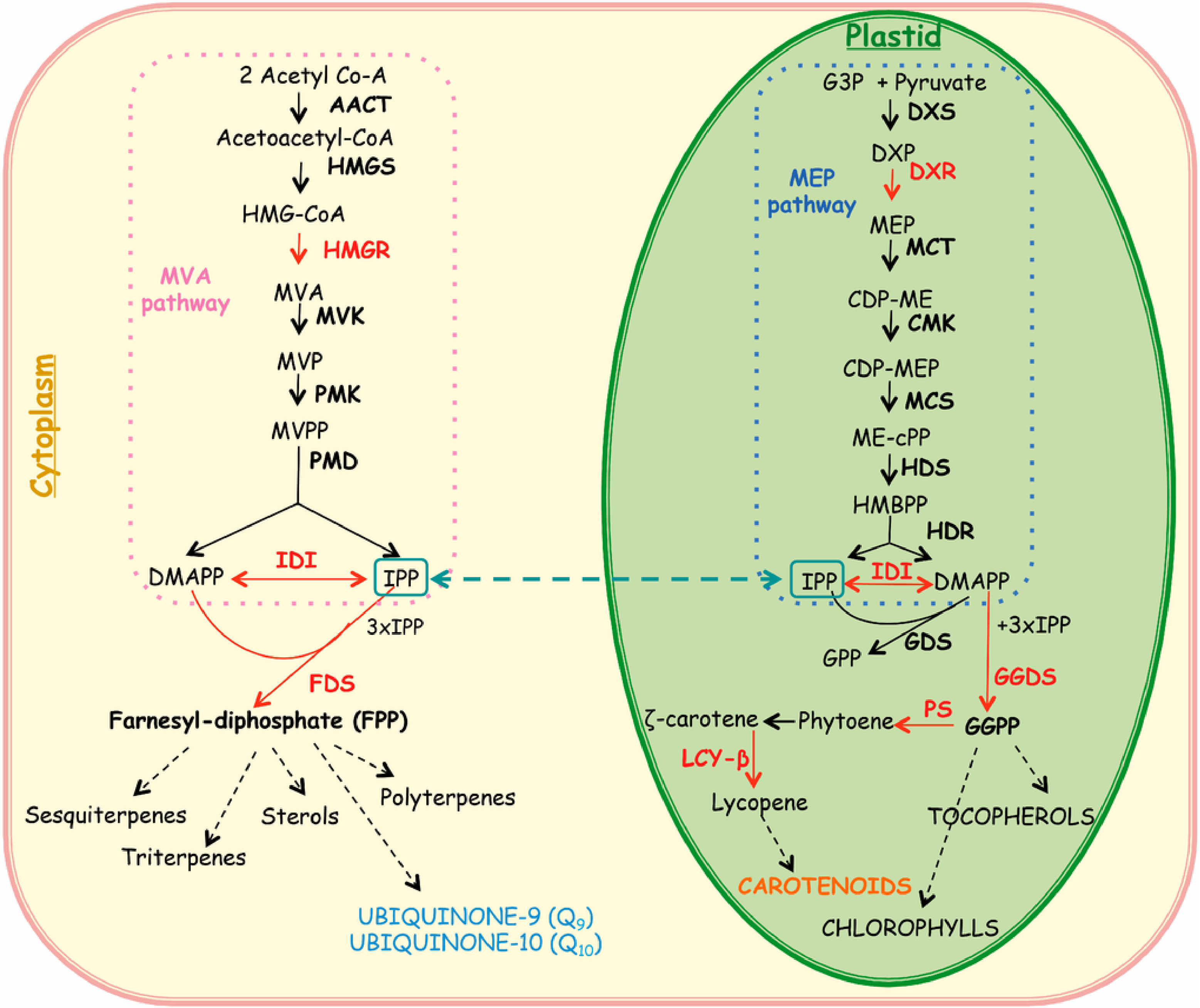
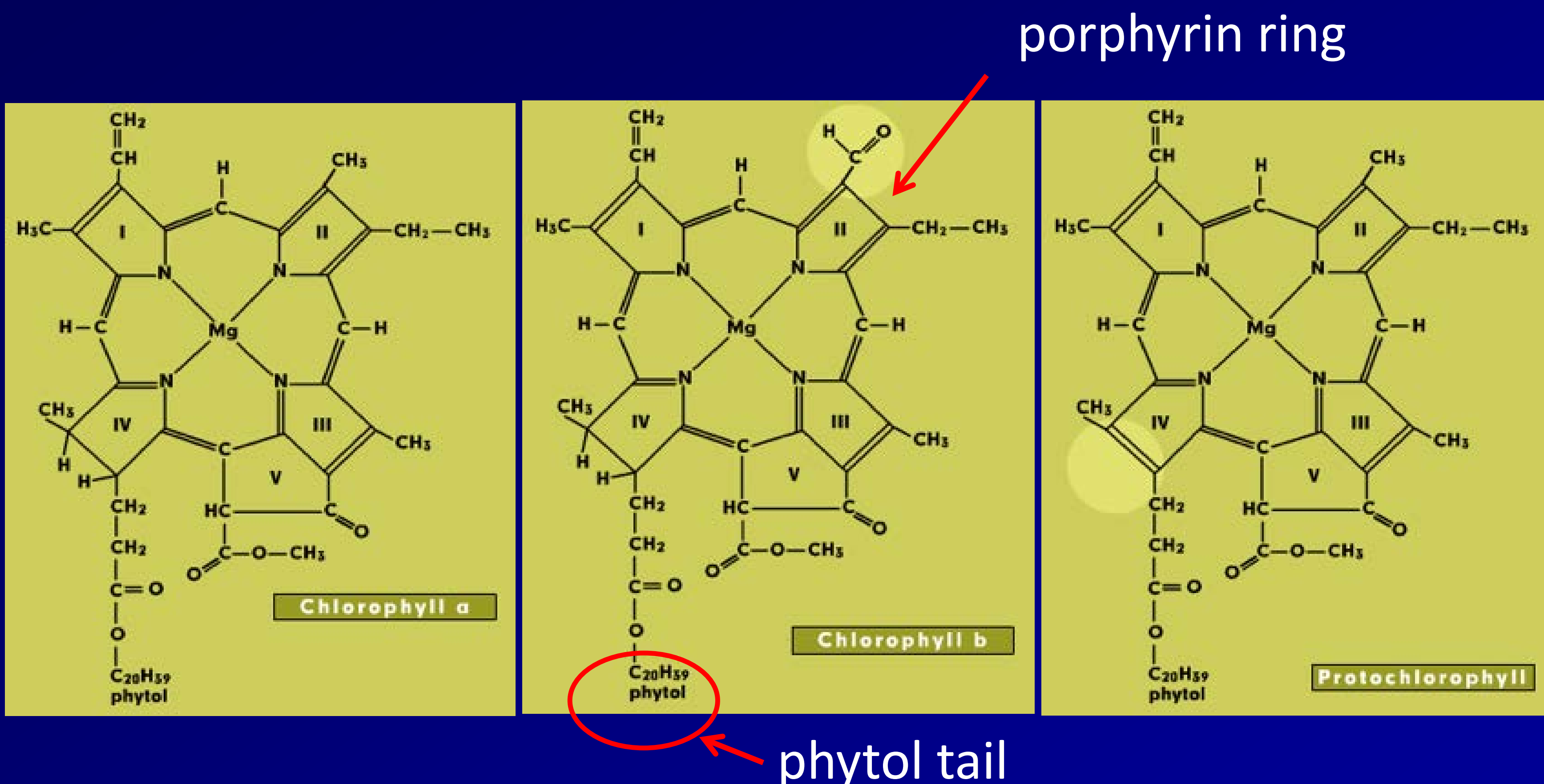


Figure 11.UN08


Plastid
Cytoplasm
2 Acetyl Co-A
AACT
Acetoacetyl-CoA
HMGS
HMG-CoA
HMGR
MVA pathway
MVA
MVK
MVP
PMK
MVPP
PMD
DMAPP
IDI
IPP
3xIPP
FDS
Farnesyl-diphosphate (FPP)
Sesquiterpenes
Triterpenes
Sterols
Polyterpenes
UBIQUINONE-9 (Q_9)
UBIQUINONE-10 (Q_{10})
G3P + Pyruvate
DXS
DXP
DXR
MEP pathway
MEP
MCT
CDP-ME
CMK
CDP-MEP
MCS
ME-cPP
HDS
HMBPP
HDR
IPP
IDI
DMAPP
+3xIPP
GDS
GPP
GGDS
ζ-carotene
Phytoene
PS
GGPP
LCY-β
Lycopene
TOCOPHEROLS
CAROTENOIDS
CHLOROPHYLLS



Chlorophylls consist of a light-absorbing with a magnesium atom at the center and a long phytol tail that anchors the molecule in a membrane (Figure 1). They absorb light in the blue and red parts of the spectrum, but the green wavelengths are transmitted or reflected.