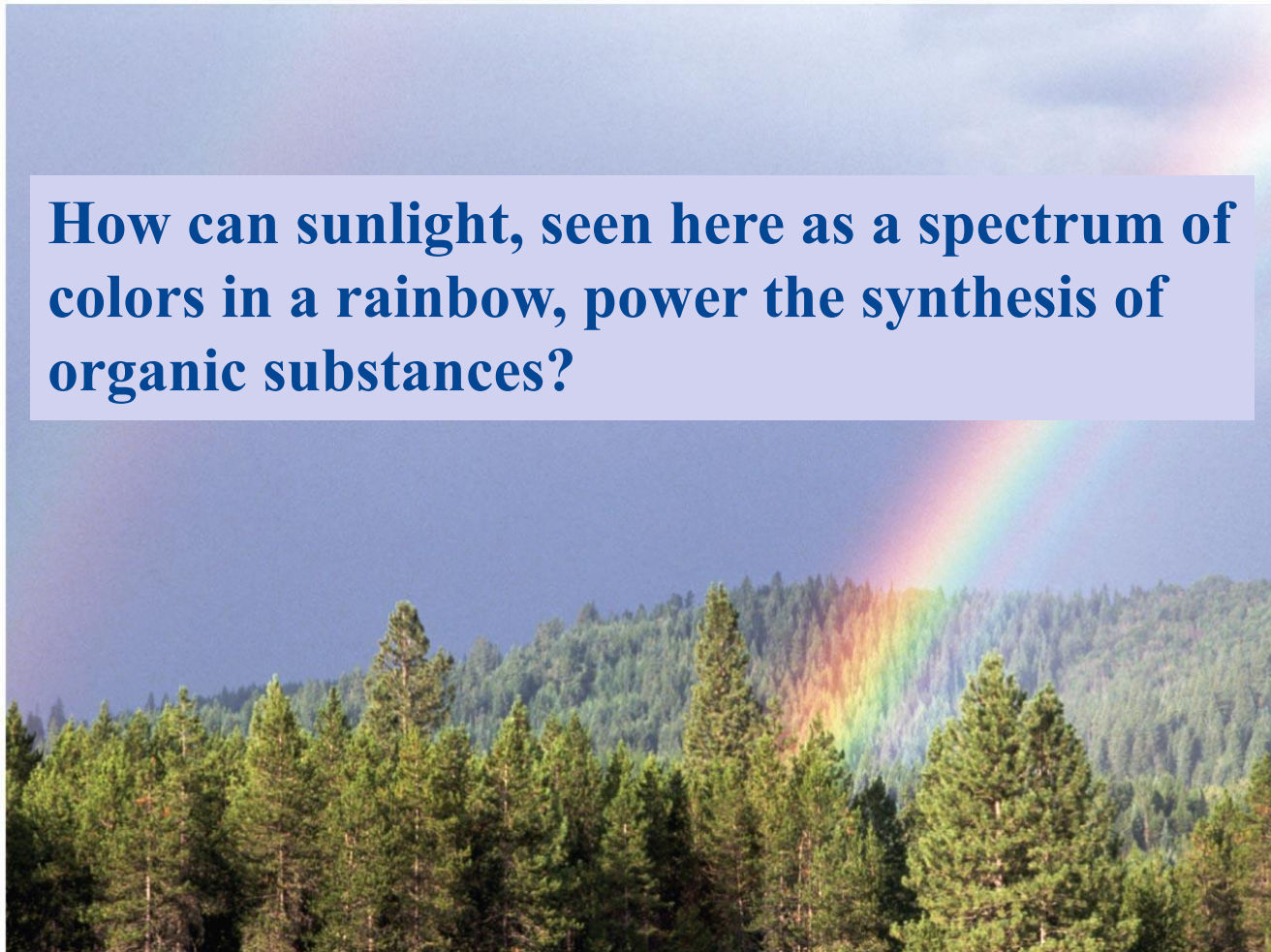


Chapter TEN

Photosynthesis

How can sunlight, seen here as a spectrum of colors in a rainbow, power the synthesis of organic substances?



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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**

Photoautotrophs



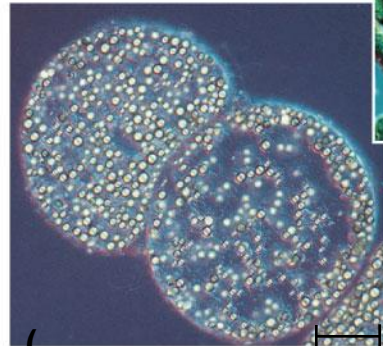
(a) Plants



(b) Multicellular
alga



(c) Unicellular
protists 10 μm



(e) Purple
sulfur



(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 O₂**

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
-

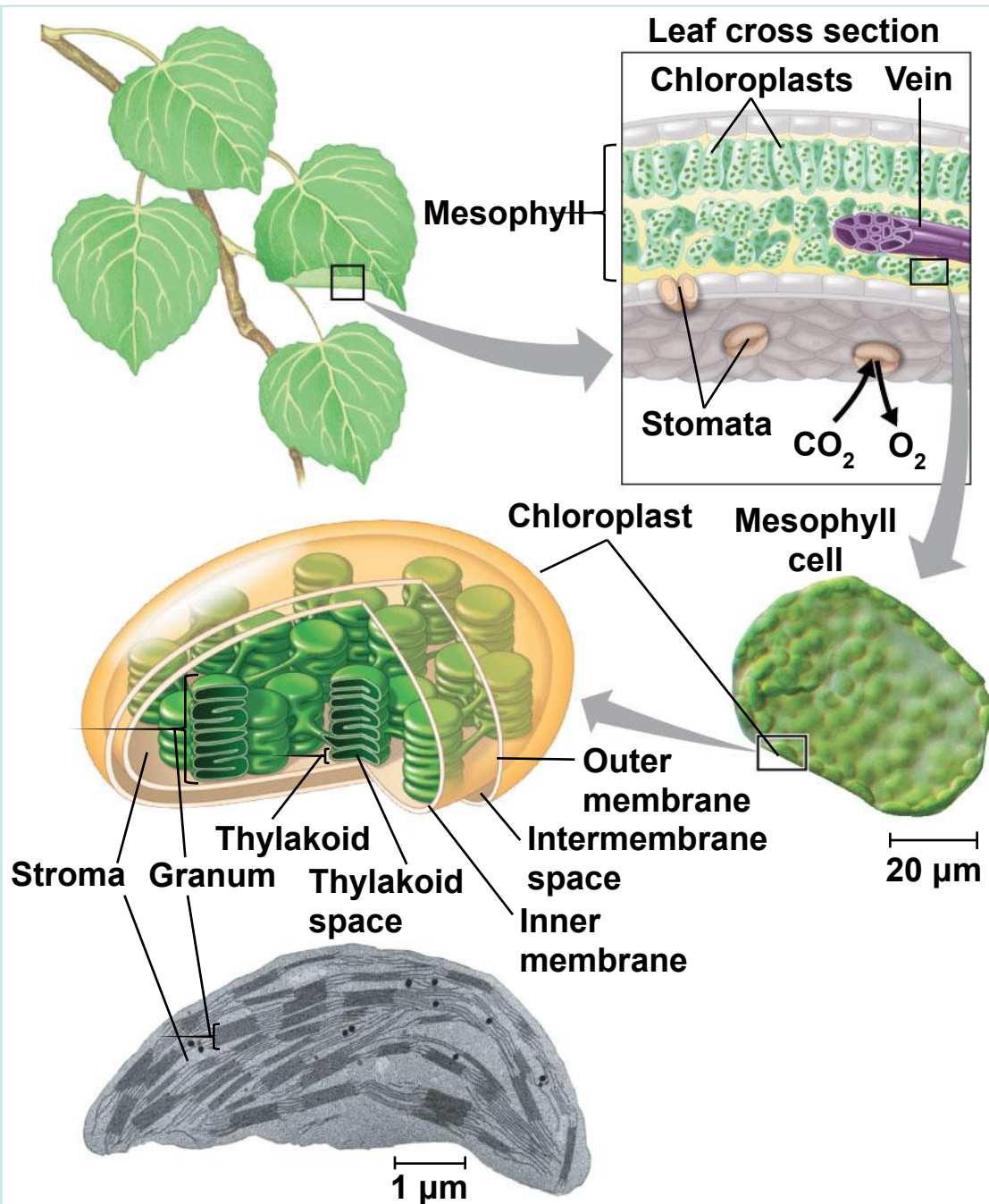
Chloroplasts: The Sites of Photosynthesis in Plants

- **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
photosynth
esis in a
plant.

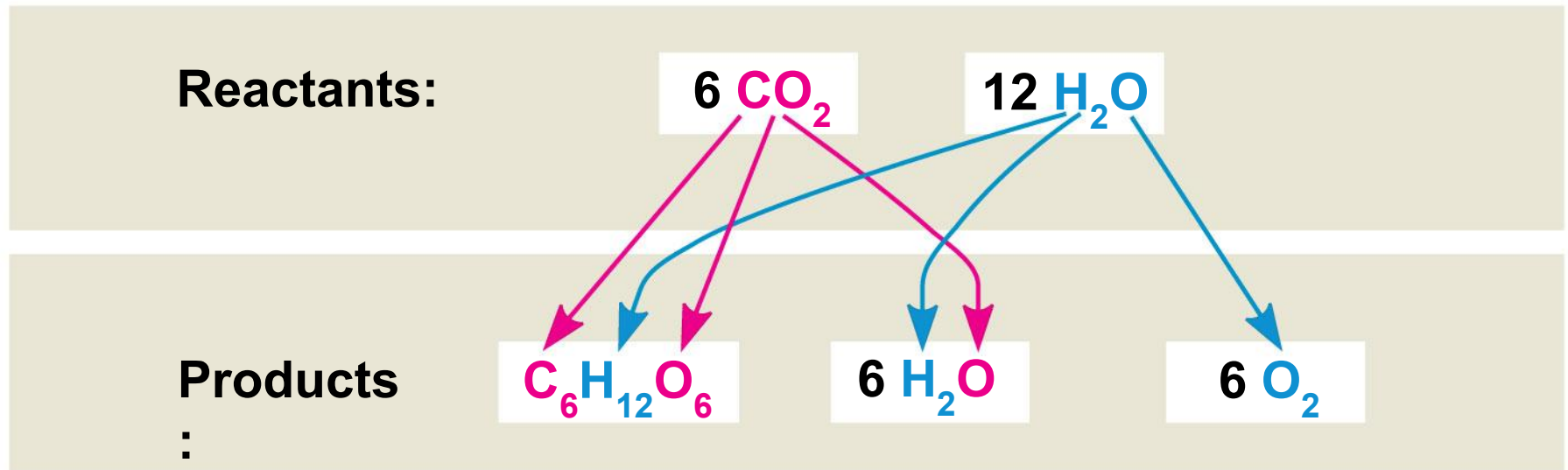


Tracking Atoms Through Photosynthesis: *Scientific Inquiry*

- Photosynthesis can be summarized as the following equation:



Tracking atoms through photosynthesis.



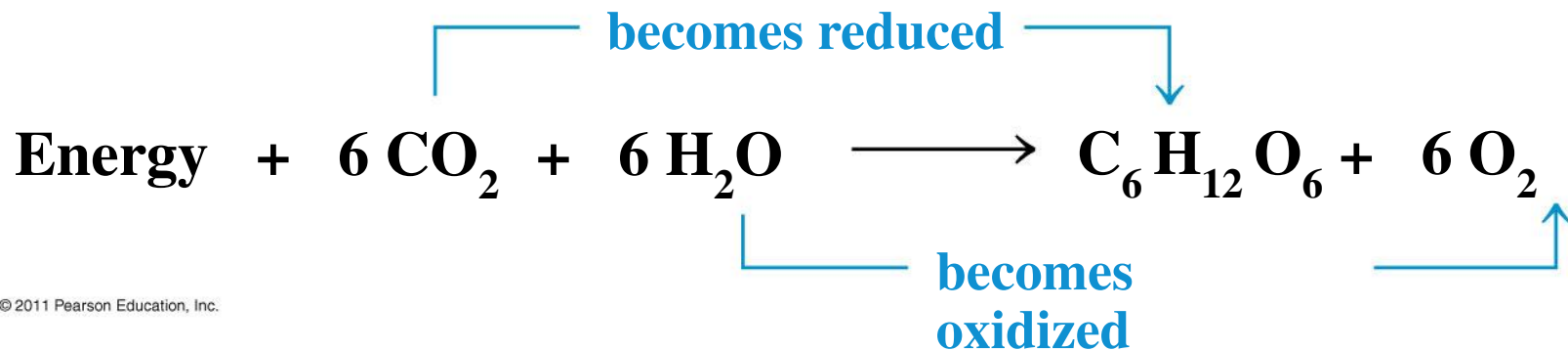
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The *Splitting* of Water

- **Chloroplasts split H_2O into hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules**
 - Plants: $\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{O}_2$
 - Sulfur bacteria: $\text{CO}_2 + \text{H}_2\text{S} \rightarrow [\text{CH}_2\text{O}] + \text{H}_2\text{O} + \text{S}_2$
- **CO_2 is not split into C and O_2 !! This hypothesis was cancelled by van Neil in 1930s**

Photosynthesis as a Redox Process

- Photosynthesis is a **redox process** in which **H₂O is oxidized** and **CO₂ is reduced**



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- **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??

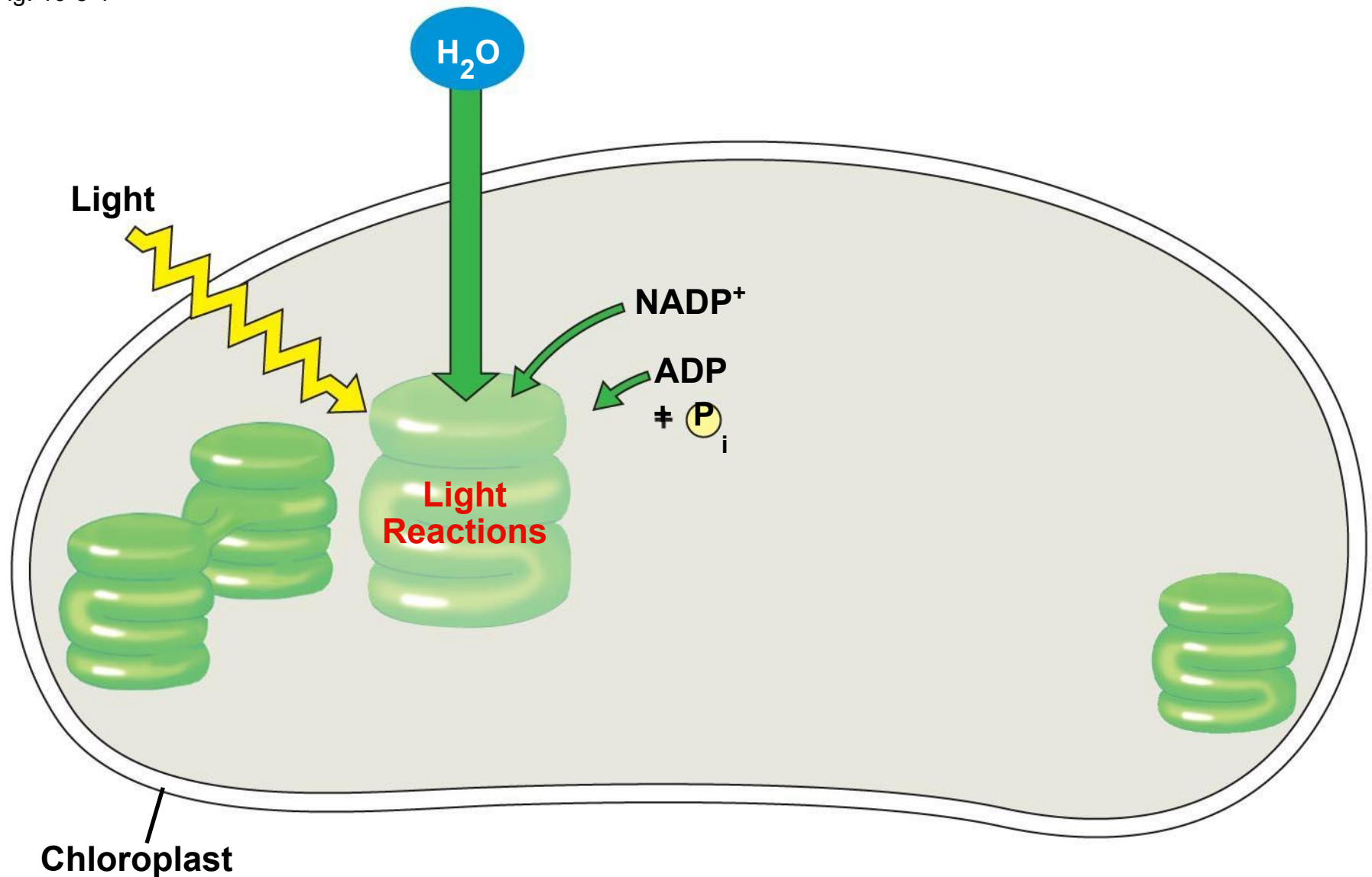


The **Two Stages** of Photosynthesis: *A Preview*

- **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

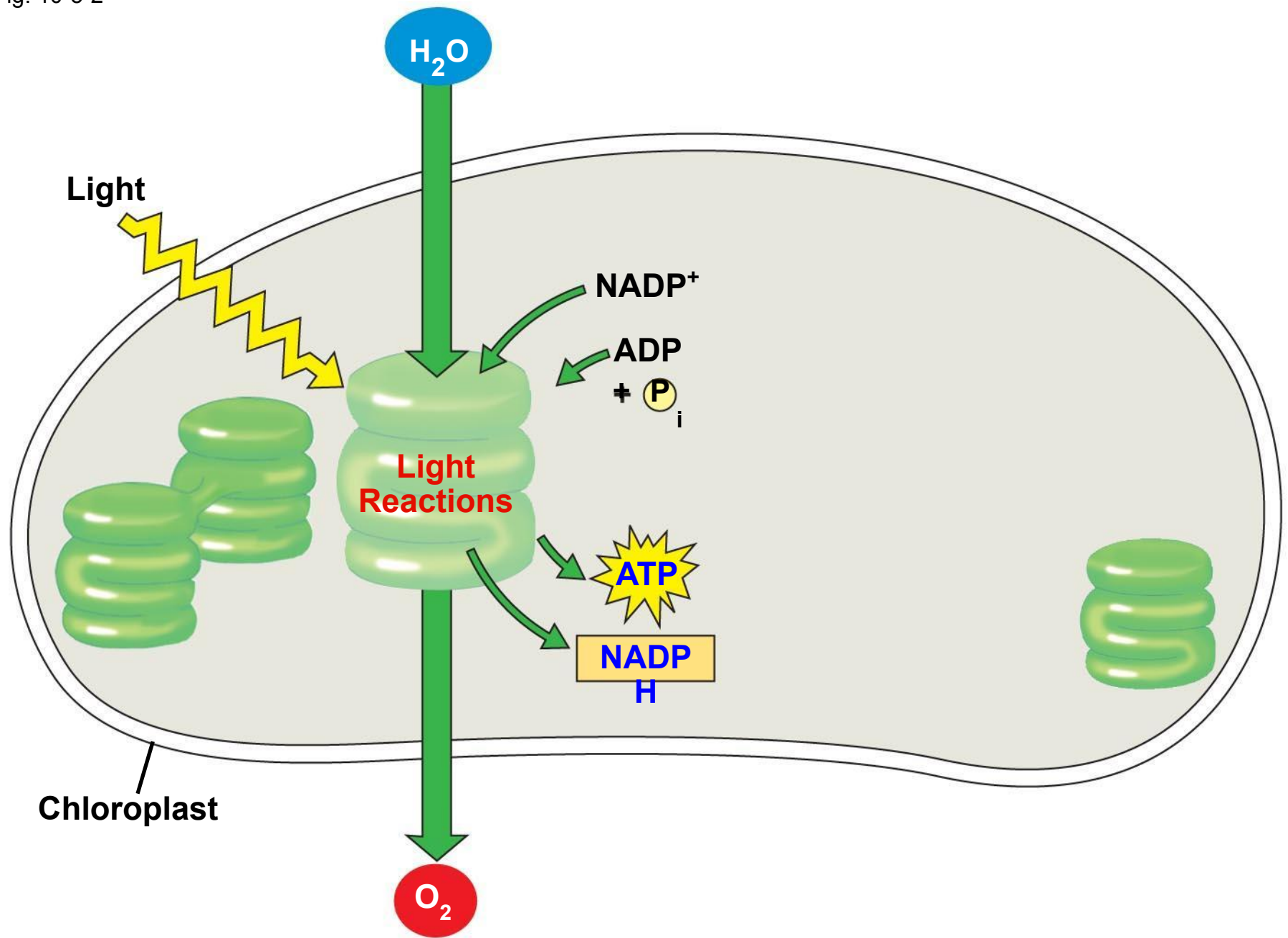


Fig. 10-5-3

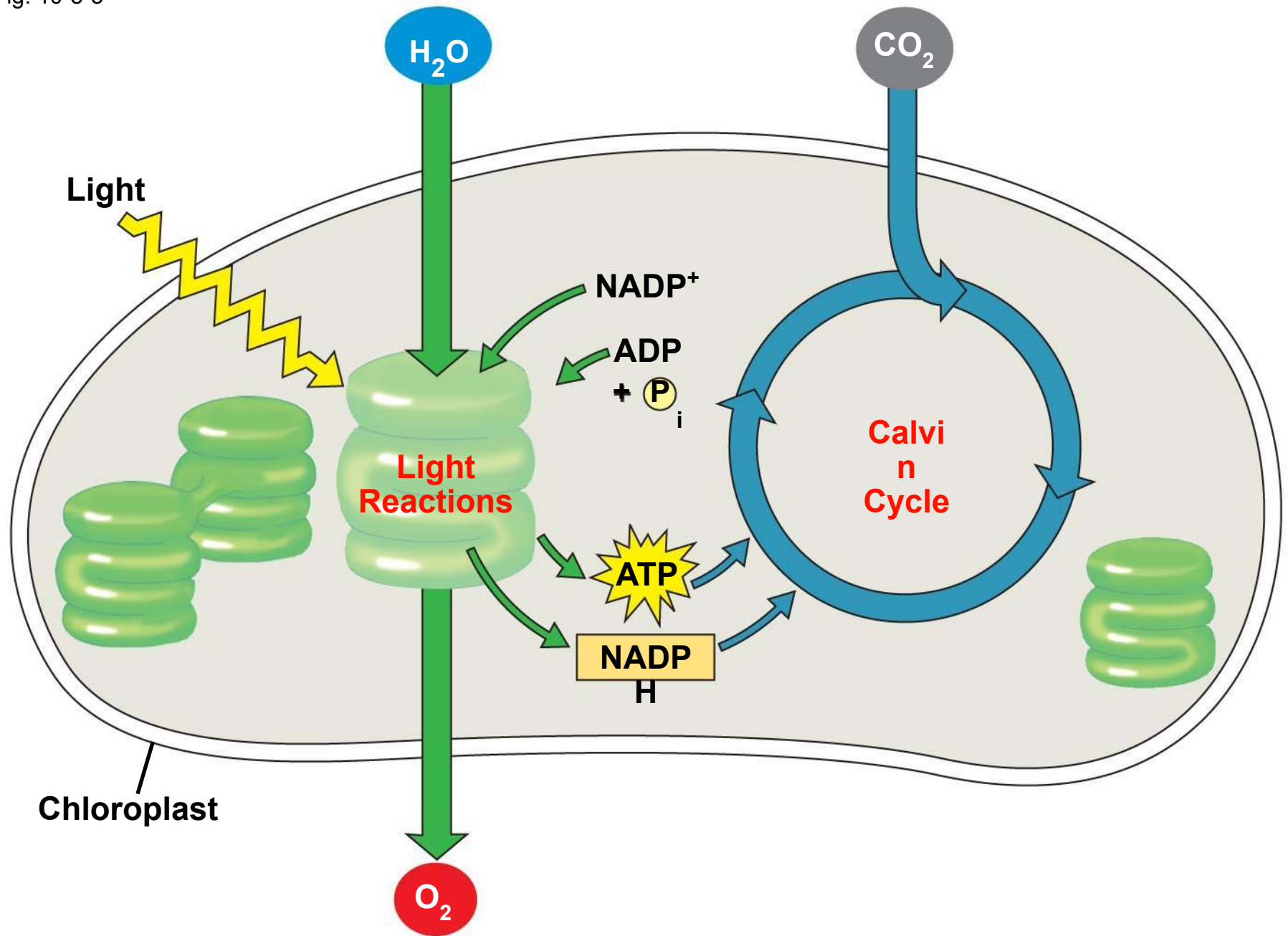
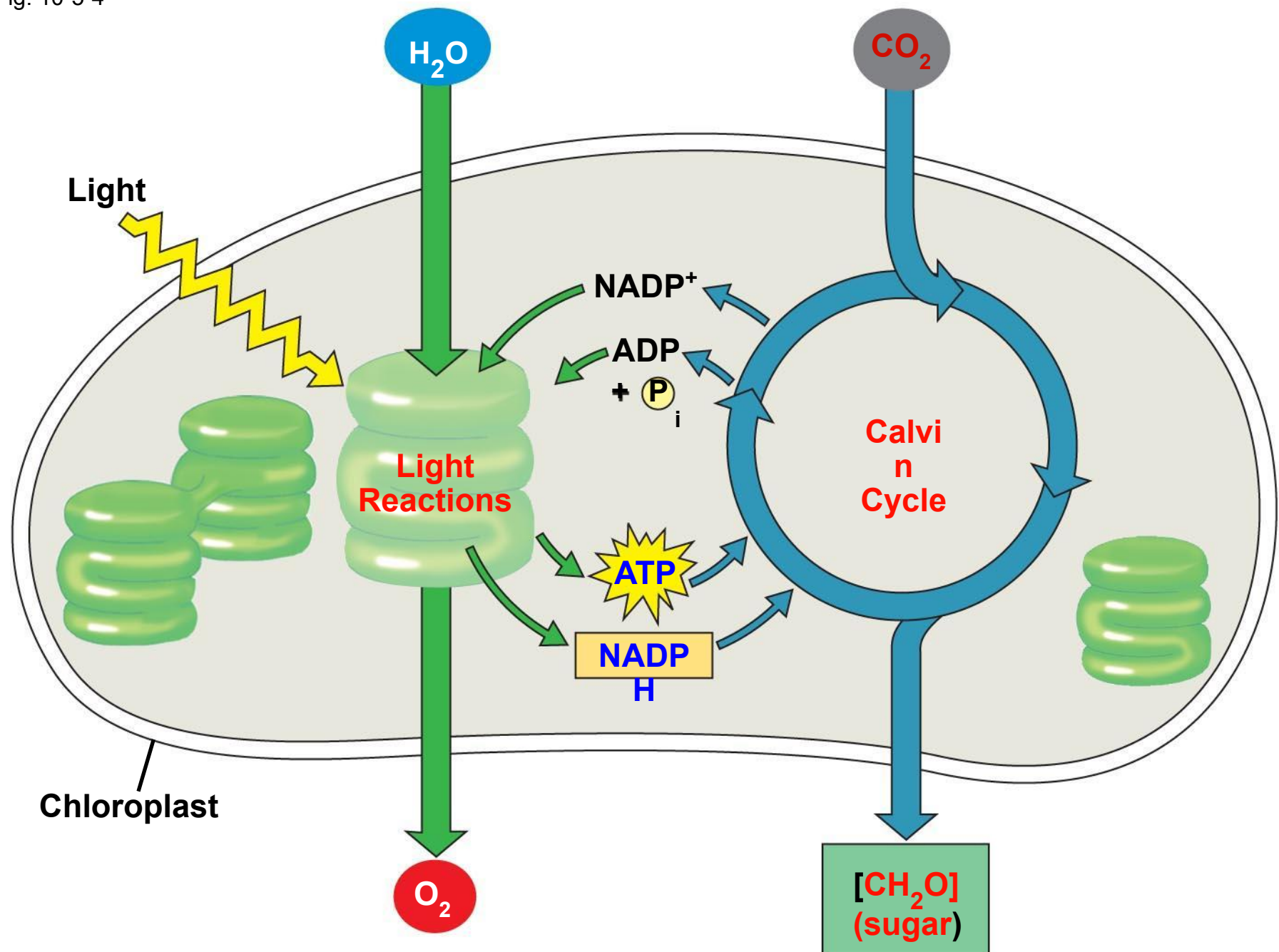


Fig. 10-5-4



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

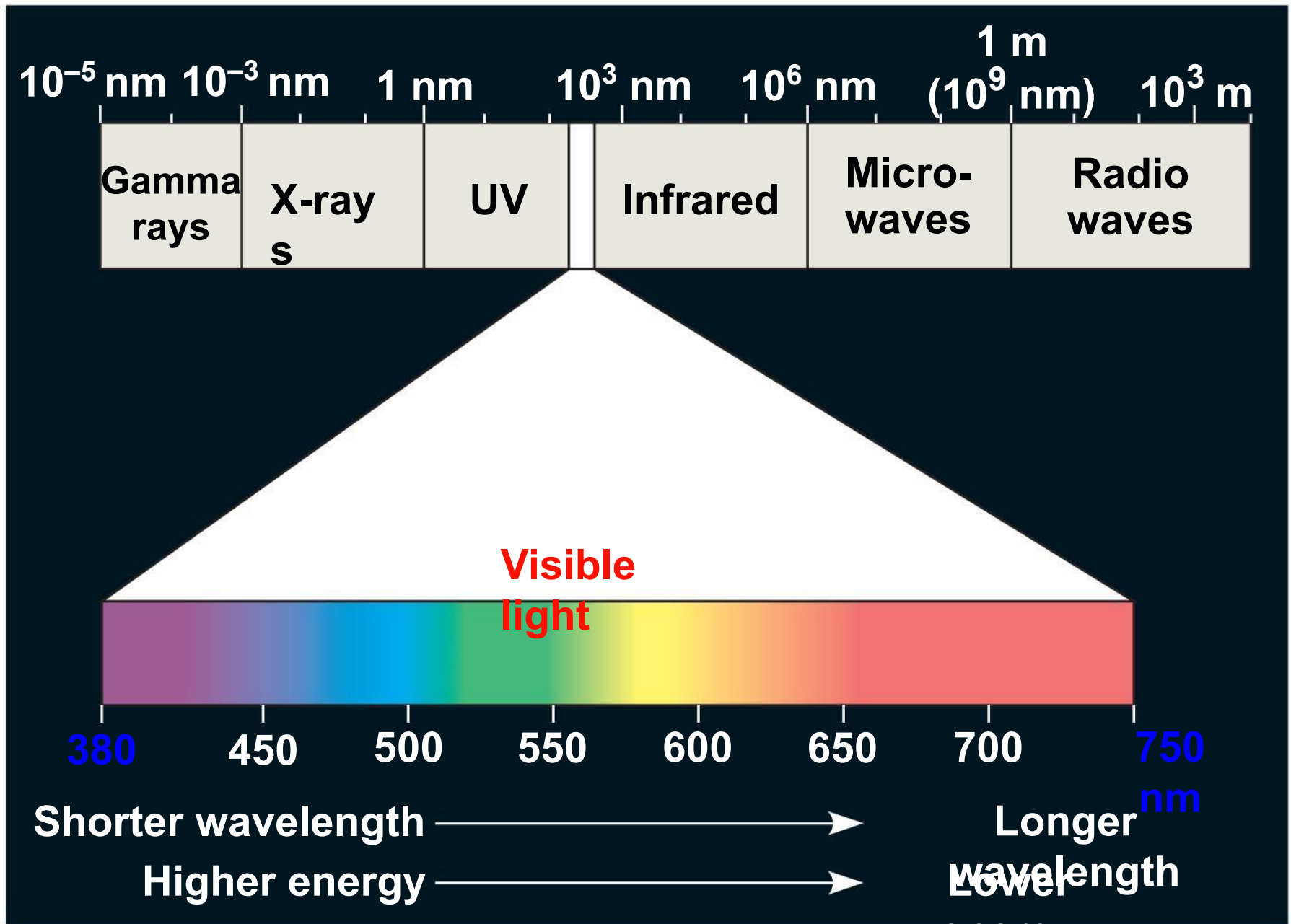
- Chloroplasts are **solar-powered chemical factories**
- Their thylakoids transform light energy into the chemical energy of **ATP and NADPH**

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**

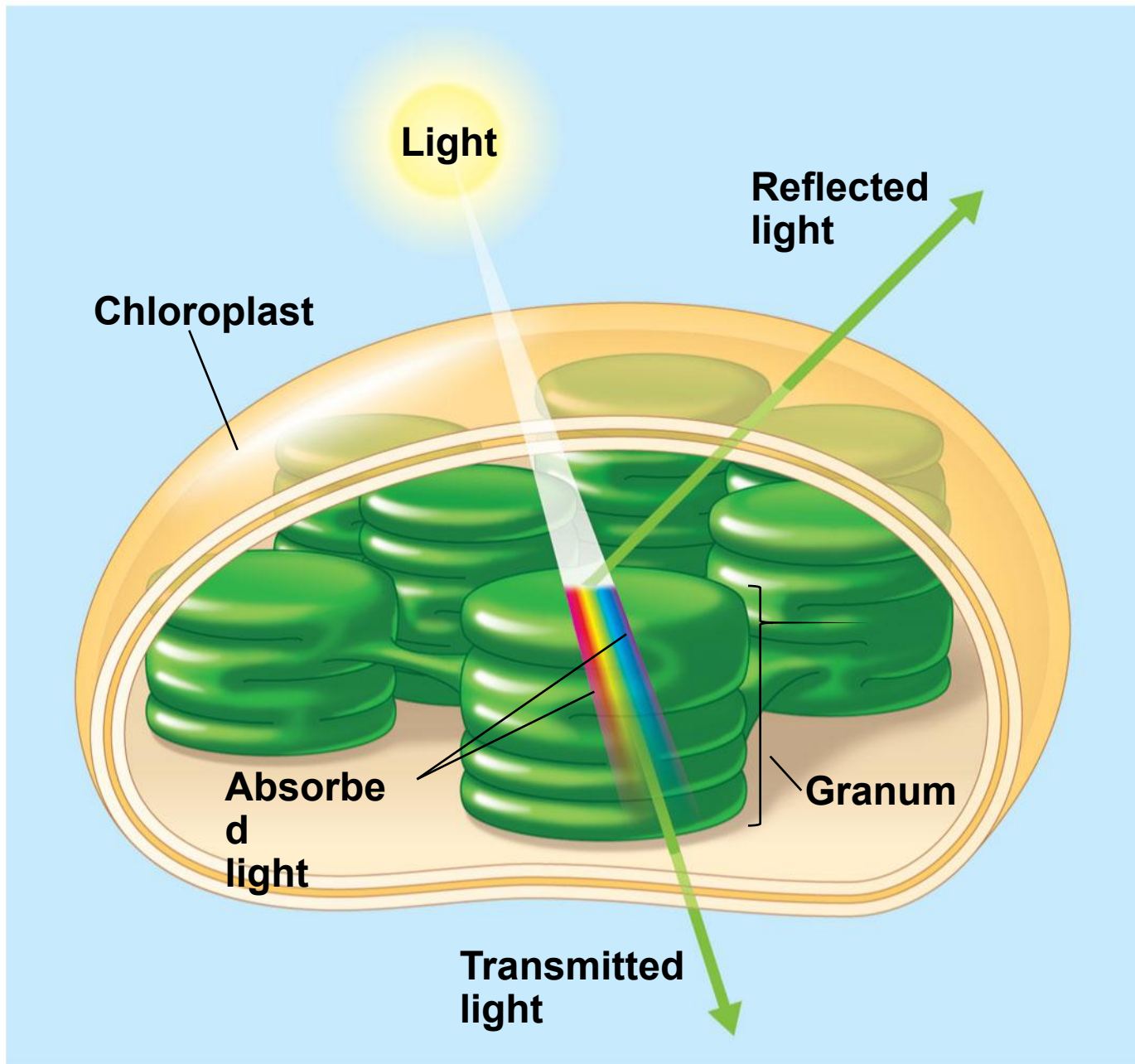
Fig. 10-6



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

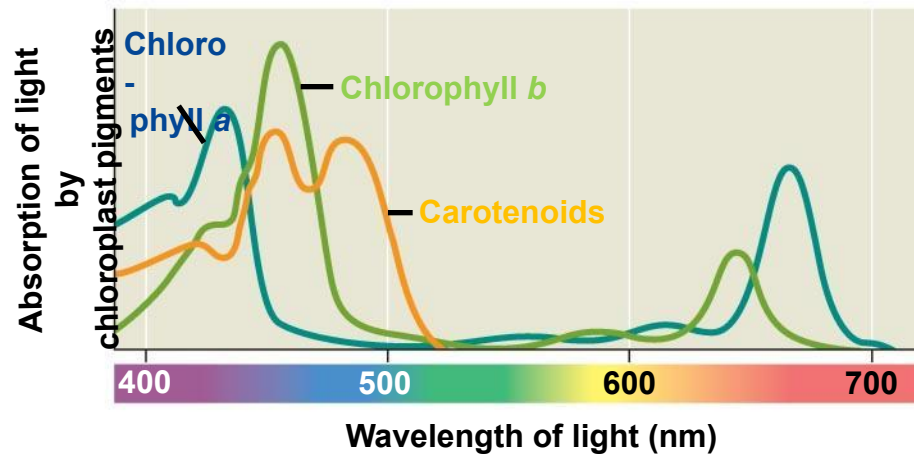


-
- A **spectrophotometer** measures a pigment's ability to absorb various wavelengths
 - This machine sends light through pigments and measures the fraction of light transmitted at each wavelength

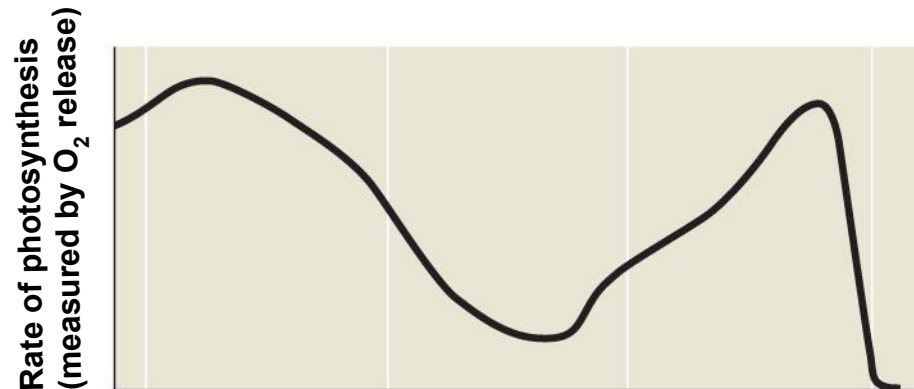
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- An **absorption spectrum** is a graph plotting a pigment's ***light absorption versus wavelength***
 - The absorption spectrum of **chlorophyll a** suggests that **violet-blue** and **red light** work best for photosynthesis

RESULTS

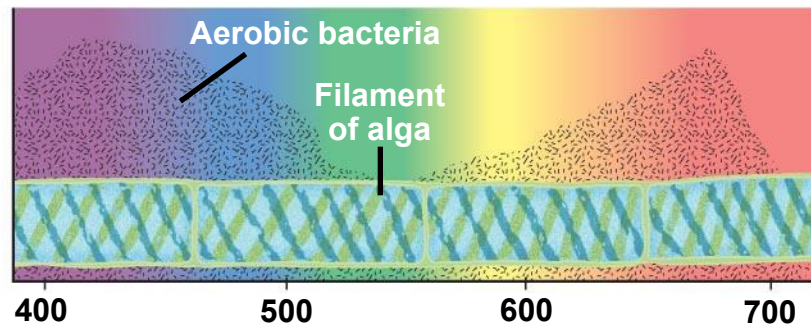
(a) Absorption spectra



(b) Action spectrum

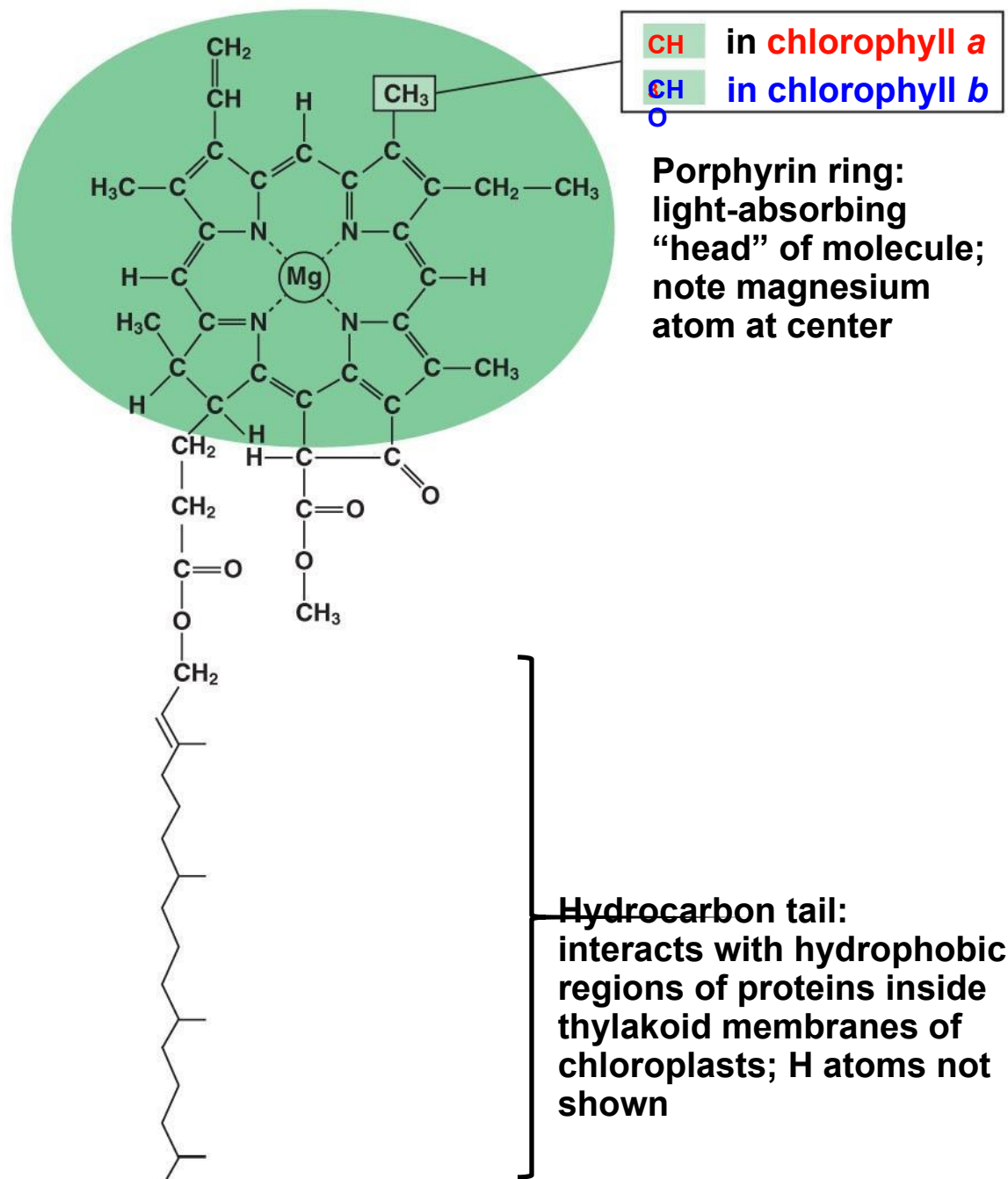


(c) Engelmann's experiment



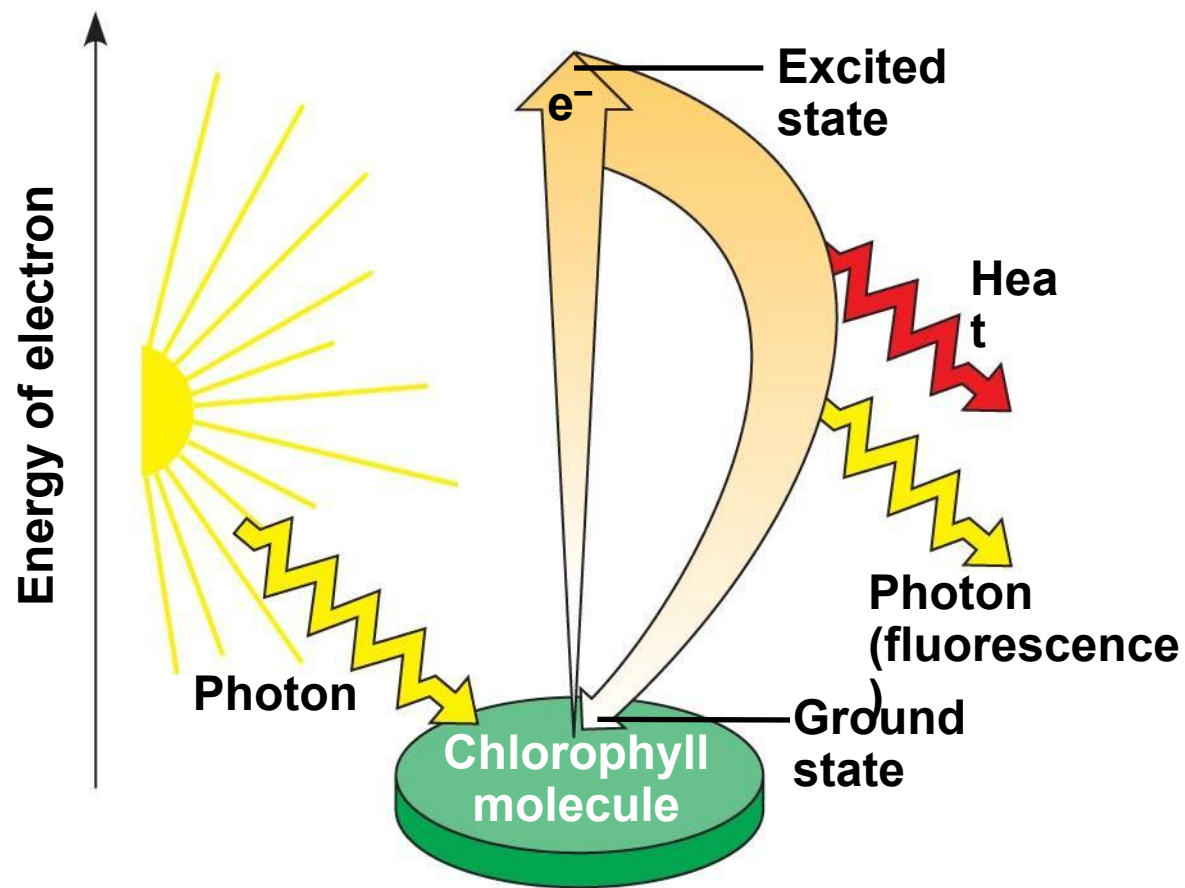
-
- ***Chlorophyll a*** is the **main photosynthetic pigment**
 - **Accessory pigments**, such as ***chlorophyll b***, **broaden the spectrum** used for photosynthesis
 - **Accessory pigments** called ***carotenoids*** **absorb excessive light** that ***would damage chlorophyll***

Fig. 10-10



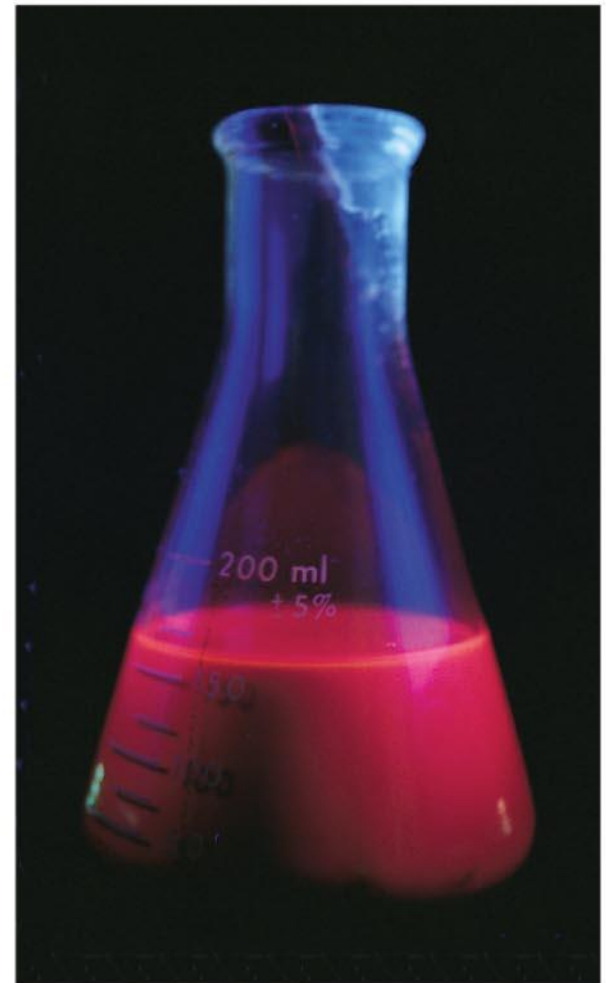
Excitation of Chlorophyll by Light

- 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**



(a) Excitation of isolated chlorophyll molecule

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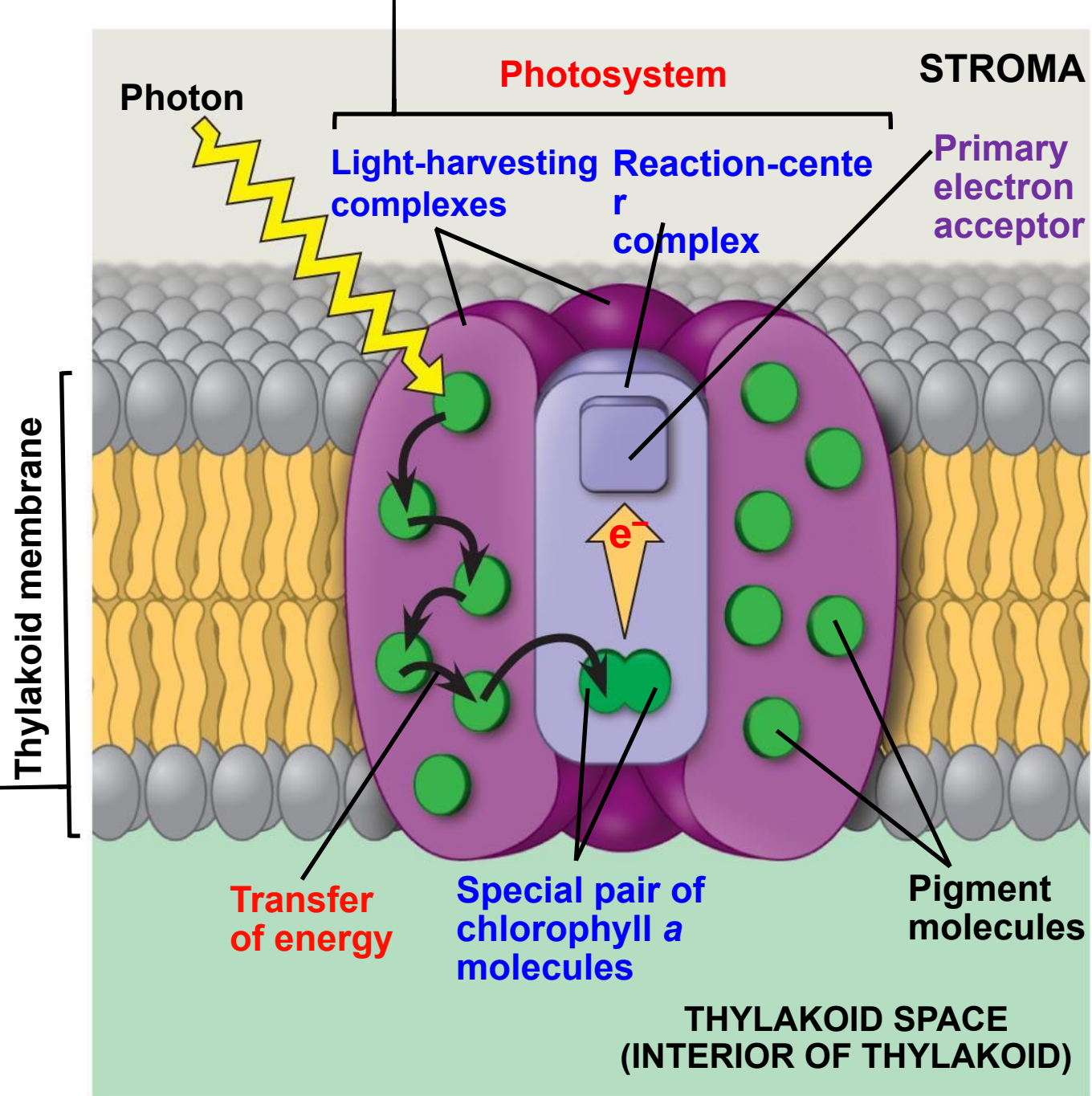
(b) Fluorescence

A Photosystem:

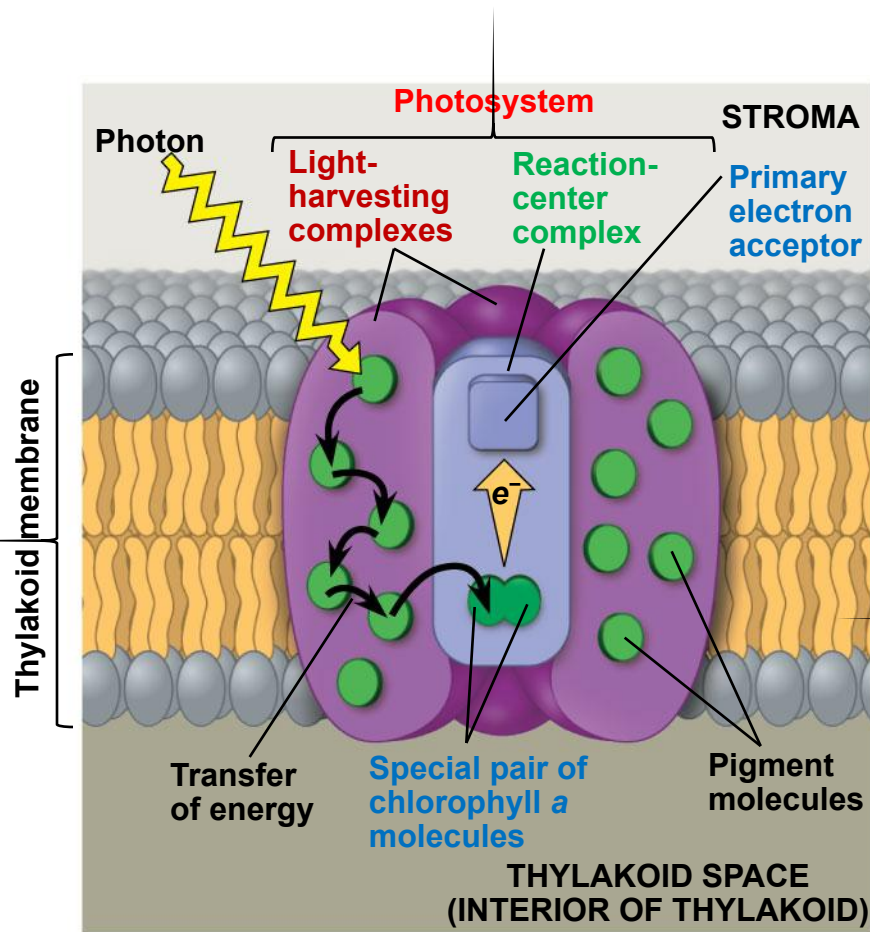
A Reaction-Center Complex Associated with Light-Harvesting Complexes

- 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

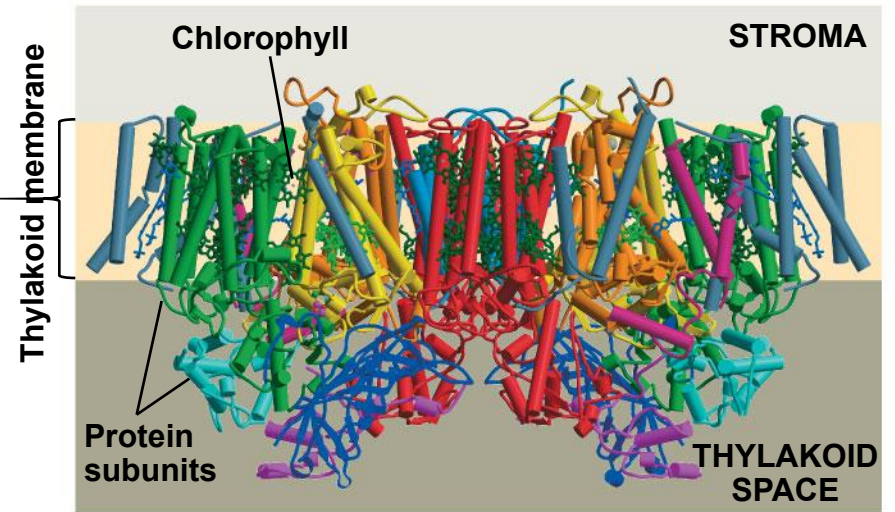


-
- A **primary electron acceptor** in the reaction center **accepts an excited electron from chlorophyll a**
 - Solar-powered **transfer of an electron from a chlorophyll a molecule to the primary electron acceptor is the first step of the light reactions**



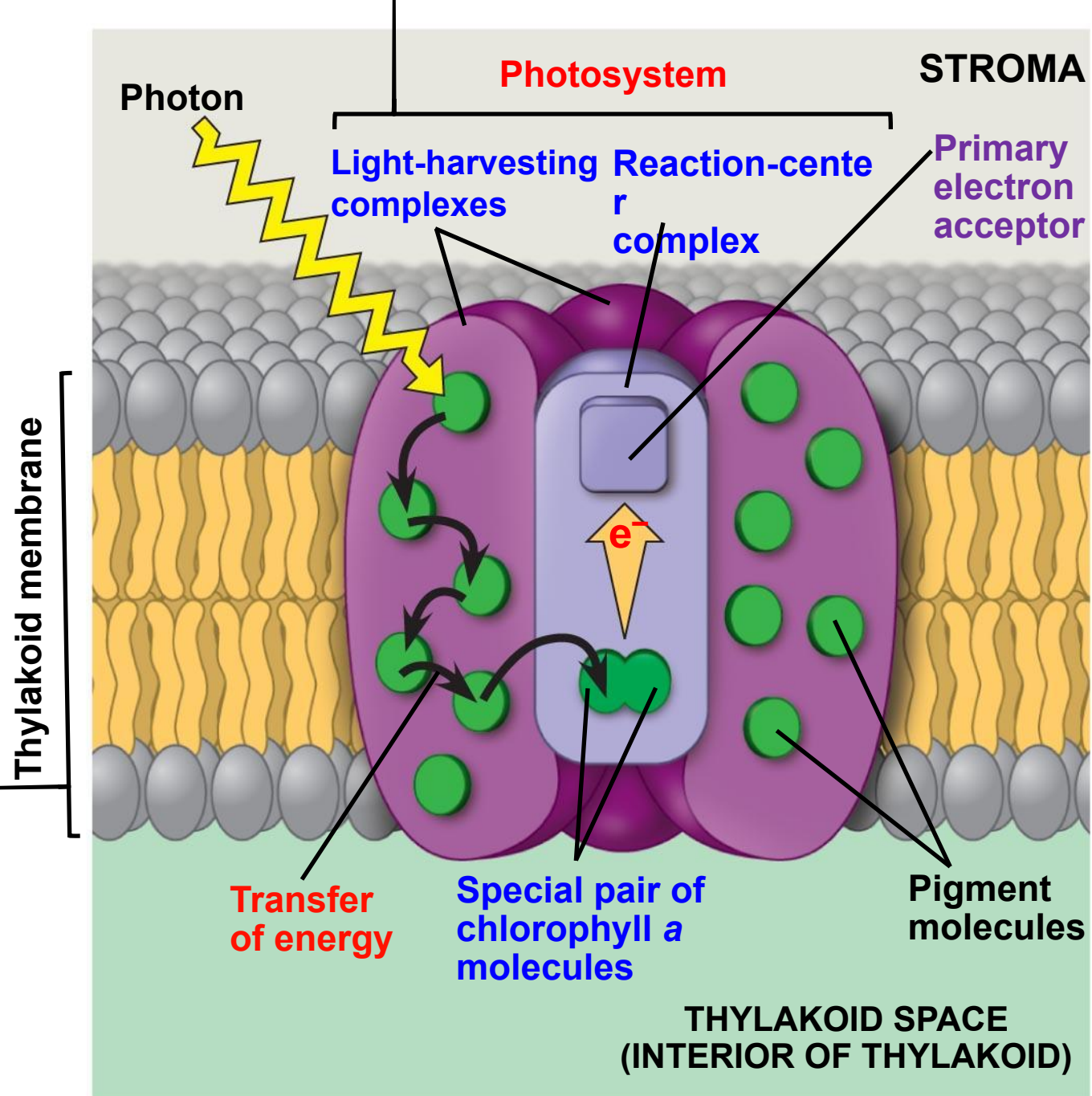
(a) How a photosystem harvests light

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(b) Structure of photosystem II

Fig. 10-12



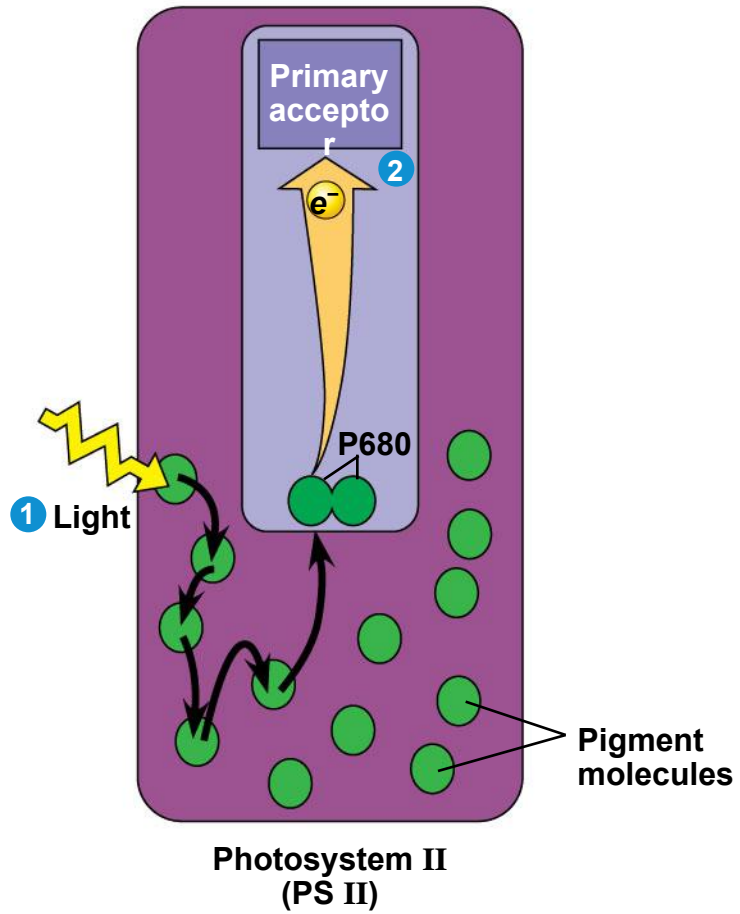
-
- **Two types of photosystems** in the thylakoid membrane
 - **Photosystem II (PS II)** functions first (the numbers reflect order of discovery) and is best at absorbing a wavelength of **680 nm**
 - The reaction-center chlorophyll *a* of PS II is called **P680**
-

-
- **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

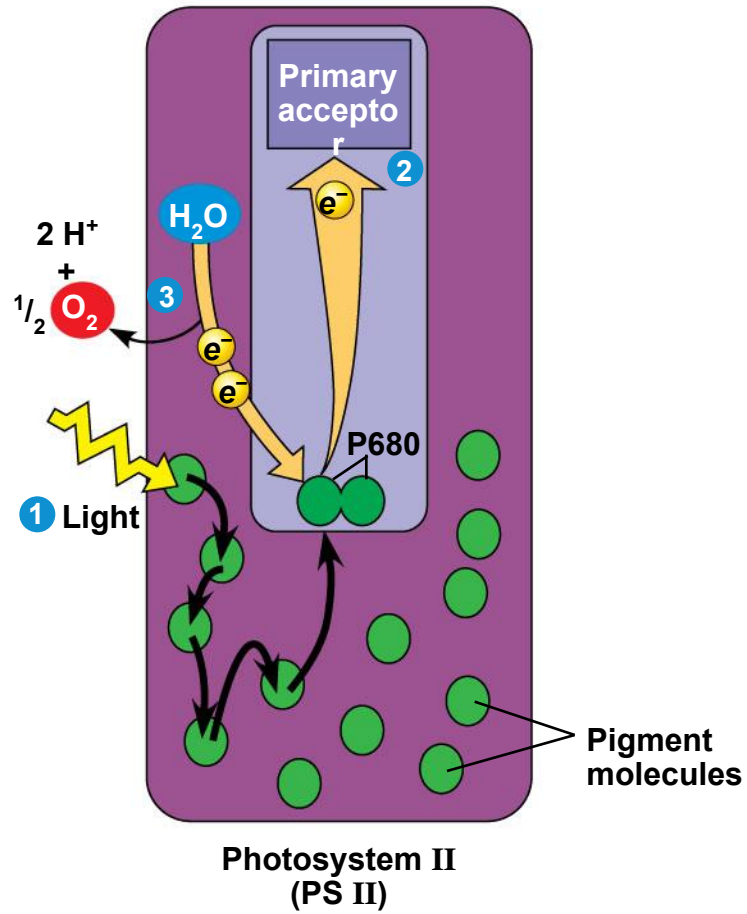
Figure 10.14-1



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- P680⁺ is a very strong oxidizing agent
- H₂O is split by enzymes, and the electrons are transferred from the hydrogen atoms to P680⁺, thus reducing it to P680
- O₂ is released as a by-product of this reaction

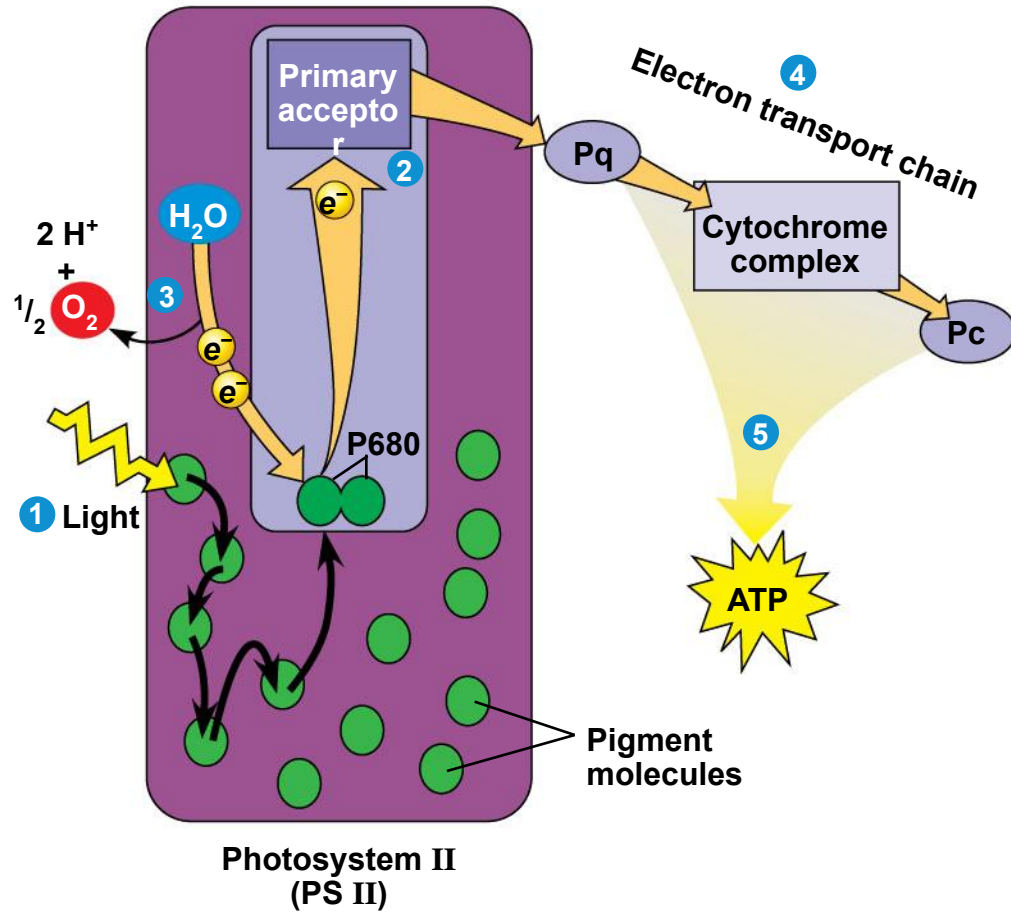
Figure 10.14-2



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- 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

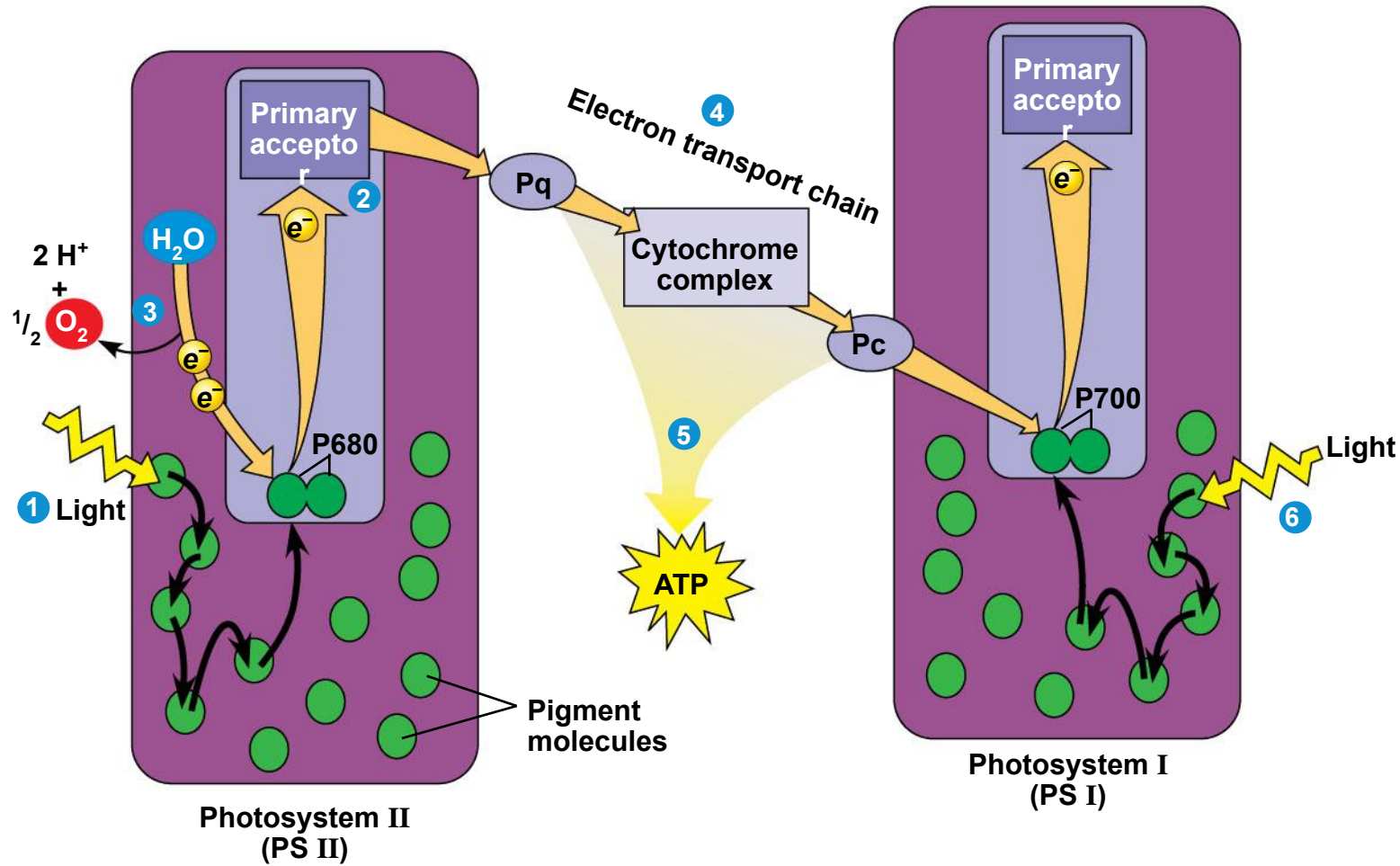
Figure 10.14-3



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- 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**

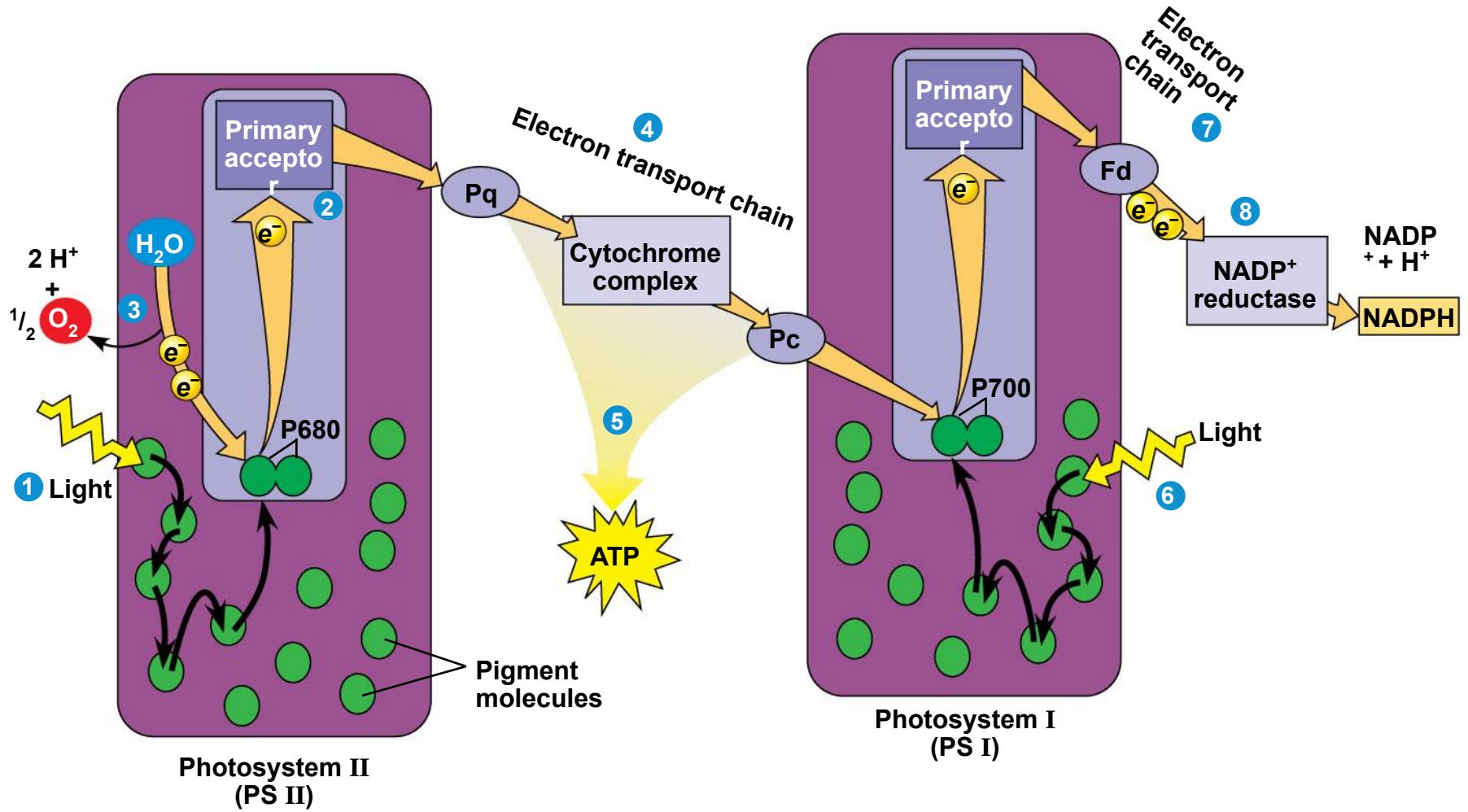
Figure 10.14-4



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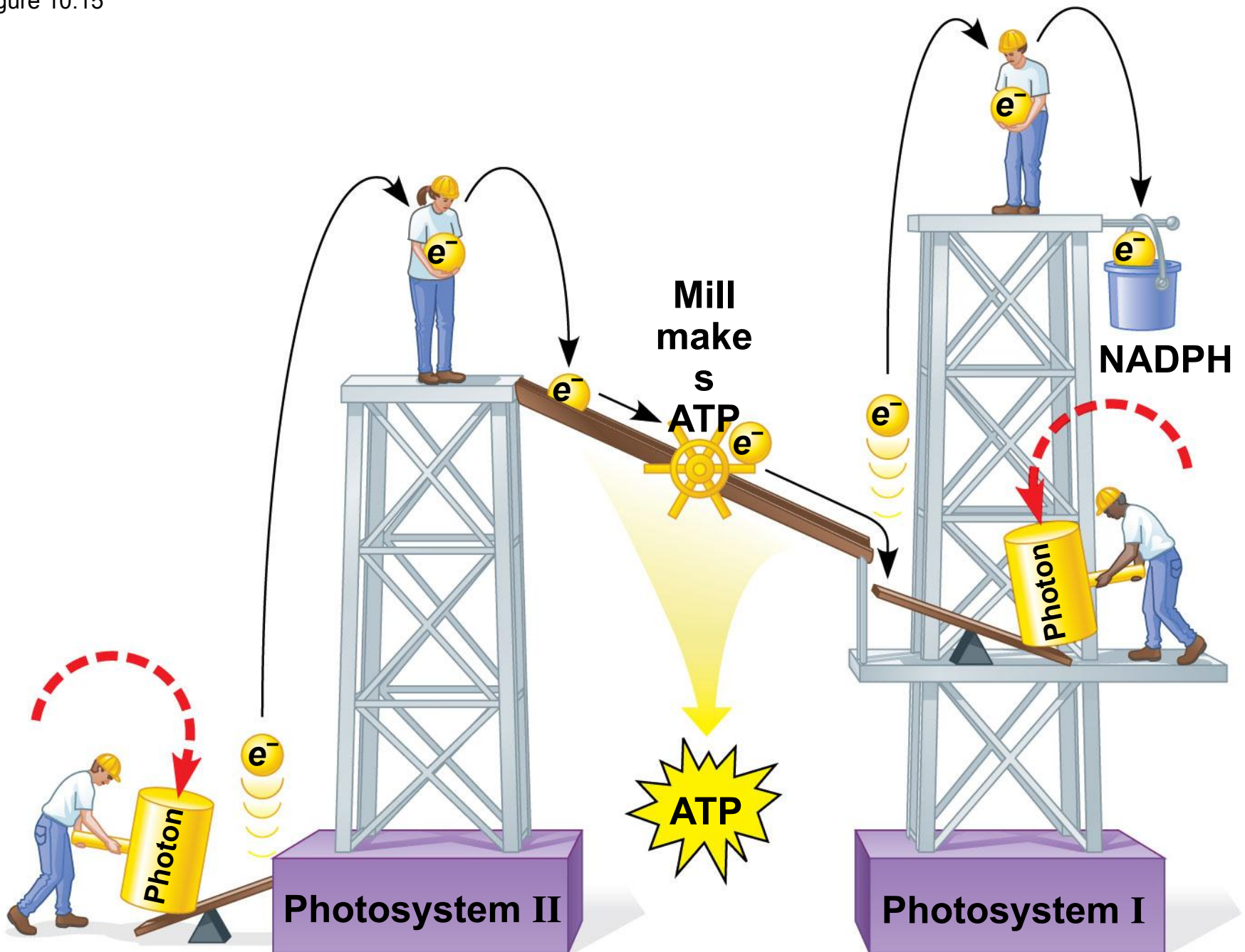
- Each electron “falls” down an electron transport chain from the primary electron acceptor of PS I to the protein ferredoxin (Fd)
- The electrons are then transferred to **NADP⁺** and reduce it to **NADPH**
- The electrons of NADPH are available for the *reactions of the Calvin cycle*
- This process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

Figure 10.14-5



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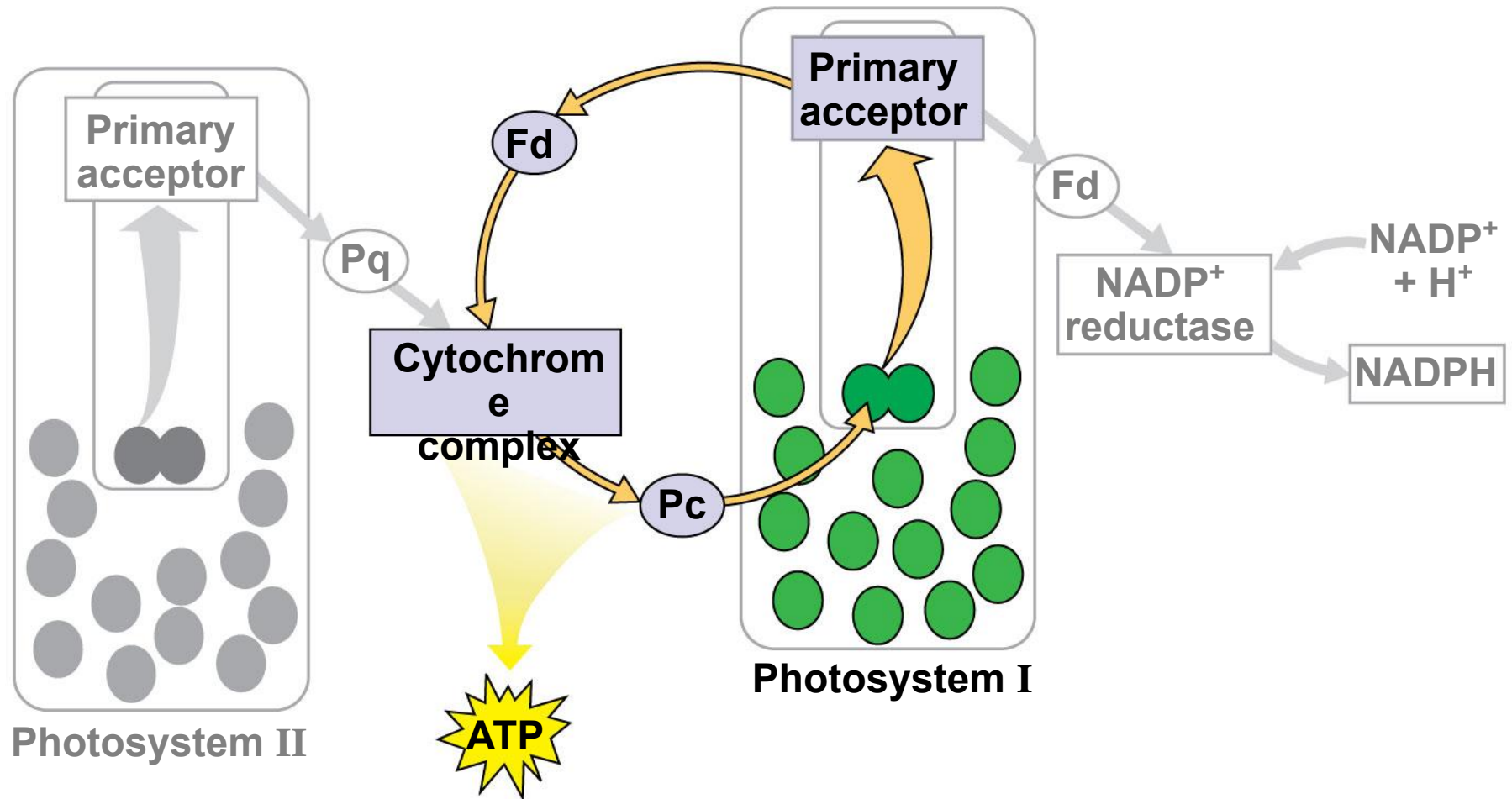
Figure 10.15



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



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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

Mitochondrion

Chloroplast

MITOCHONDRION STRUCTURE

CHLOROPLAST STRUCTURE

Intermembrane
space

Inner
membrane

Matrix

Electron
transport
chain

ATP
synthase

ADP + P_i

H^+ Diffusion

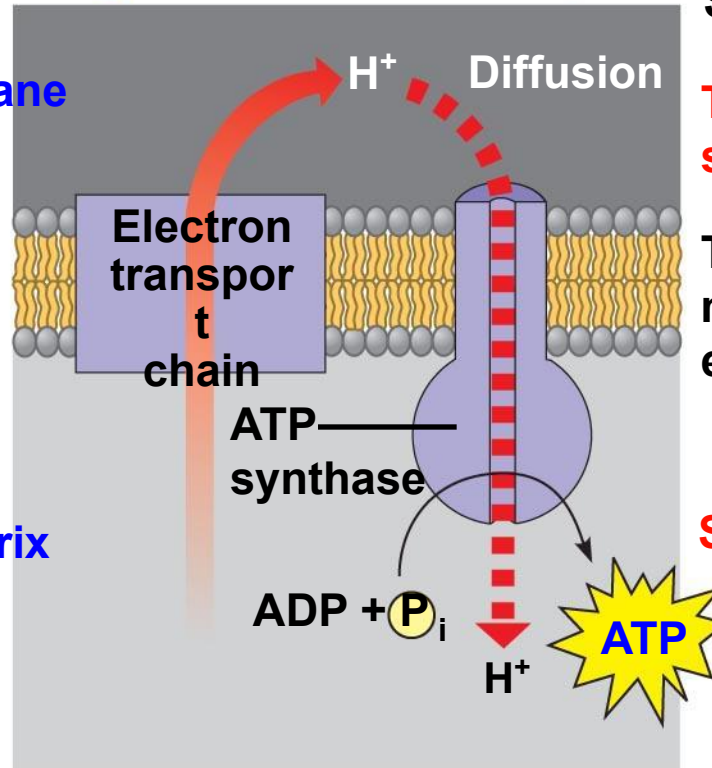
Thylakoid
space

Thylakoid
membrane

Stroma

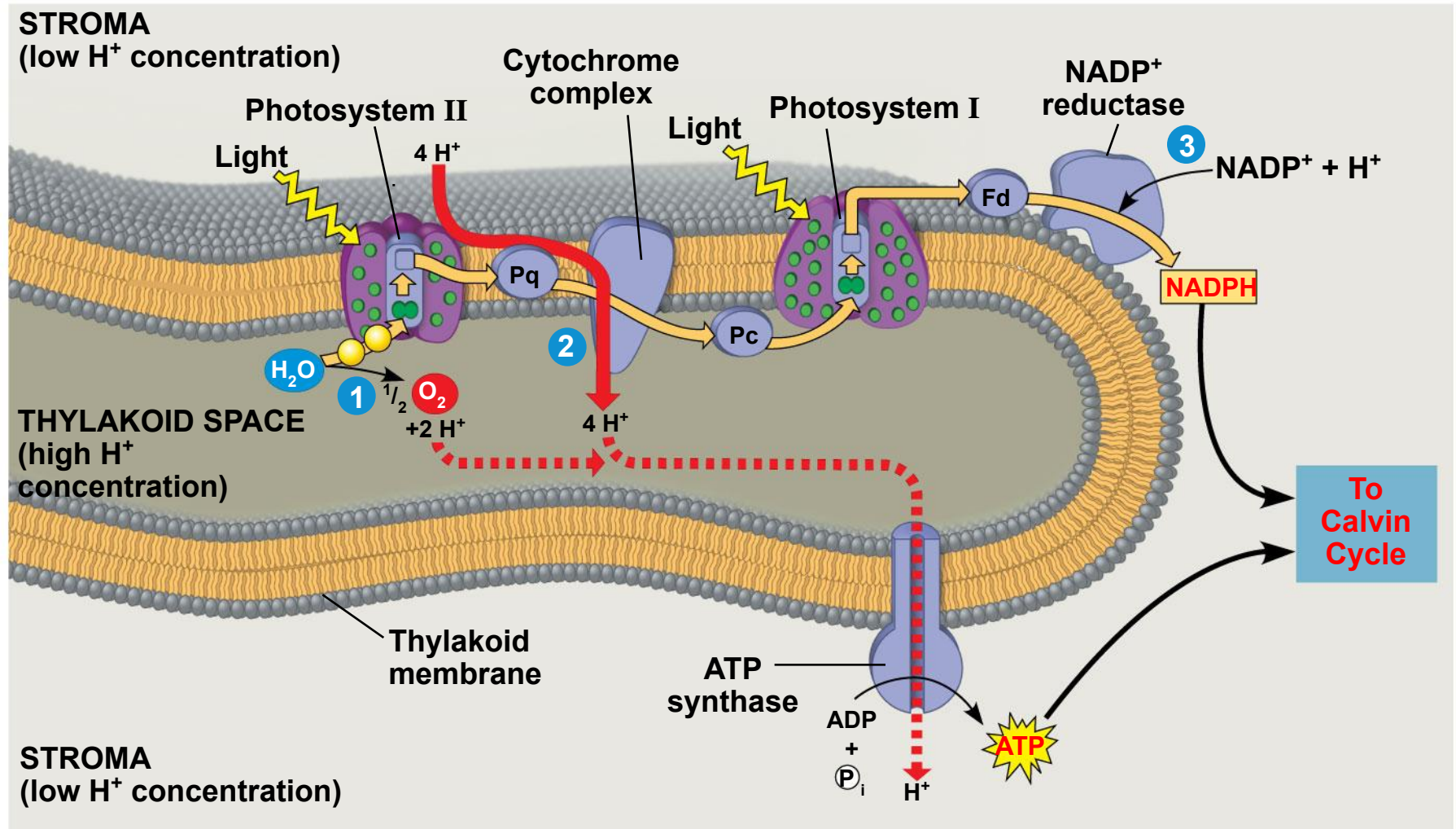
Key

Higher
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



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Concept 10.3: The Calvin cycle uses ATP and NADPH to convert CO₂ 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-phosphate (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

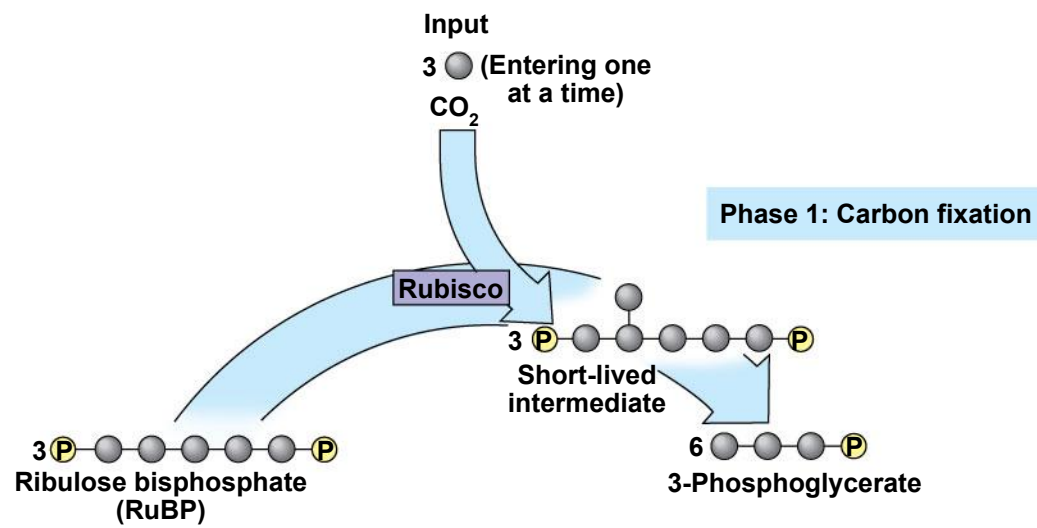


Figure 10.19-2

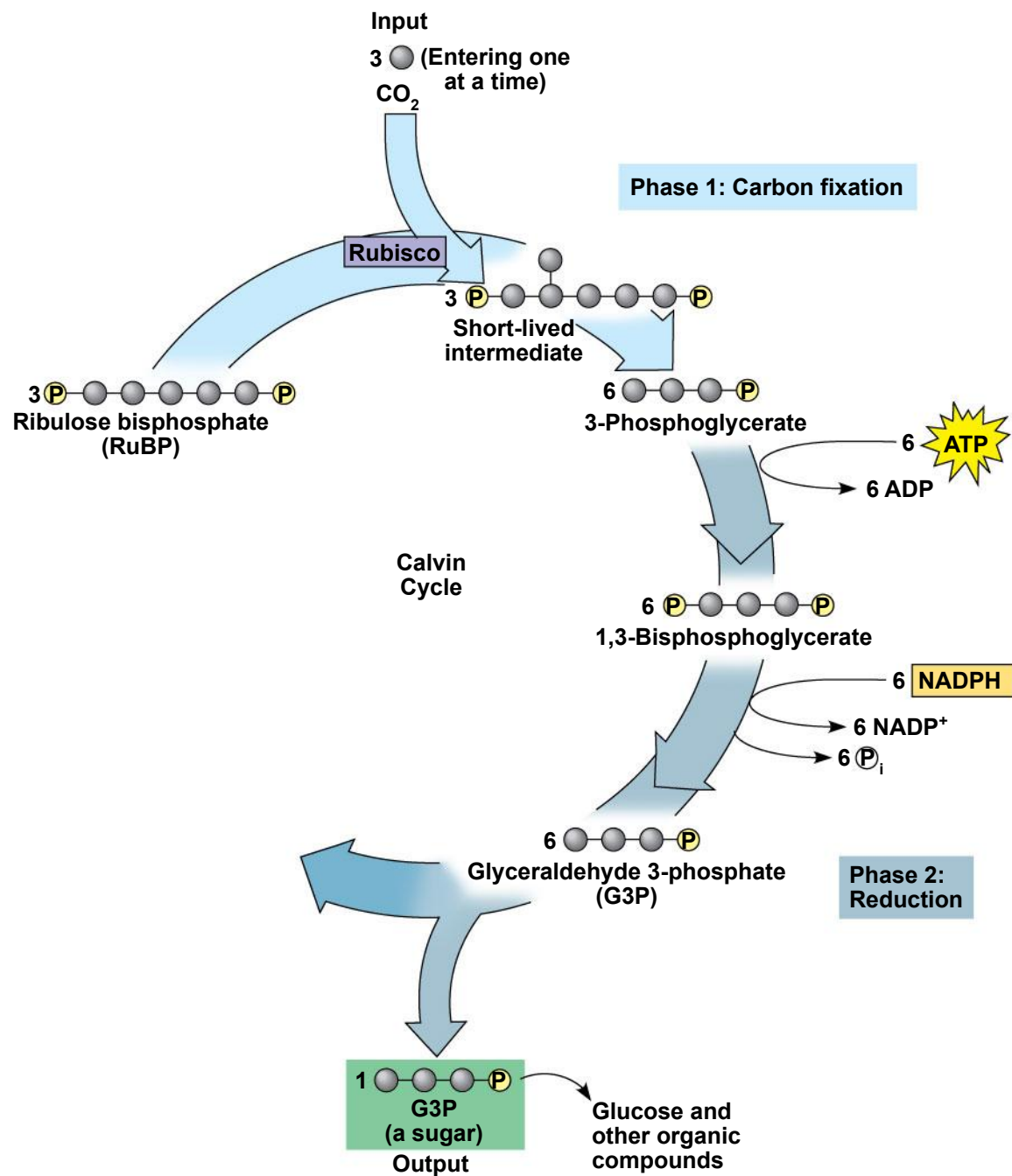


Figure 10.19-3

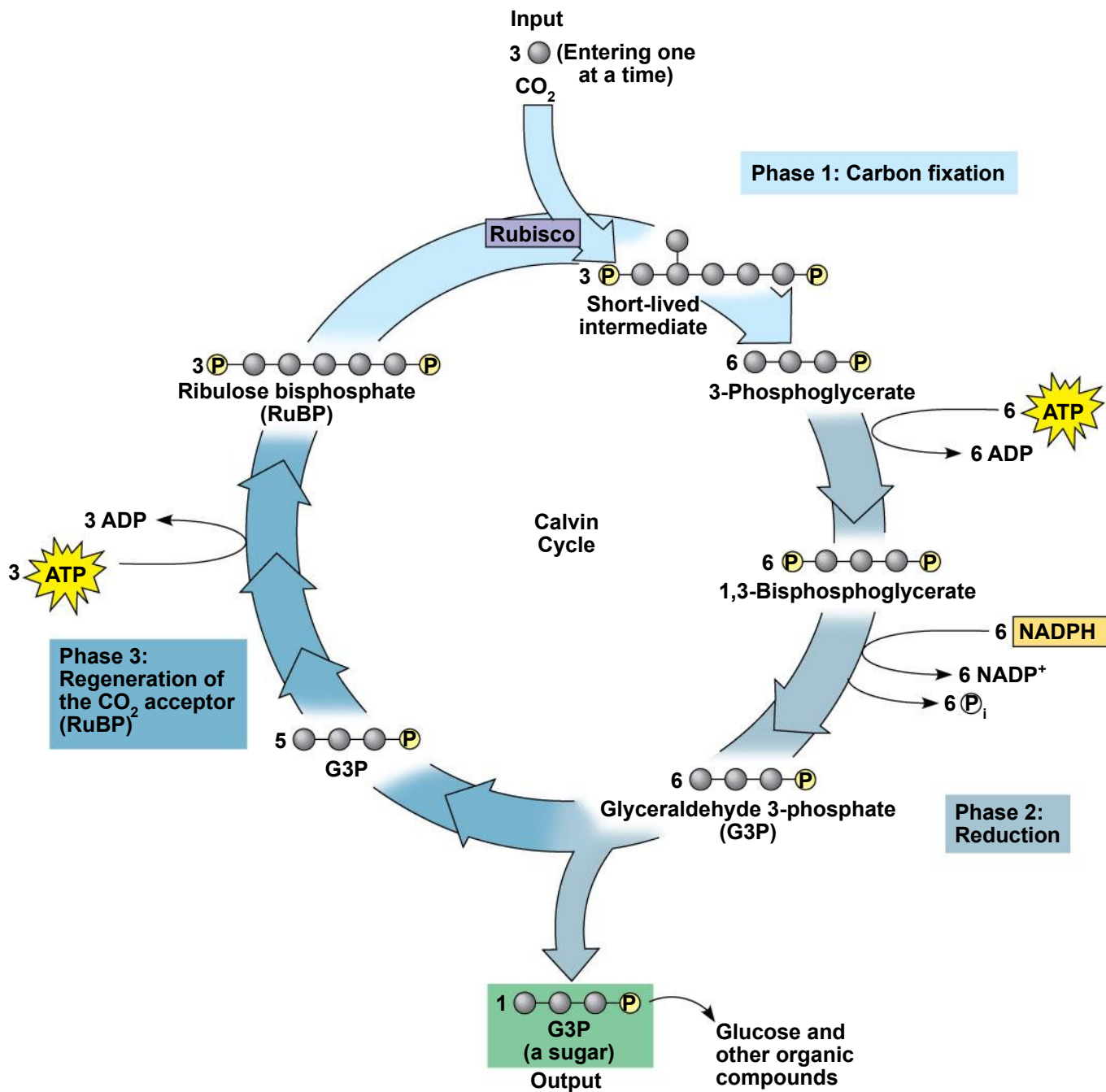


Figure 10.22

