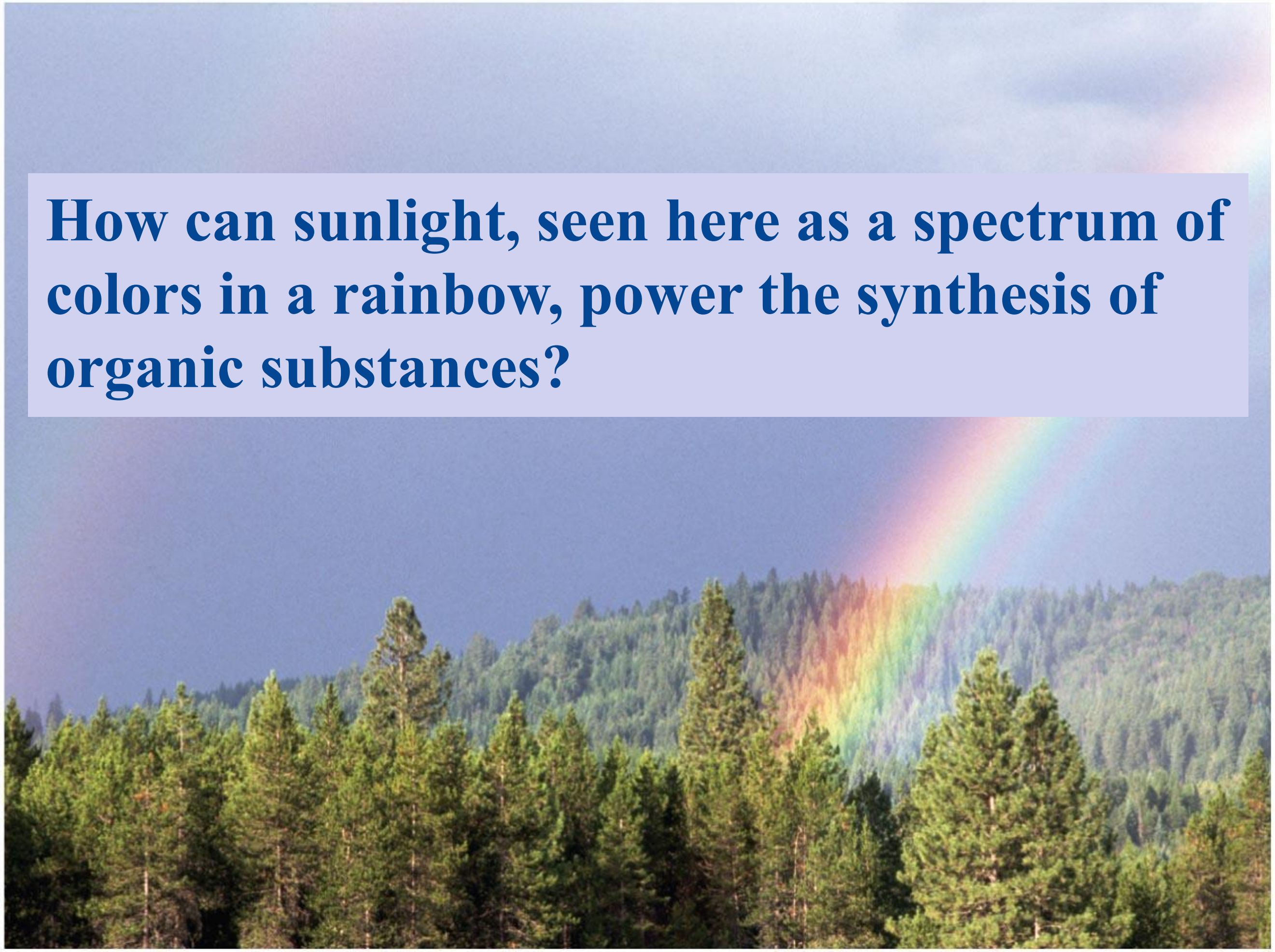
Chapter TEN

Photosynthesis



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**

Figure 10.2

Photoautotrophs

(a) Plants

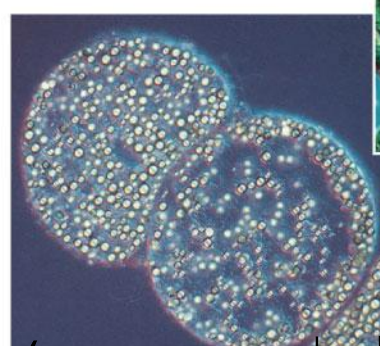
(b) Multicellular alga

(c) Unicellular protists

10 µm

(d) Cyanobacteria

40 µm



1 µm

(e) Purple sulfur

- **Heterotrophs** obtain their organic material **from other organisms**

- Heterotrophs are the ***consumers*** of the biosphere

- Almost all heterotrophs, including humans, **depend** on photoautotrophs for **food and O_2**

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

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

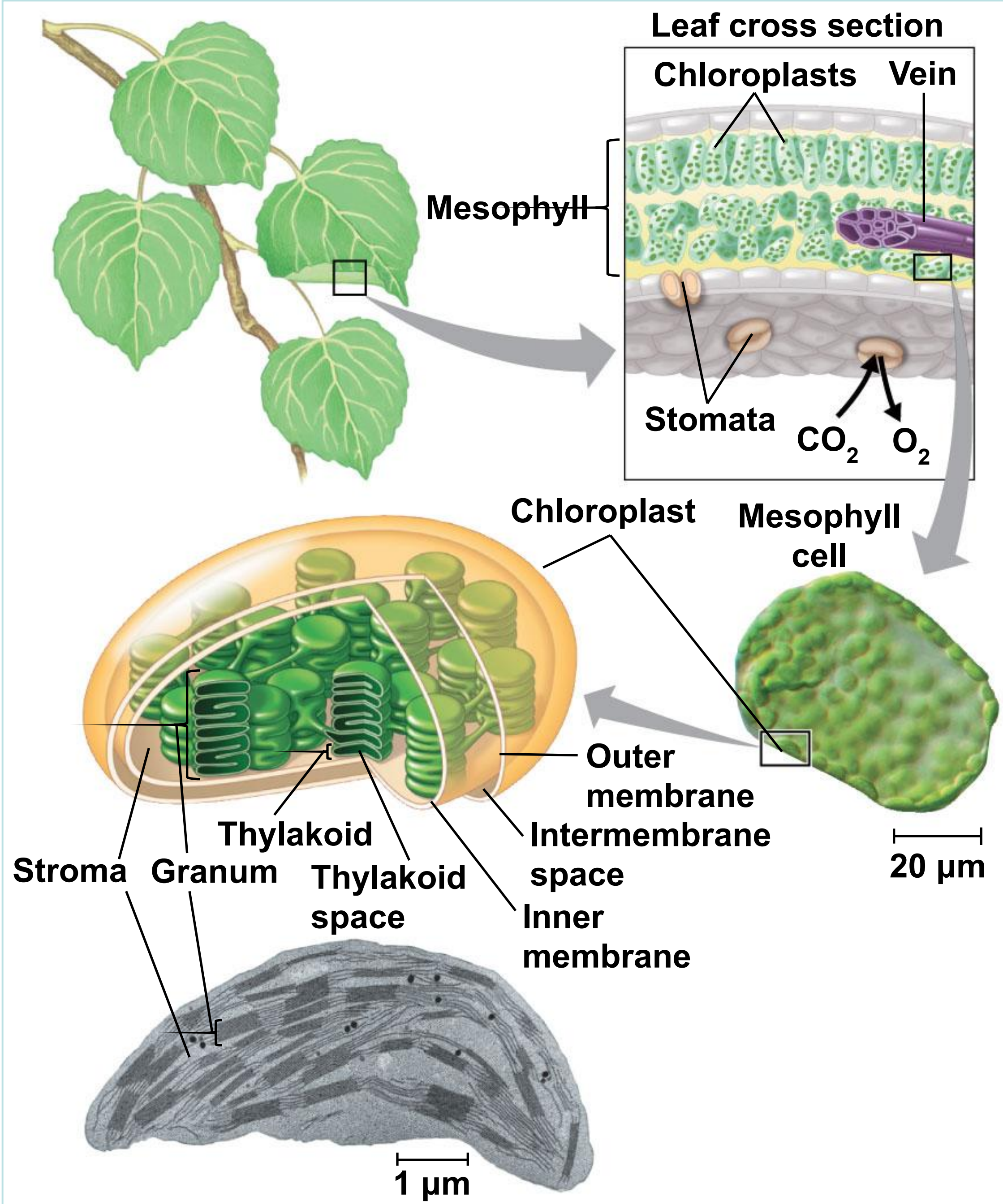
Chloroplasts: The Sites of Photosynthesis in Plants

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

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

Figure 10.4

Zooming in on the location of photosynthesis in a plant.



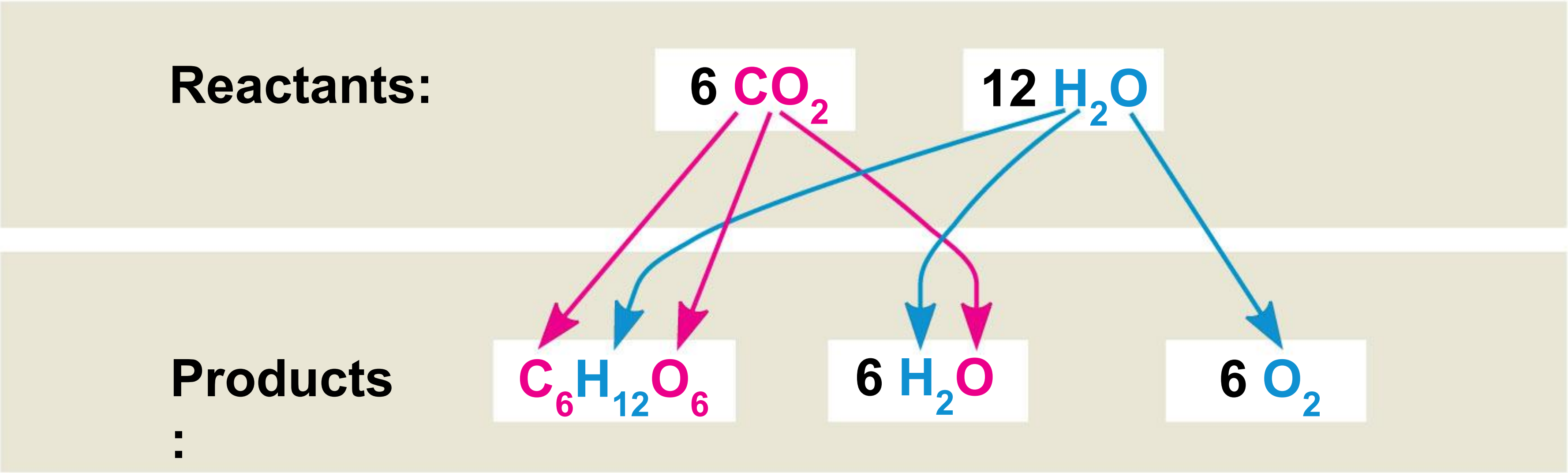
Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:

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

Figure 10.5

Tracking atoms through photosynthesis.



The Splitting of Water

- **Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules**
  - **Plants: $CO_2 + 2H_2O$ □[CH_2O] + $H_2O + O_2$**
  - **Sulfur bacteria: $CO_2 + H_2S$ □ [CH_2O] + H_2O + S_2**

- **CO2 is not split into C and O2!! This hypothesis was <u>cancelled</u> by van Neil in 1930s**

Photosynthesis as a Redox Process

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

Figure 10.UN01

becomes reduced

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

becomes oxidized

- **Summary:**
- **H2O is split, & electrons are transferred *along with H ions* from H2O to CO2 reducing it to sugars!**
- **Endergonic reaction.**

"absorbing energy in the form of work."

How this reaction relates to cellular respiration??

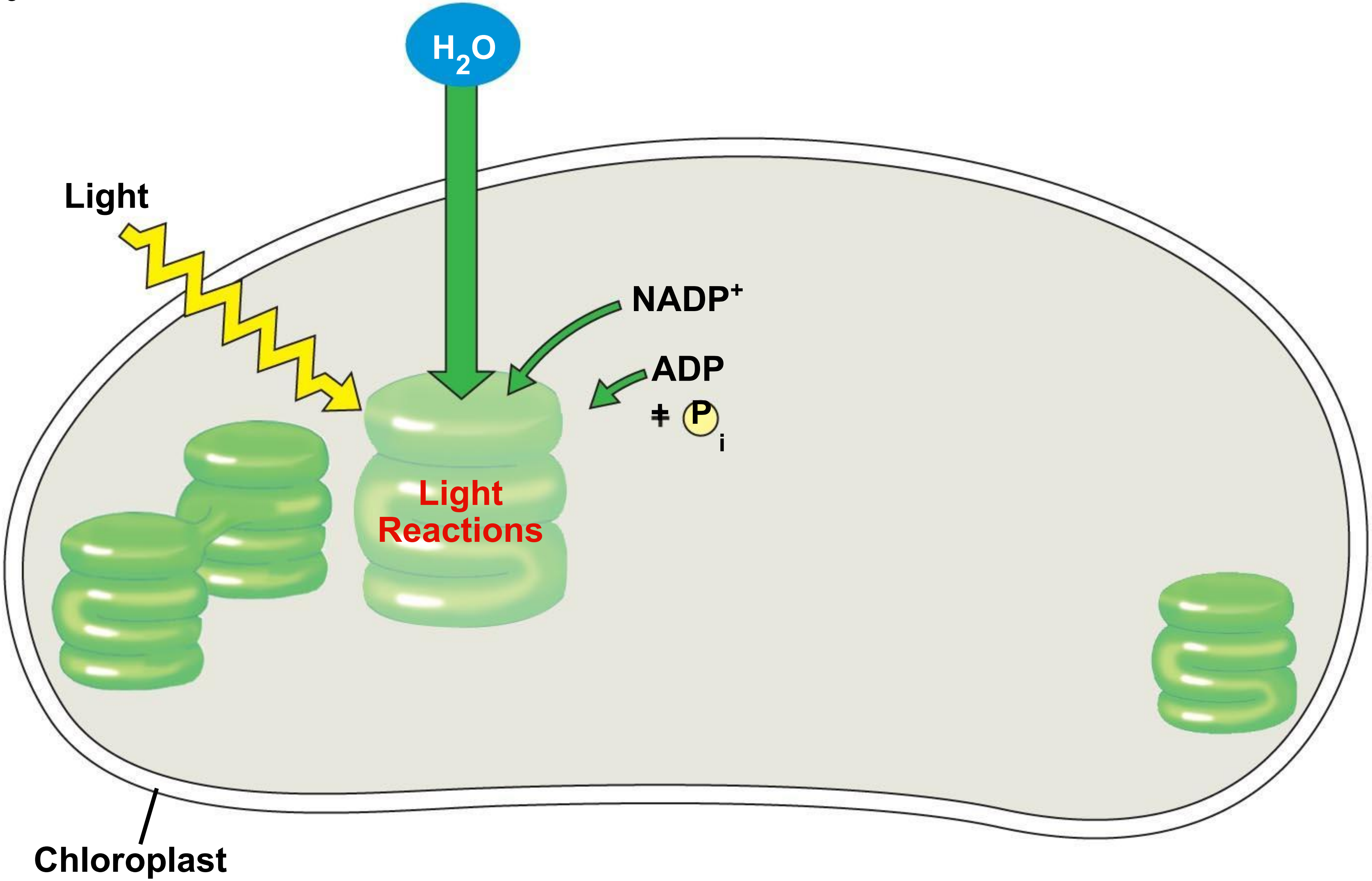
The Two Stages of Photosynthesis: *A Preview*

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

- **The Calvin cycle** (***in the stroma***) **forms sugar from CO_2, using ATP and NADPH**

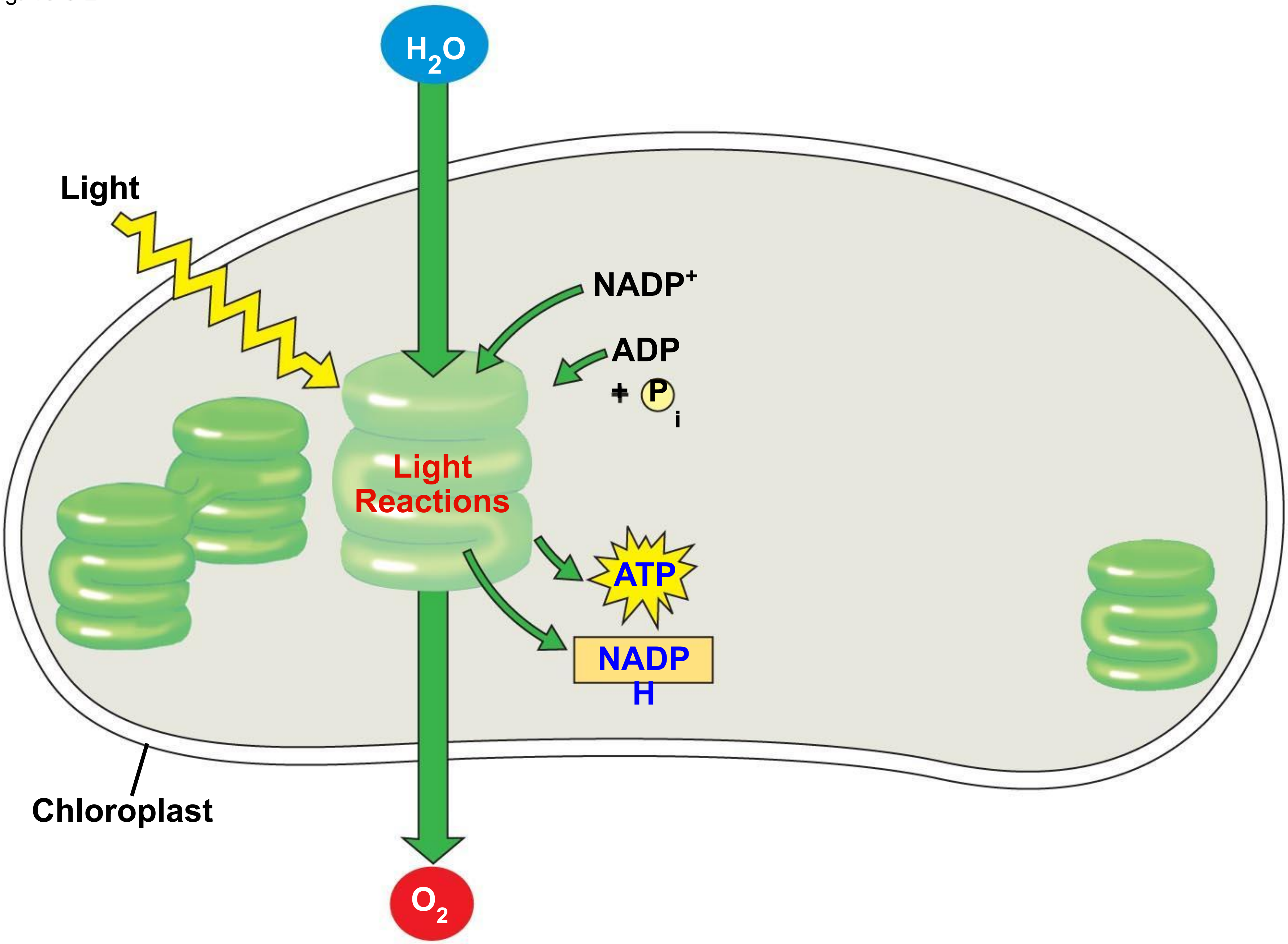
- **The Calvin cycle begins with carbon fixation, incorporating CO_2 into organic molecules**

Fig. 10-5-1



An overview of photosynthesis: cooperation of the light reactions and the Calvin cycle.

Fig. 10-5-2



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

Fig. 10-5-3

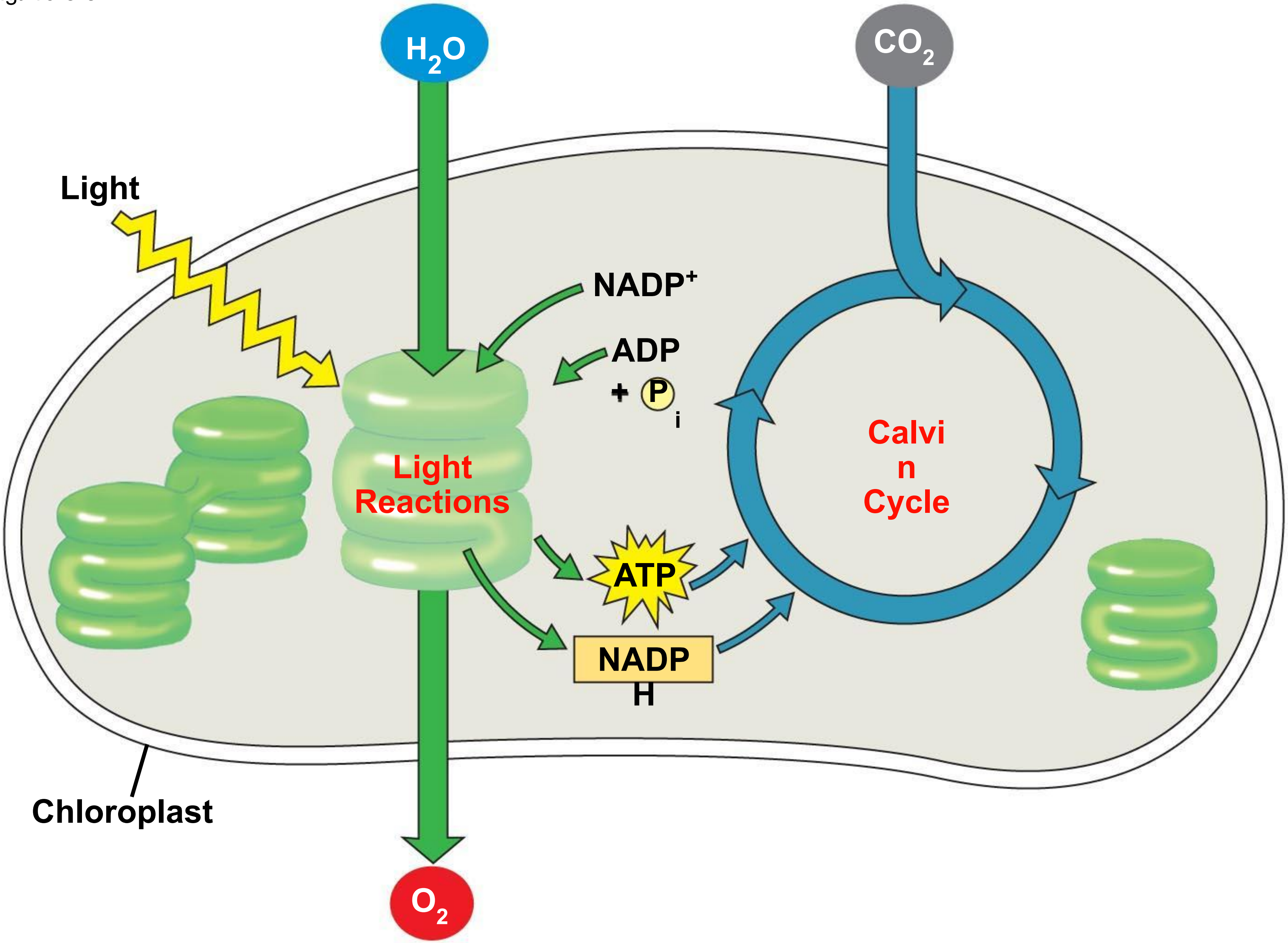
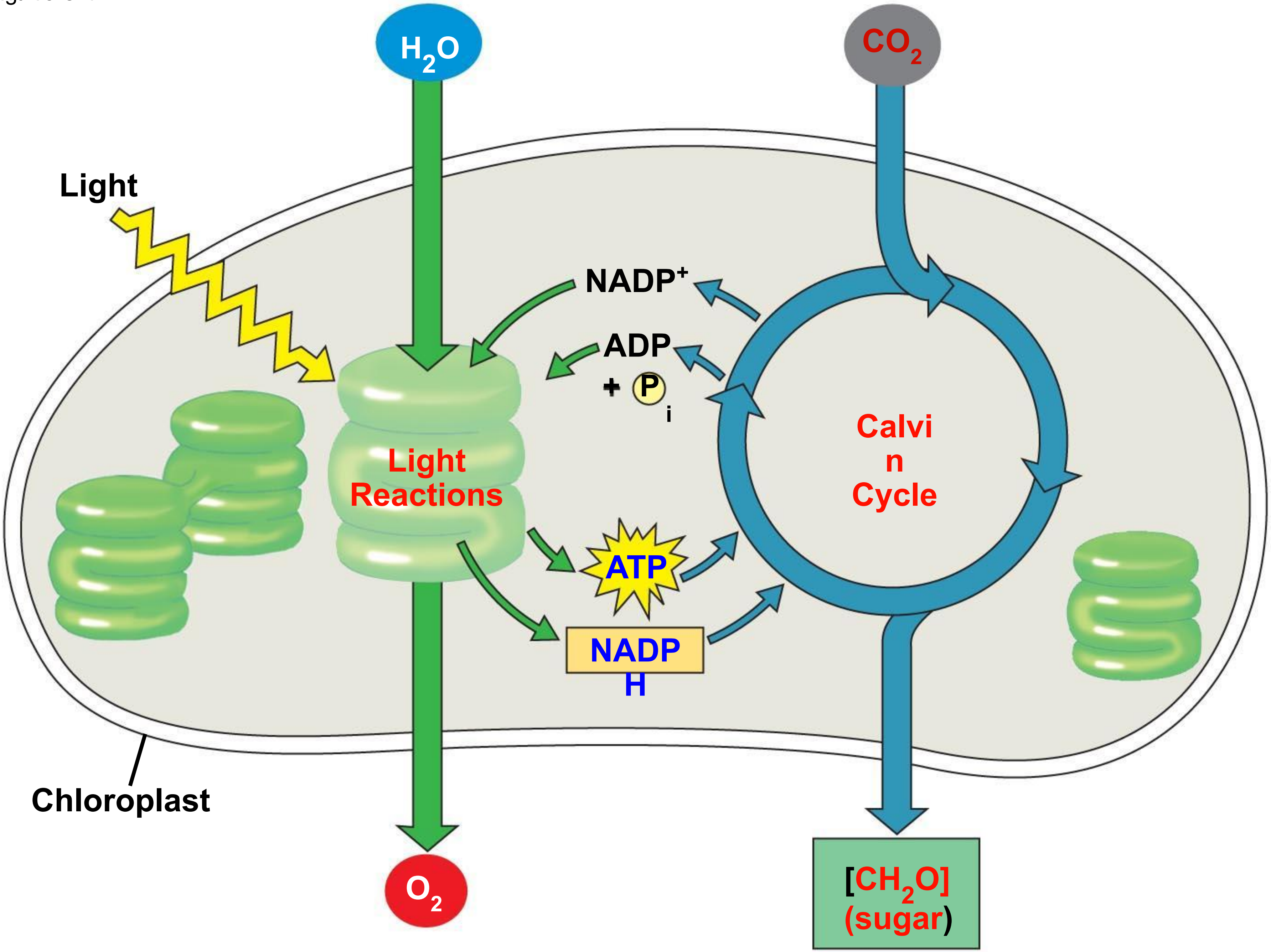

H_2O
CO_2
Light
$NADP^+$
ADP
+ P_i
Light Reactions
Calvi
n
Cycle
ATP
NADP
H
Chloroplast
O_2

Fig. 10-5-4



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

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

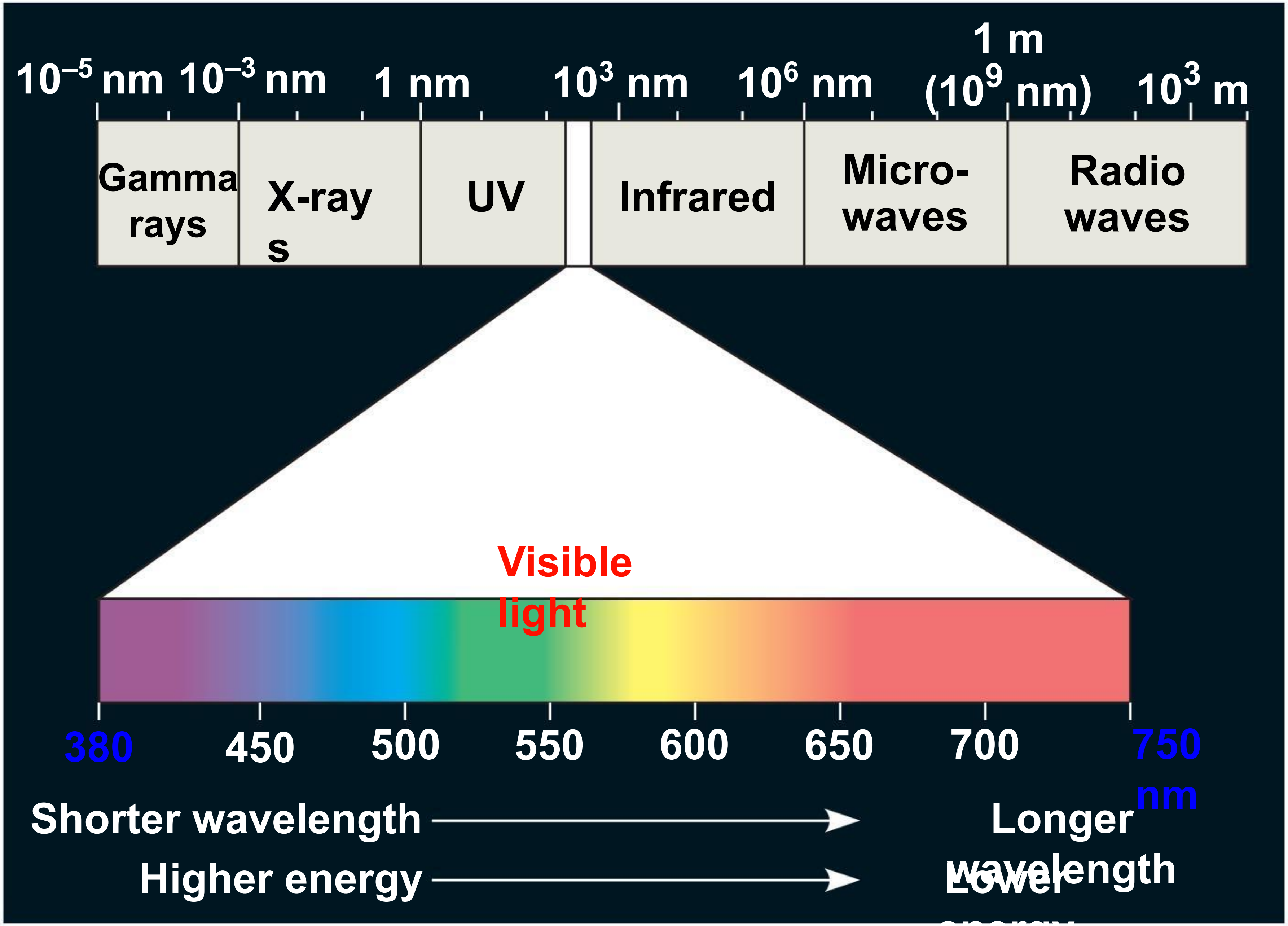
- Chloroplasts are solar-powered chemical factories
- Their thylakoids transform light energy into the chemical energy of ATP and NADPH

The Nature of Sunlight

- Light is a form of electromagnetic energy = electromagnetic radiation
- Light travels in rhythmic waves
- Wavelength is the distance between crests of waves
- Wavelength determines the type of electromagnetic energy

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

Fig. 10-6



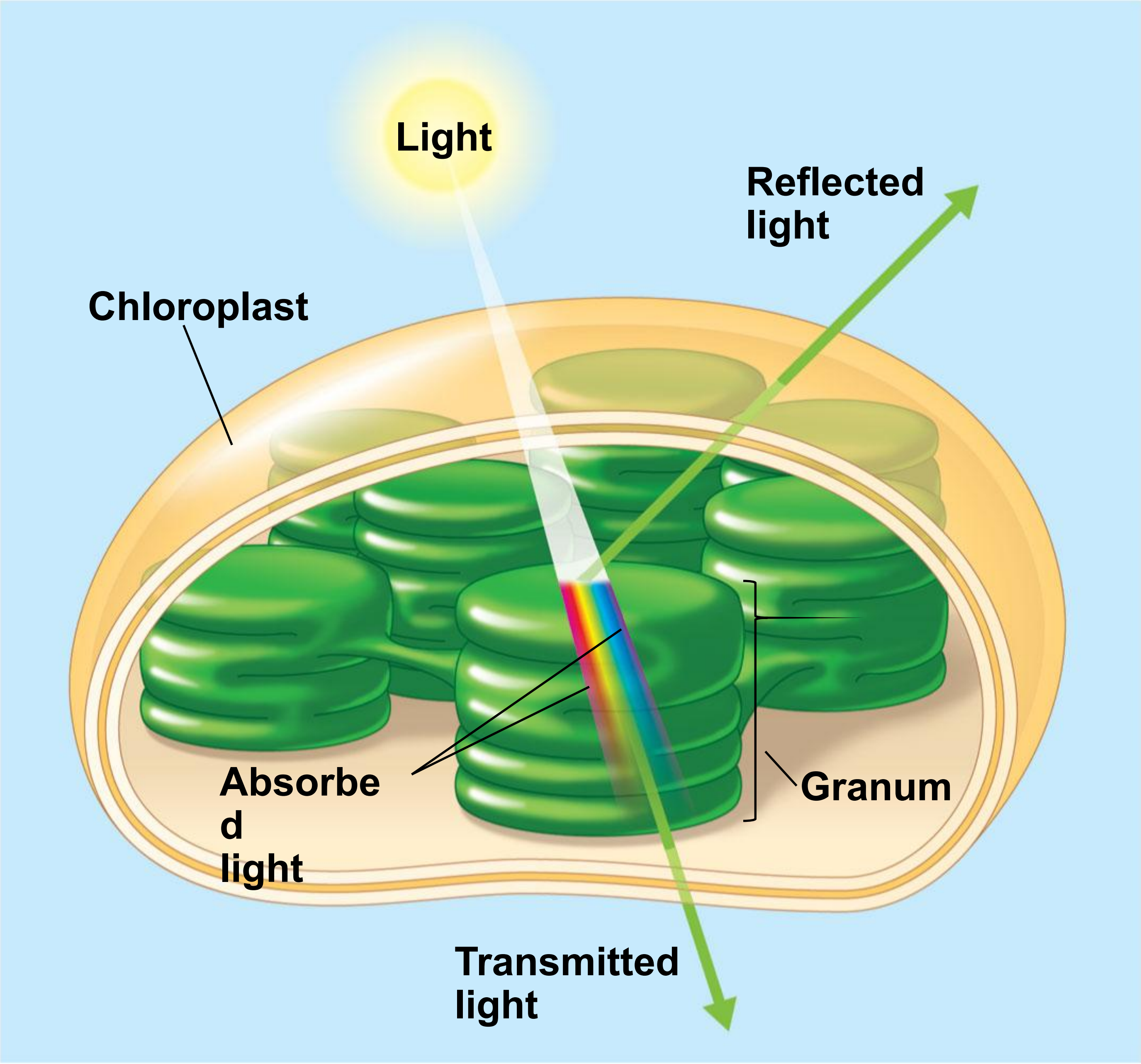
10⁻⁵ nm
10⁻³ nm
1 nm
10³ nm
10⁶ nm
1 m (10⁹ nm)
10³ m
Gamma rays
X-rays
UV
Infrared
Micro-waves
Radio waves
Visible light
380
450
500
550
600
650
700
750 nm
Shorter wavelength
Higher energy
Longer wavelength
Lower energy

Photosynthetic Pigments: The Light Receptors

- 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 10.8


Light
Reflected light
Chloroplast
Absorbe
d
light
Granum
Transmitted light

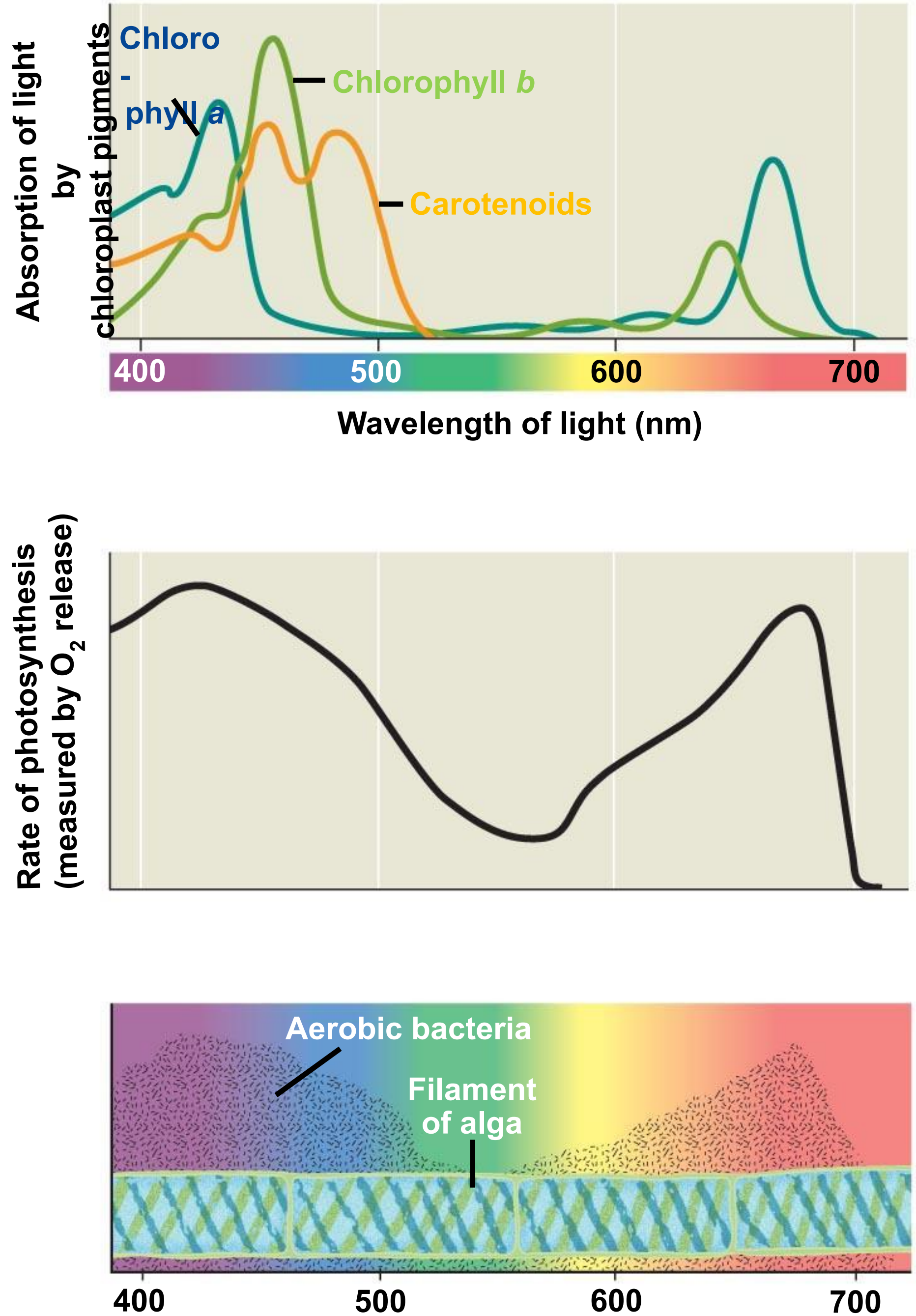
- A spectrophotometer measures a pigment’s ability to absorb various wavelengths
- This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

- **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**

Fig. 10-9

RESULTS



(a) Absorption spectra

(b) Action spectrum

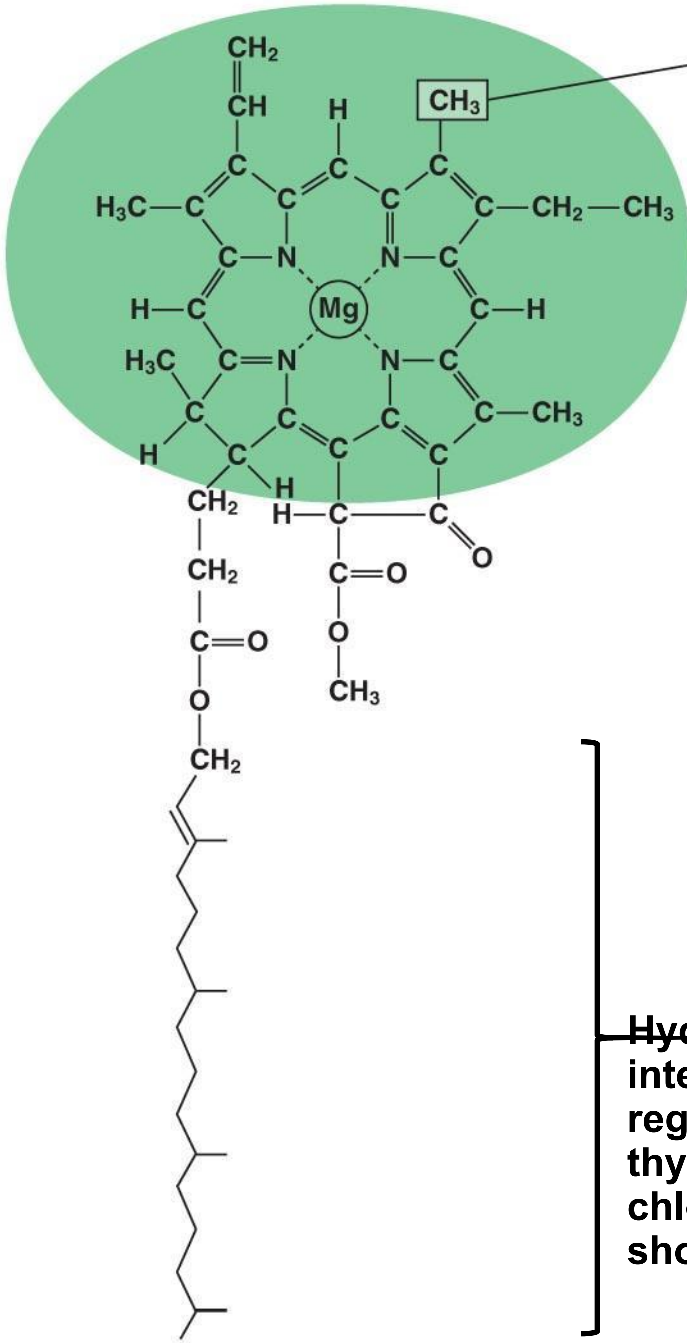
(c) Engelmann's experiment

- ***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***

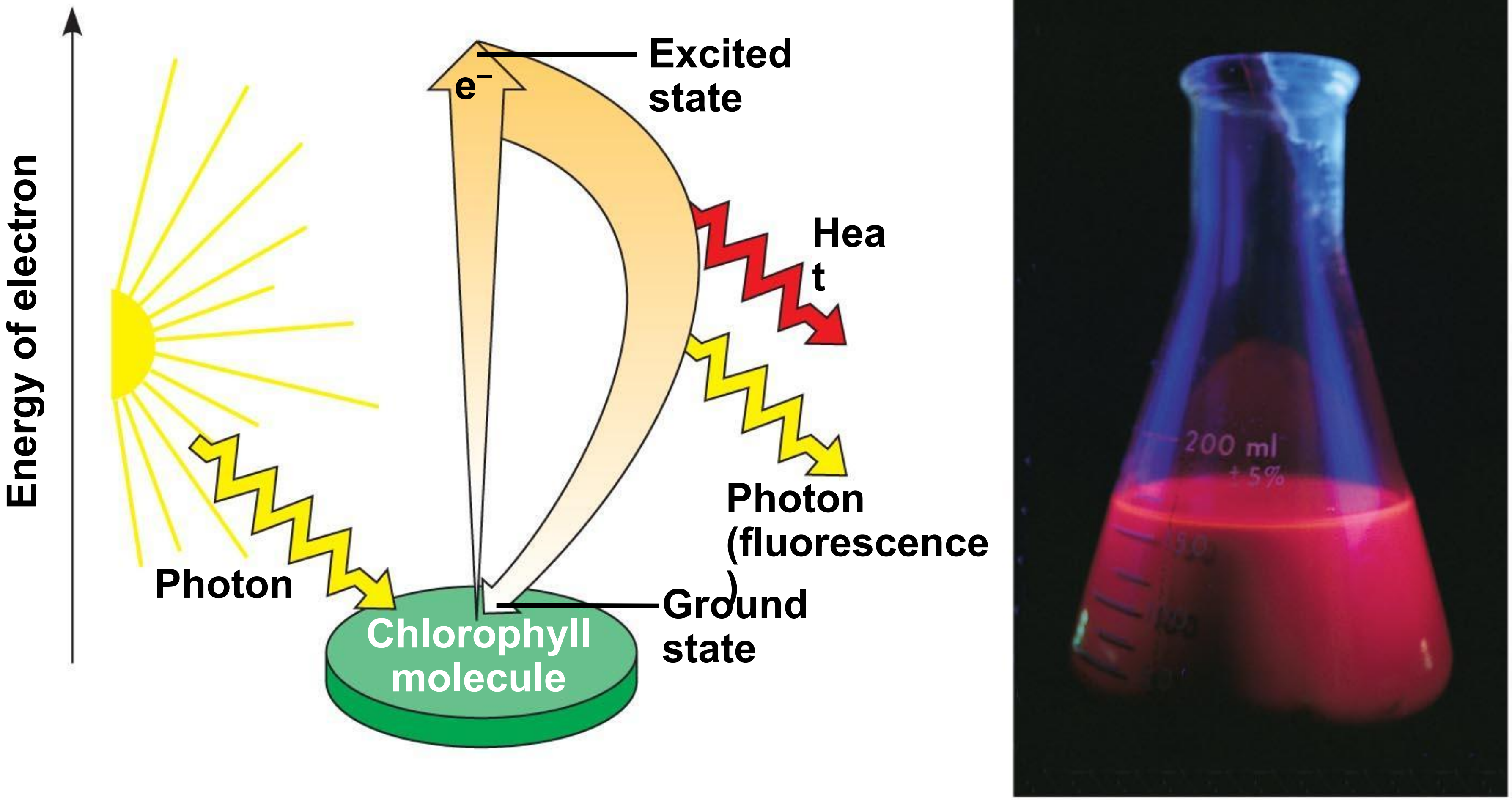
Porphyrin ring: light-absorbing "head" of molecule; note magnesium atom at center

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

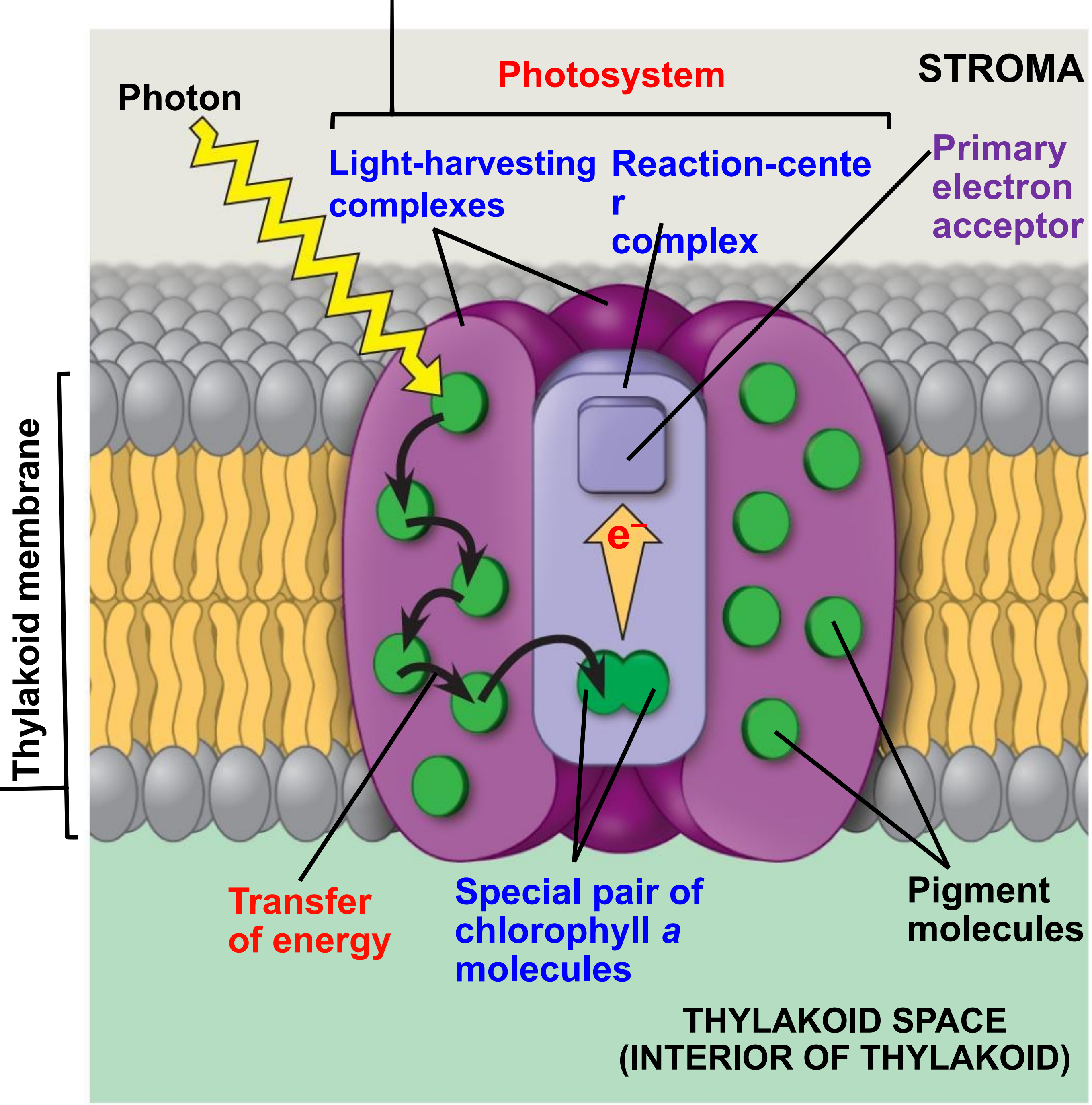
(b) Fluorescence

A Photosystem:

A Reaction-Center Complex Associated with Light-Harvesting Complexes

- A photosystem consists of a reaction-center complex (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***

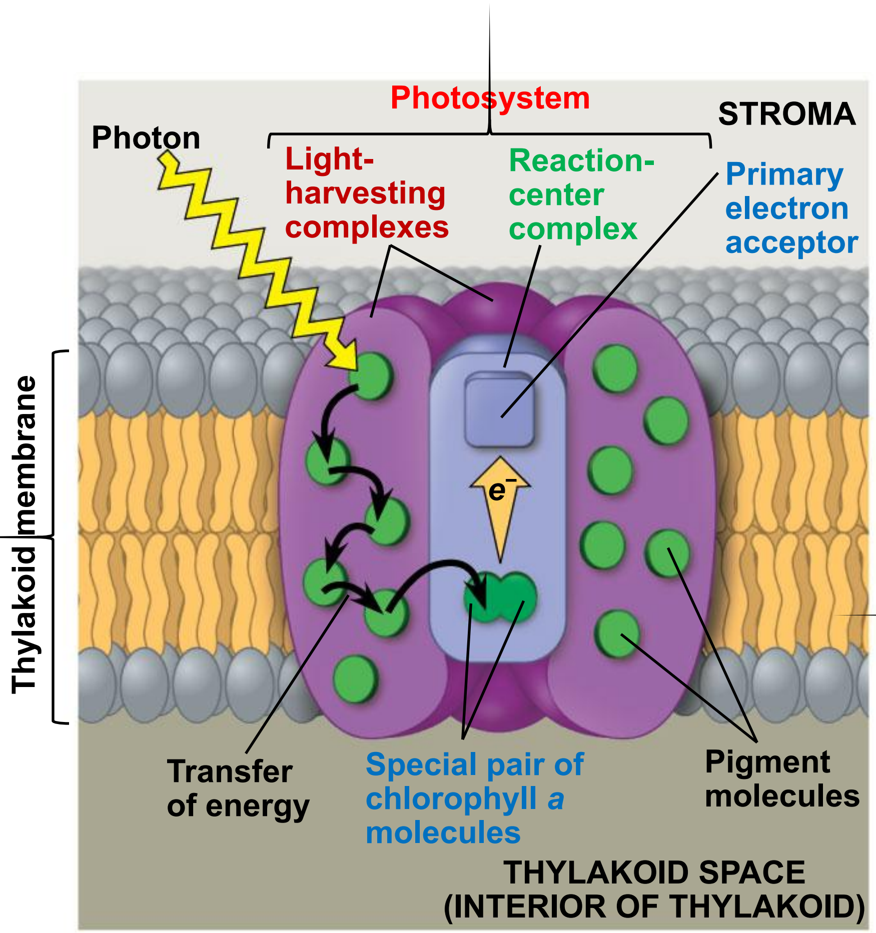
Fig. 10-12


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

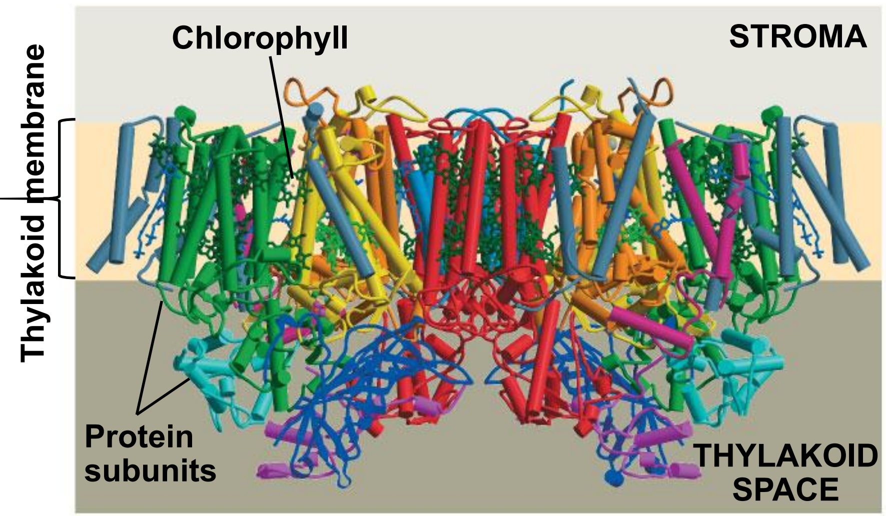
- A ***primary electron acceptor*** **in the reaction center accepts an excited electron from chlorophyll *a***

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

Figure 10.13

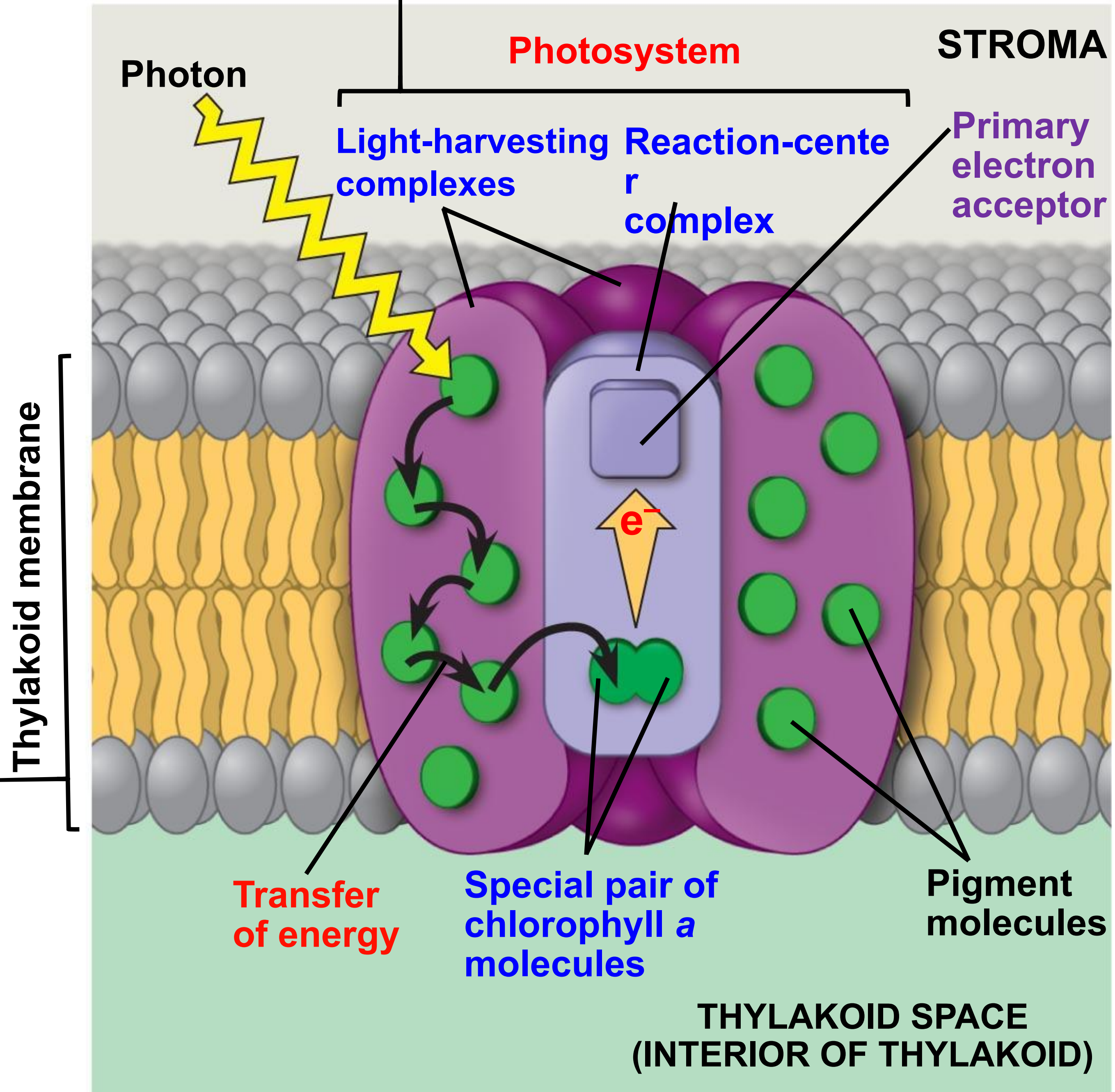


(a) How a photosystem harvests light



(b) Structure of photosystem II

Fig. 10-12



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

- **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**

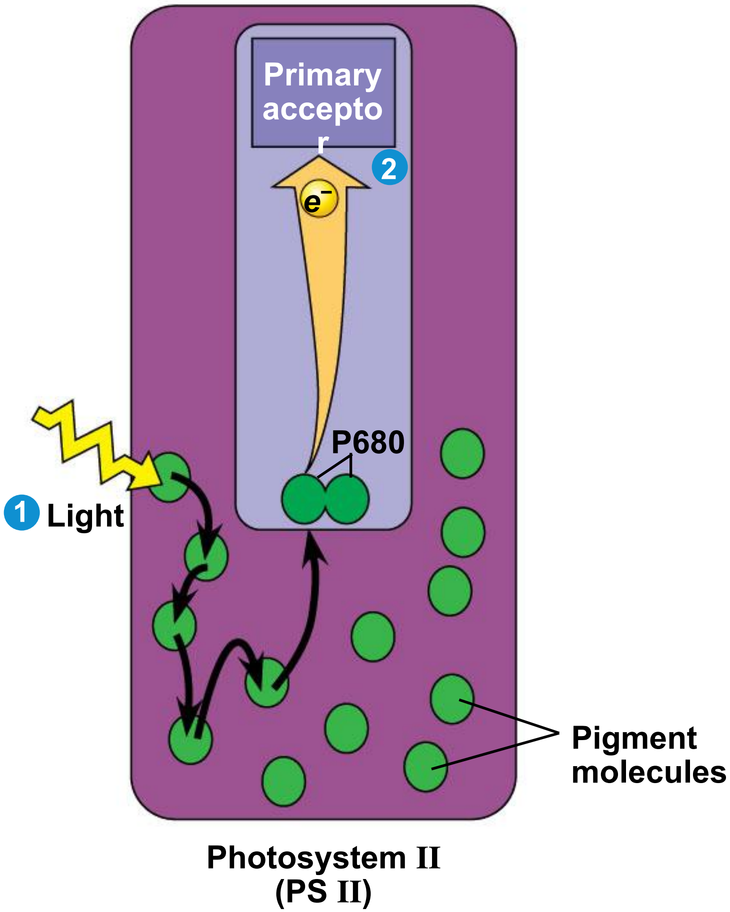
Linear Electron Flow

- 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

Figure 10.14-1

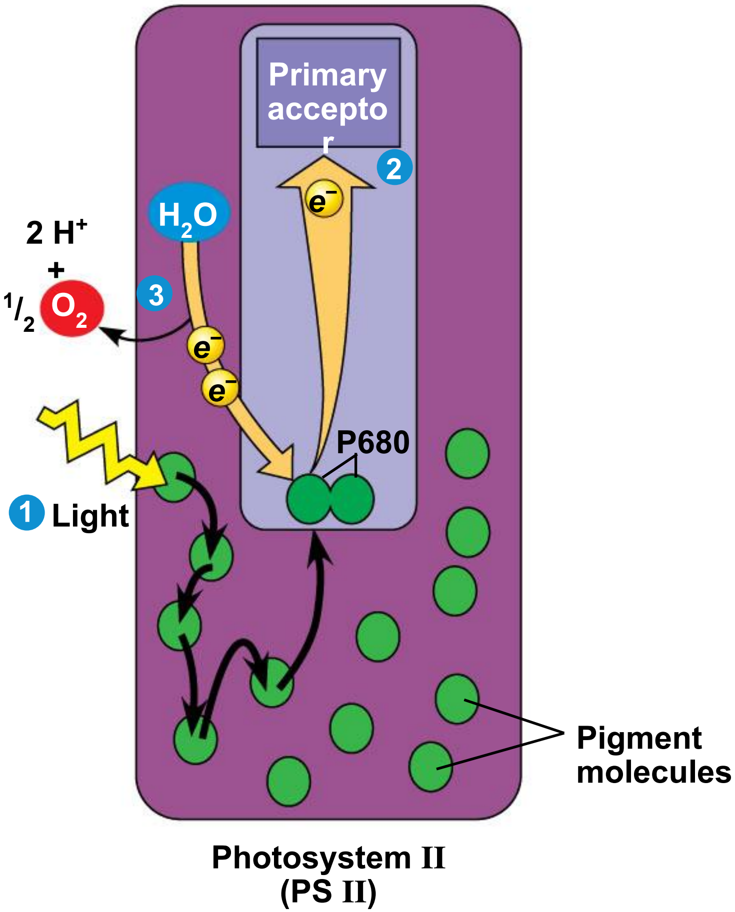


- $P680^+$ is a very **strong oxidizing** agent

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

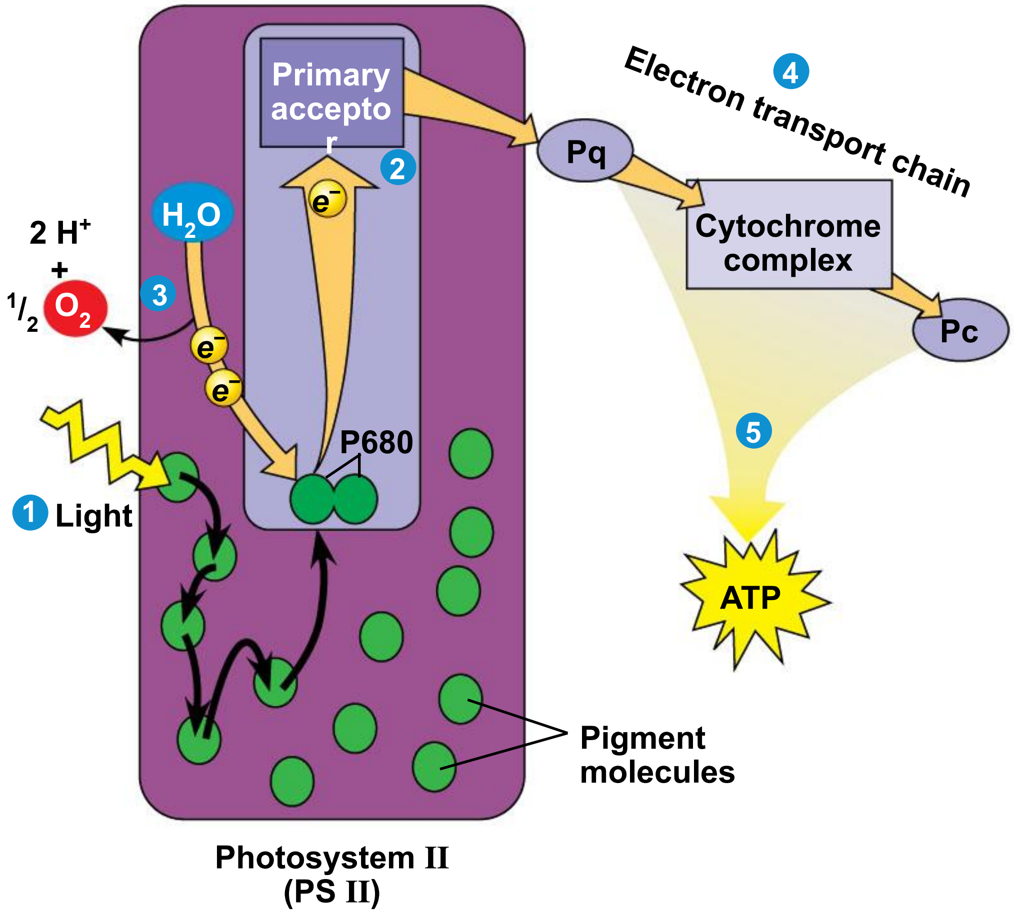
- O_2 is released as a **by-product** of this reaction

Figure 10.14-2



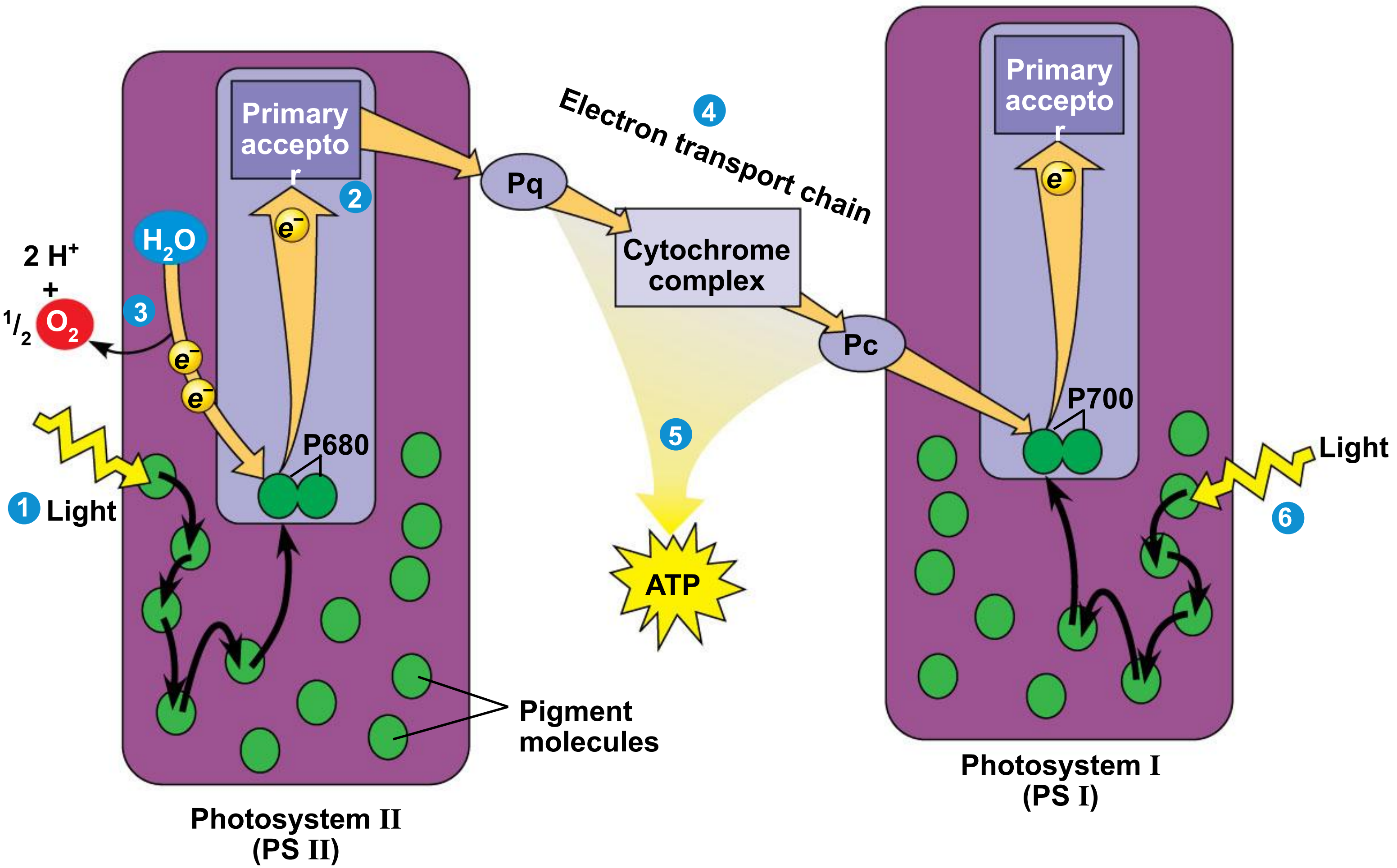
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS II to PS I
- Energy released by the fall drives the creation of a proton gradient across the thylakoid membrane
- Diffusion of H^+ (protons) across the membrane drives **ATP synthesis**

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

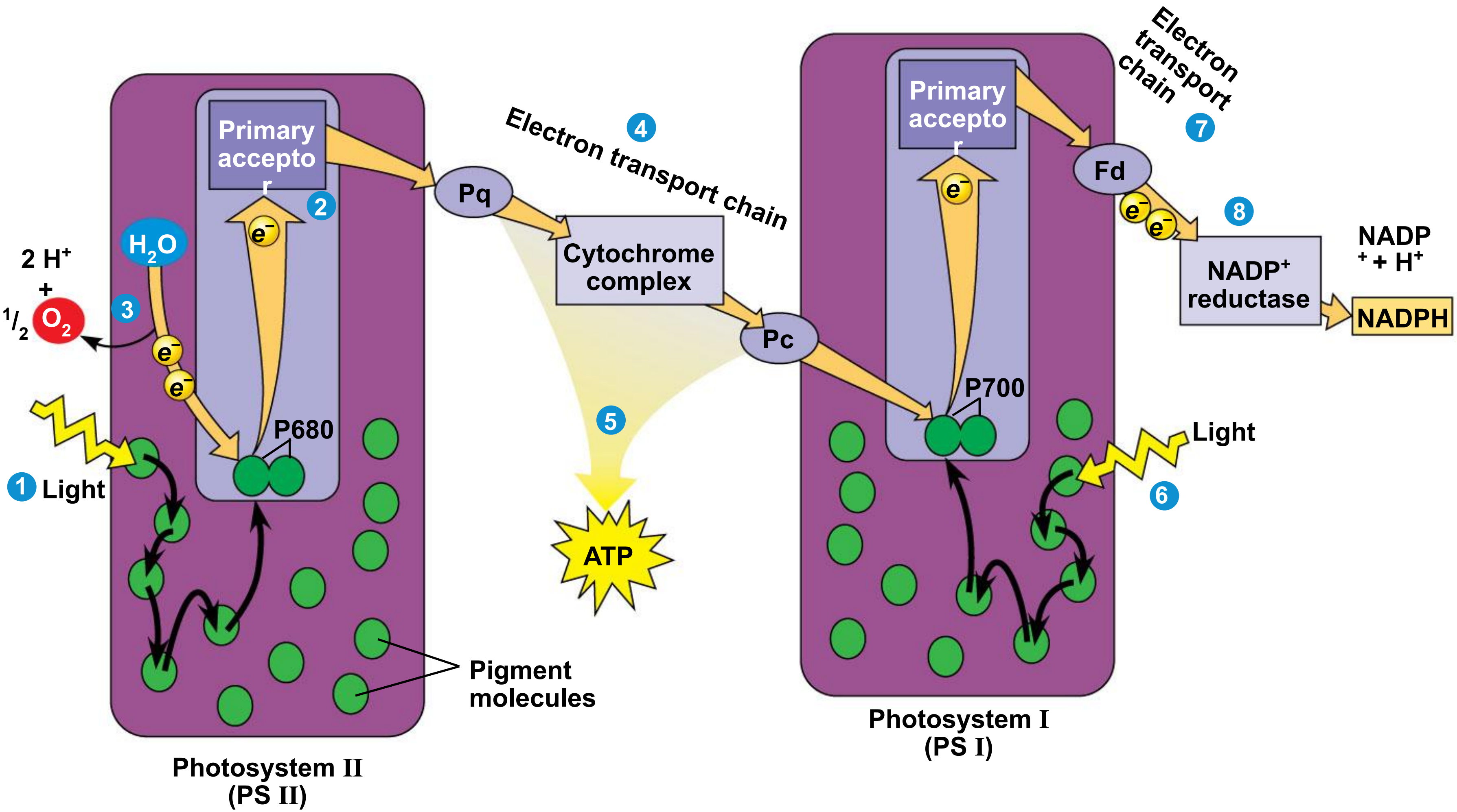
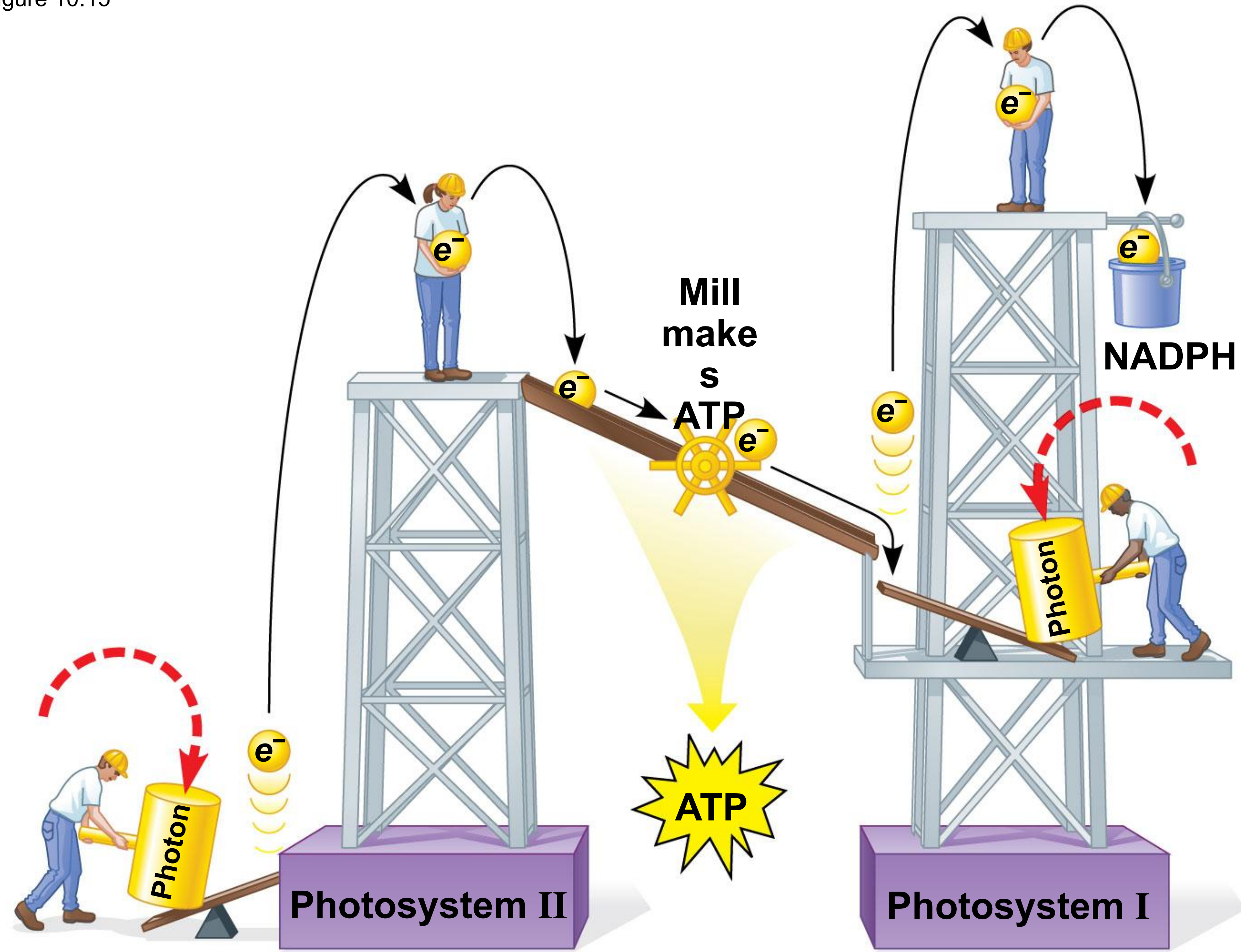


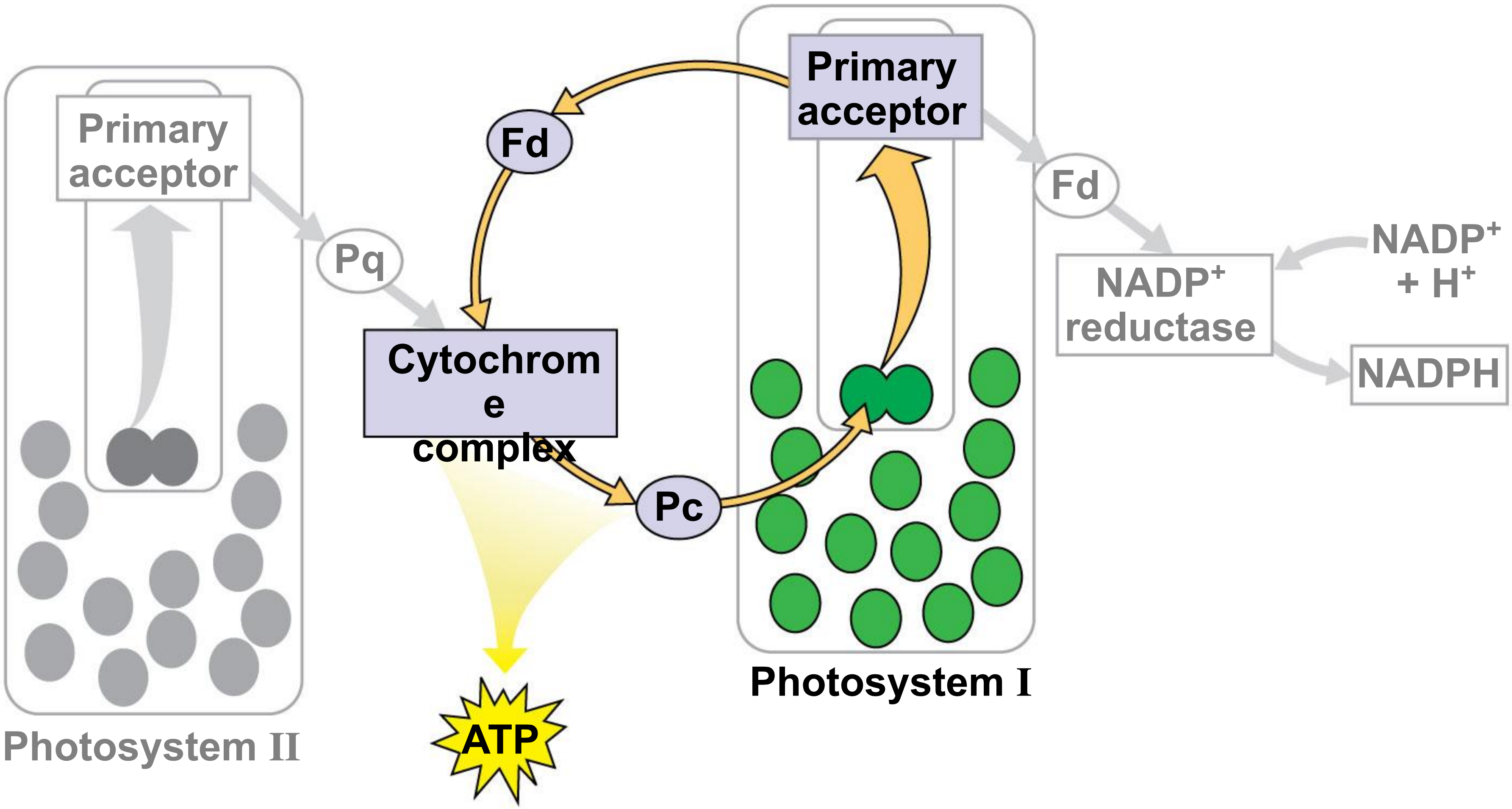
Figure 10.15


e–
e–
e–
Mill
make
s
ATP
e–
e–
e–
NADPH
e–
Photon
Photon
e–
ATP
Photosystem II
Photosystem I

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*

Figure 10.16



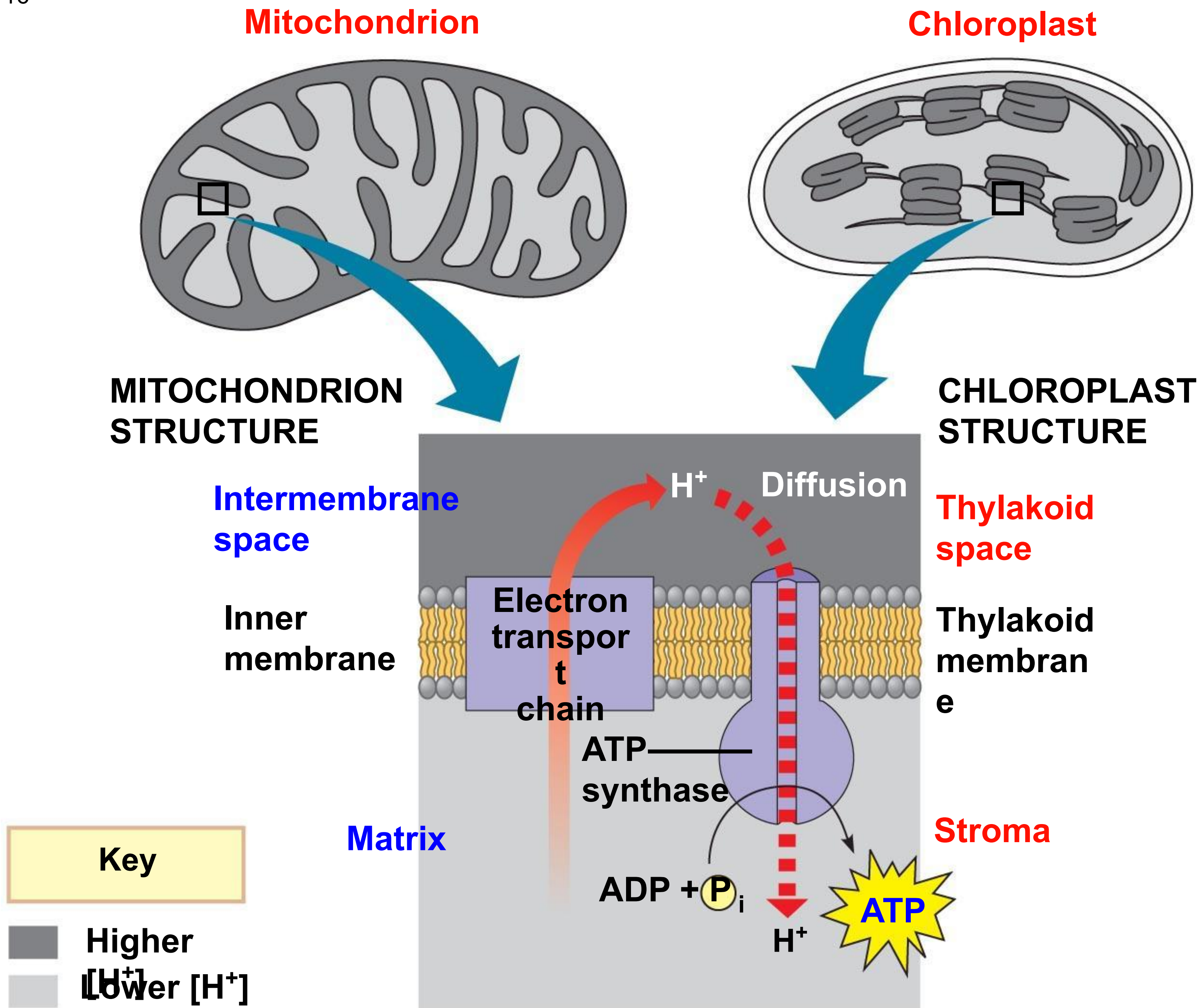
Primary acceptor
Pq
Photosystem II
Fd
Cytochrome complex
ATP
Pc
Primary acceptor
Photosystem I
Fd
NADP+ reductase
NADP+ + H+
NADPH

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

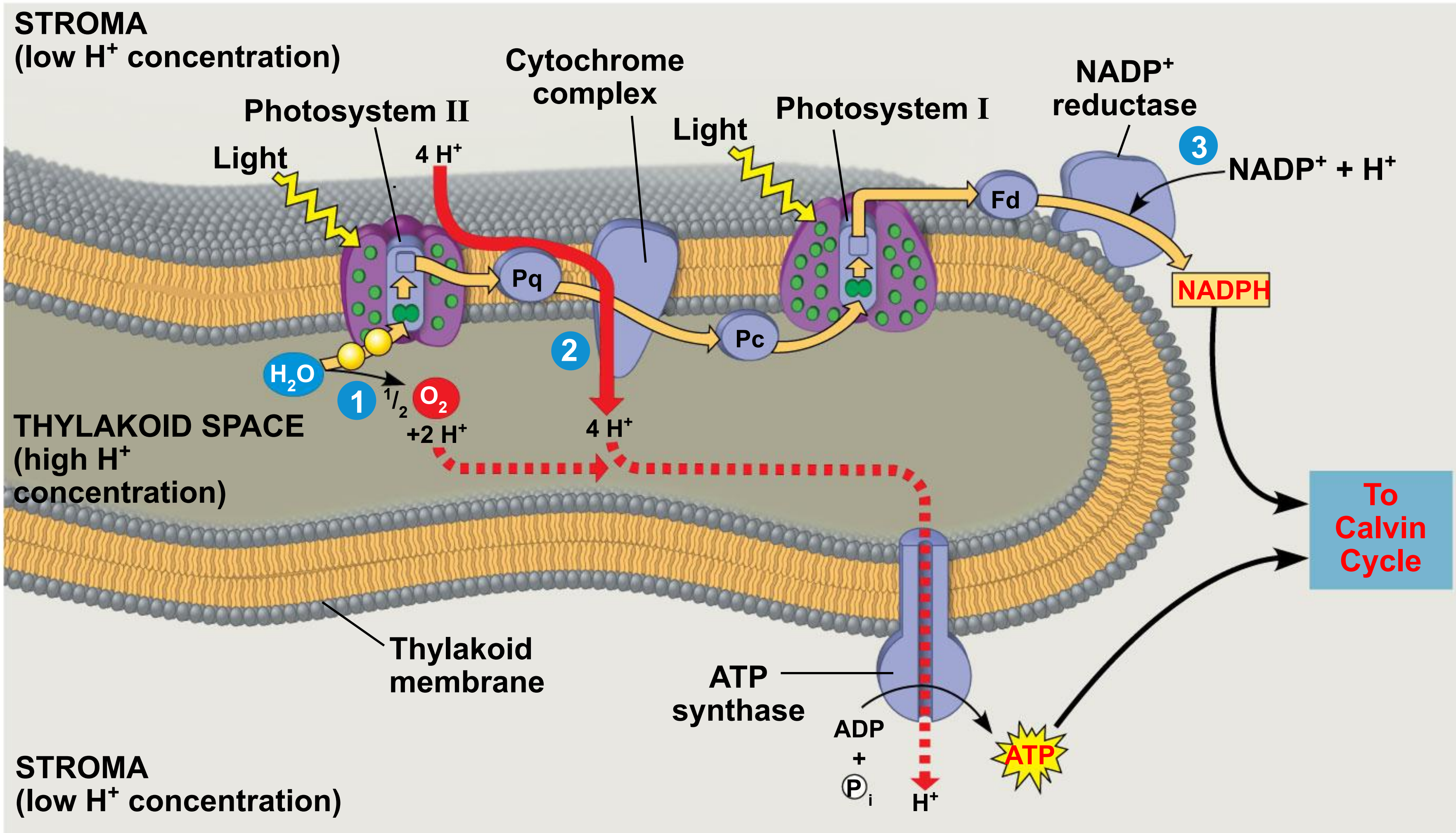
Fig. 10-16


Mitochondrion
Chloroplast
MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
H+
Diffusion
Intermembrane space
Thylakoid space
Inner membrane
Electron transport chain
Thylakoid membrane
ATP synthase
Matrix
Stroma
ADP + P i
H+
ATP
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
+
Pi
H+
ATP
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)
  - Reduction
  - Regeneration of the CO_2 acceptor (RuBP)

Figure 10.19-1

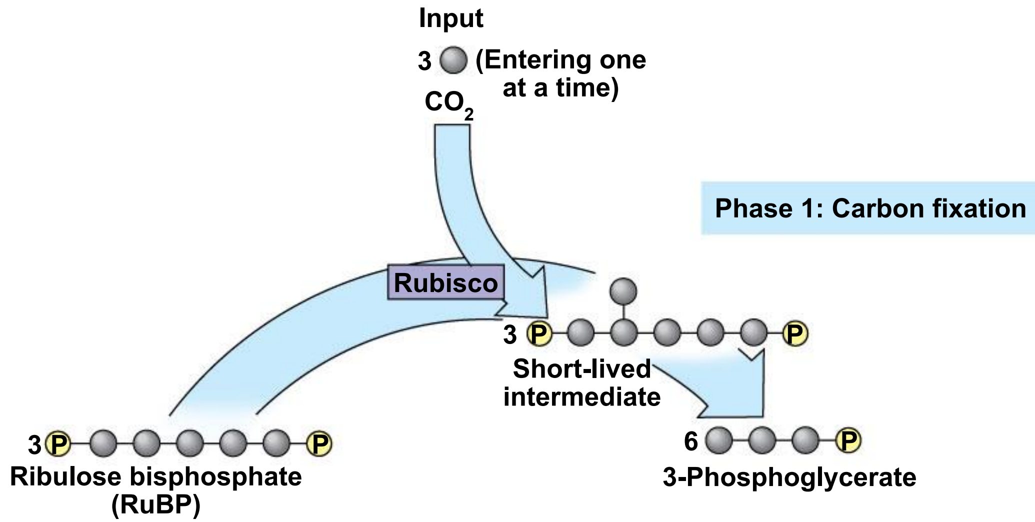


Figure 10.19-2

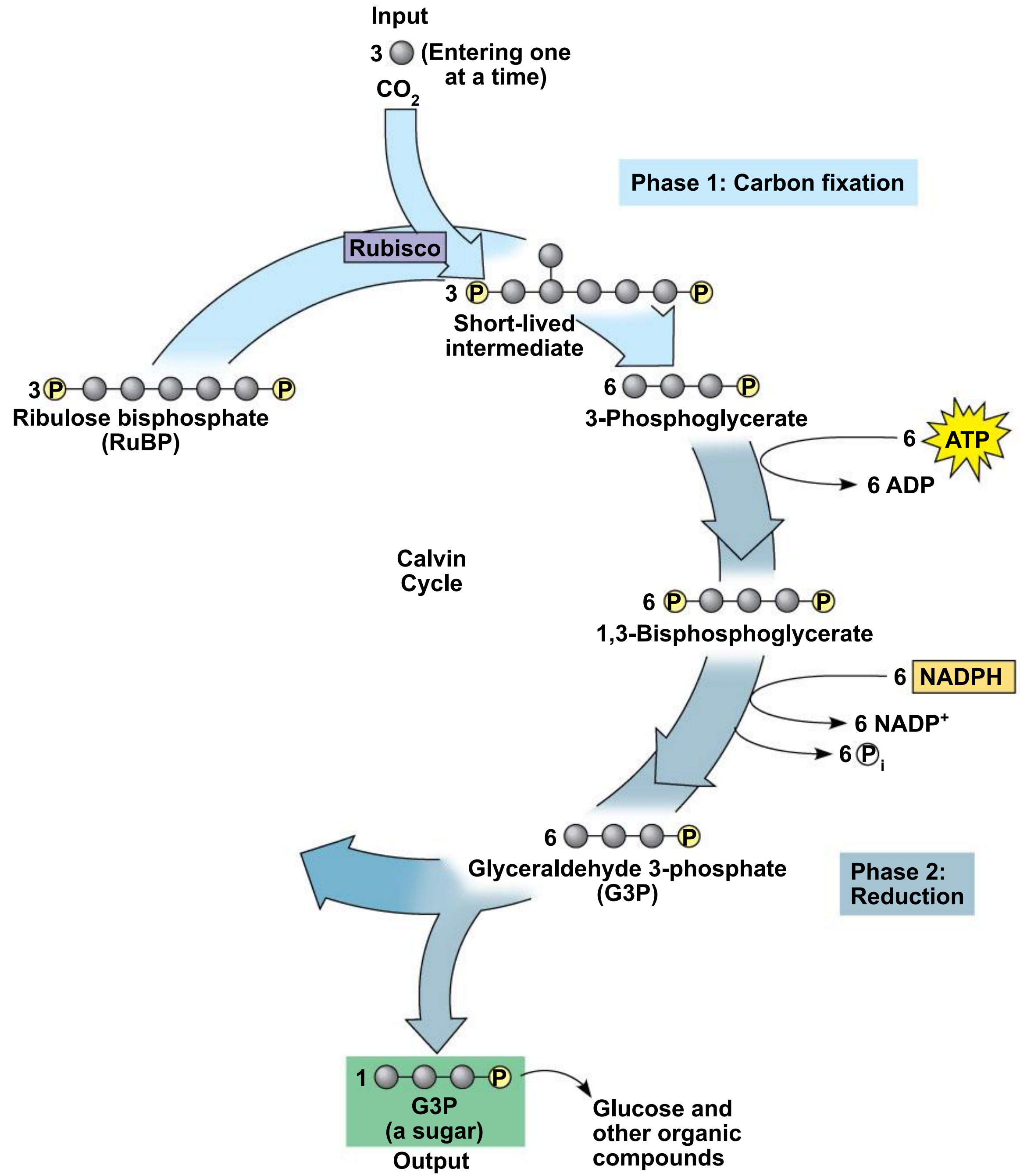


Figure 10.19-3

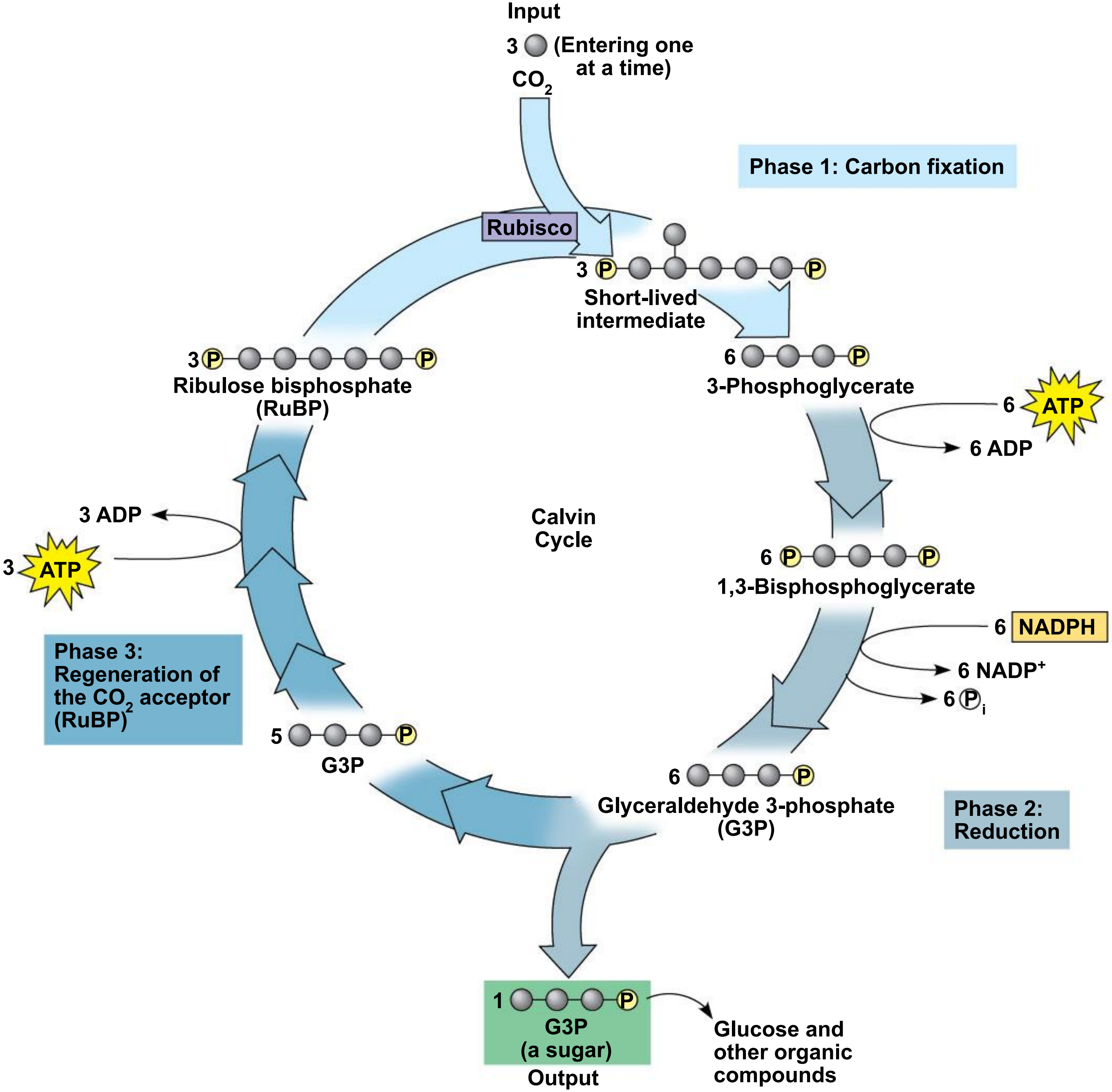
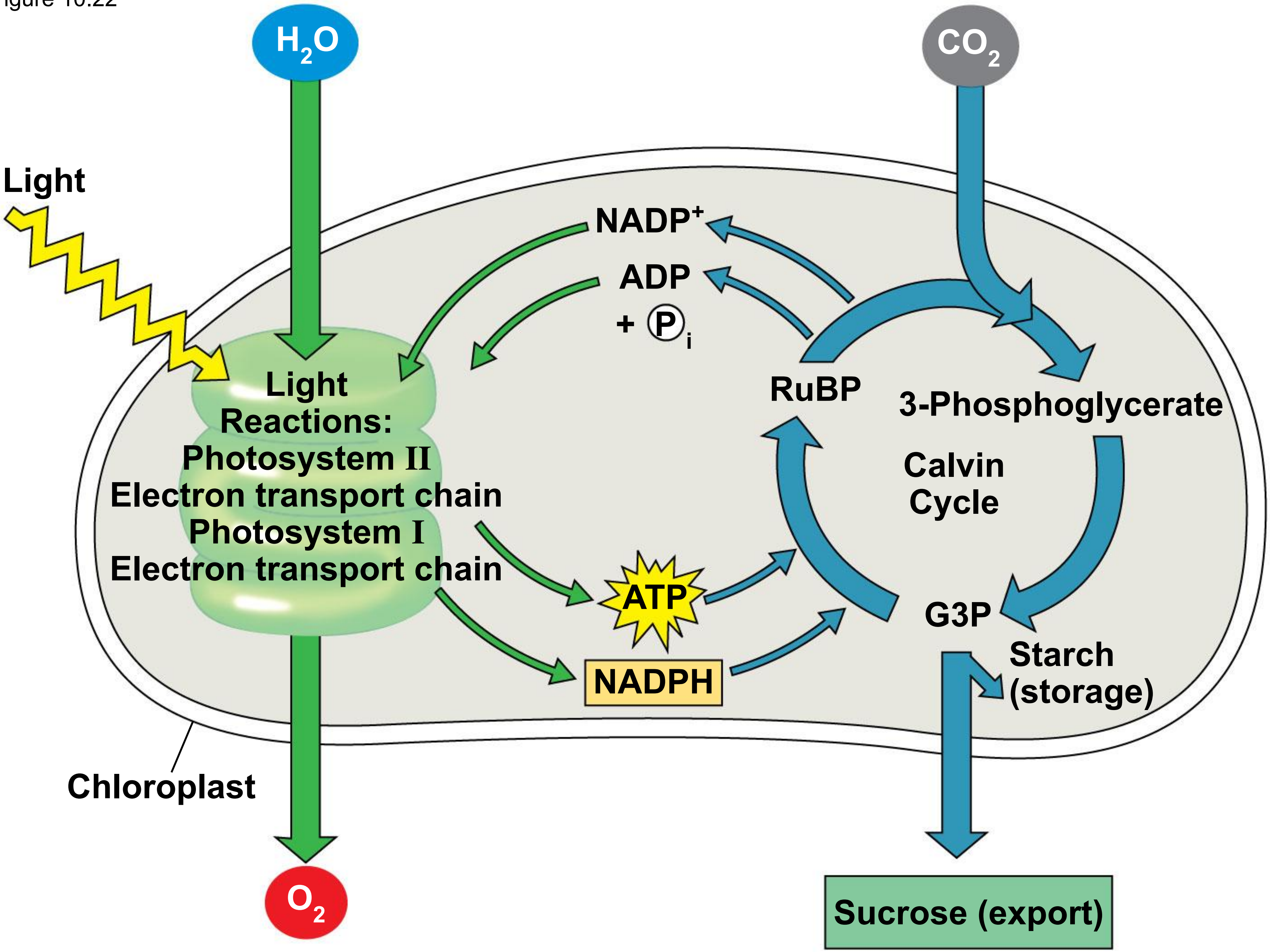


Figure 10.22



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