10

Photosynthesis: Energy from Sunlight

Valencia College

Chapter objectives:

- What Is Photosynthesis?
- How Does Photosynthesis Convert Light Energy into Chemical Energy?
- How Is Chemical Energy Used to Synthesize Carbohydrates?
    - How to carbons become linked to form carbohydrates?
- How Do Plants Adapt to the Inefficiencies of Photosynthesis?
- How Does Photosynthesis Interact with Other Pathways?

Photosynthesis: “Synthesis from light”

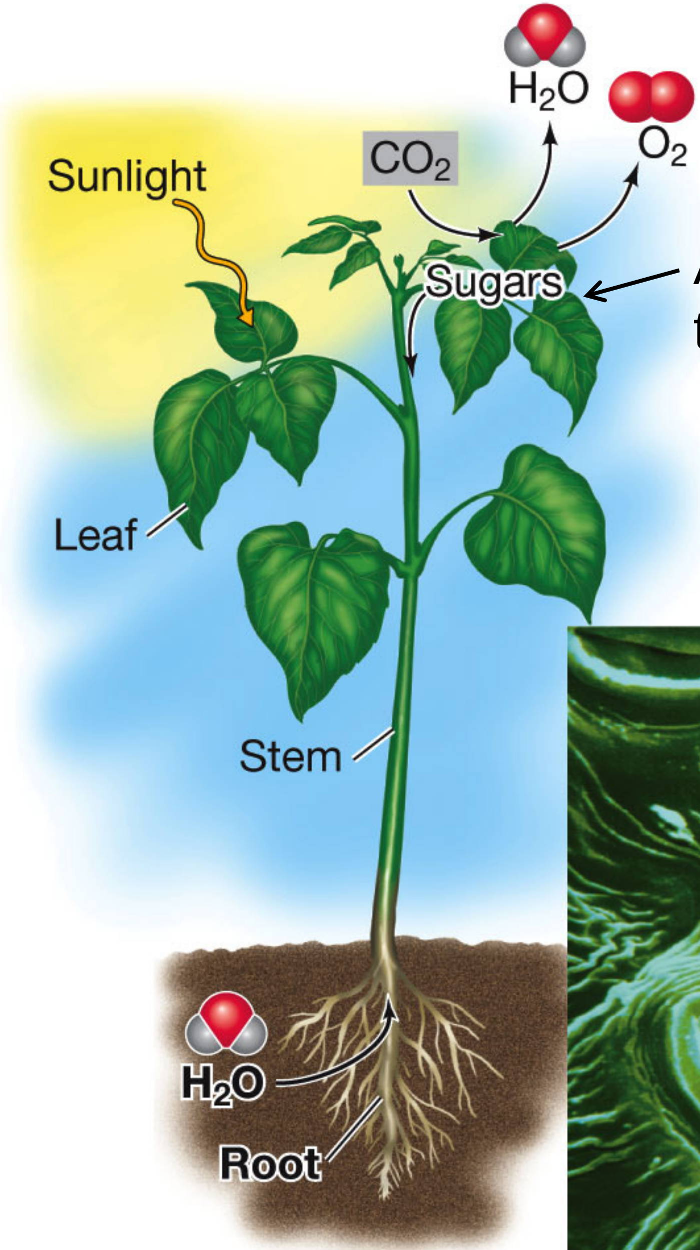
- Converts light energy into chemical energy

The broad outline:

- Plants take in CO_2 from the air, and H_20 from soil, to produce carbohydrates and release O_2 to the air
- Light is required

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

Figure 10.1 The Ingredients for Photosynthesis



Are transported throughout the plant body

stomata

10.1 Where does the oxygen gas come from: O_2 or CO_2?

Using radioisotope tracers, Ruben and Kamen determined that water is the source of O_2 released during photosynthesis:

$$6CO_2 + 12H_2\dot{O} \rightarrow C_6H_{12}O_6 + 6\dot{O}_2 + 6H_2O$$

This equation accounts for all the water molecules needed for all the oxygen gas produced.

Figure 10.2 The Source of the Oxygen Produced by Photosynthesis

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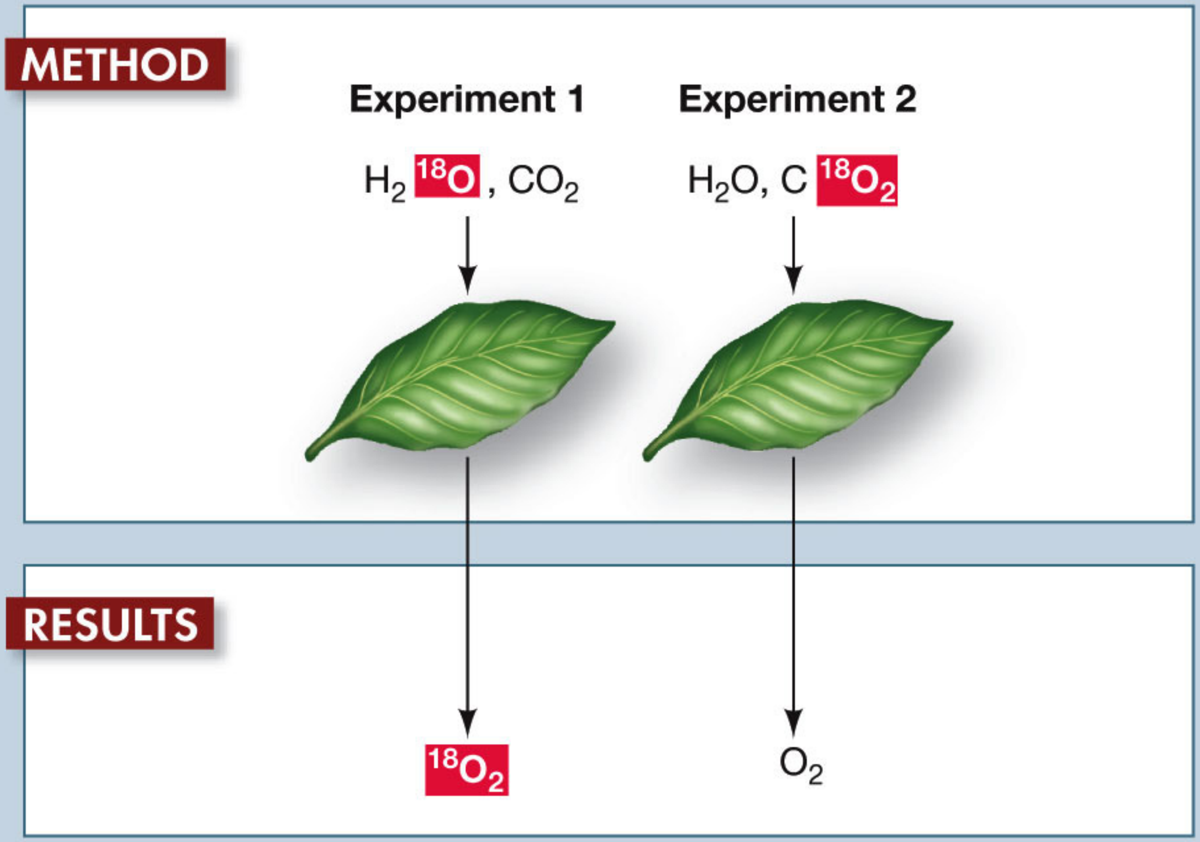
HYPOTHESIS The oxygen released by photosynthesis comes from water rather than CO_2.



CONCLUSION Water is the source of the O_2 produced by photosynthesis.

LIFE 9e, Figure 10.2

Photosynthesis involves Two pathways:

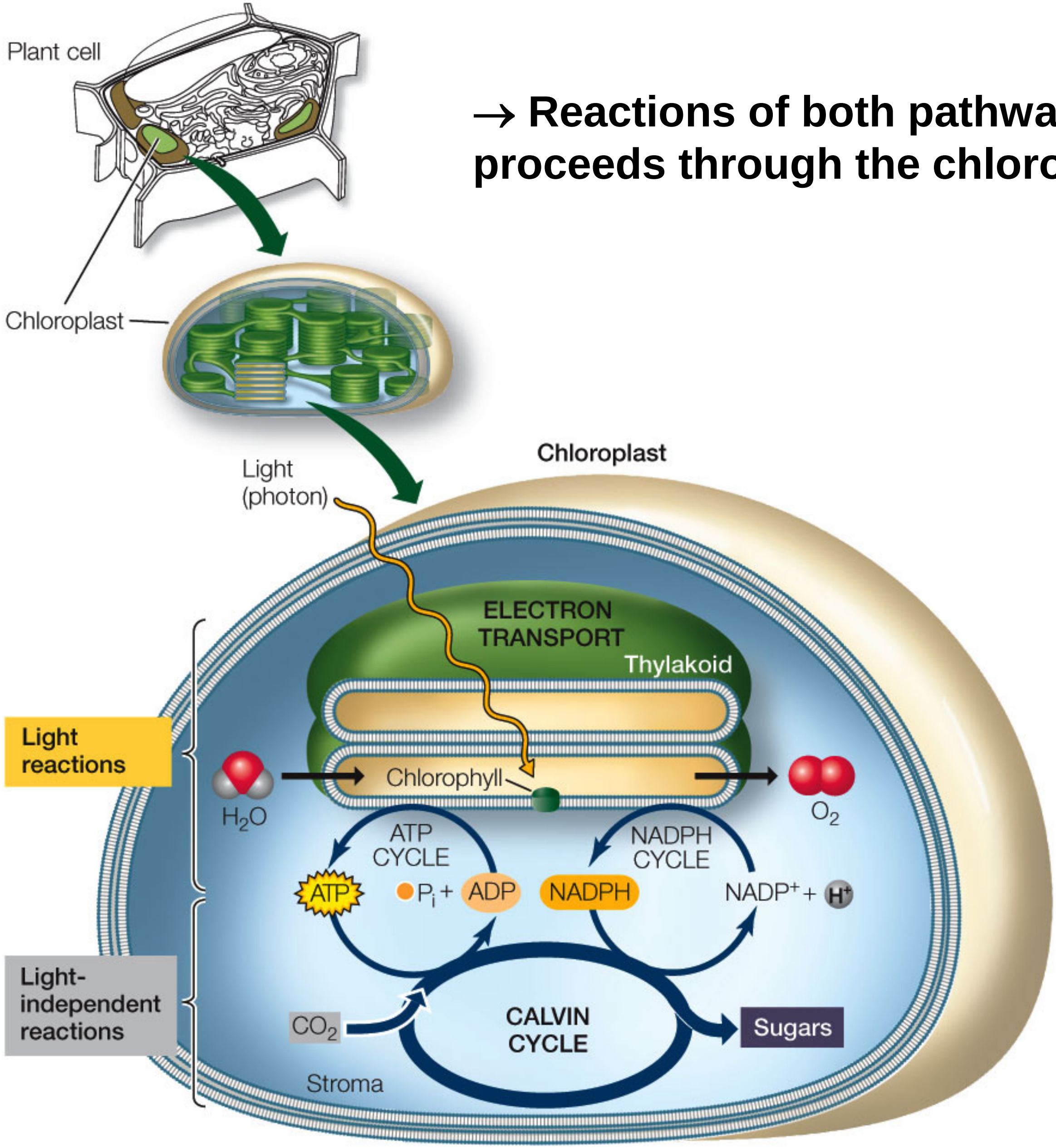
- **Light reactions**: Convert light energy to chemical energy as ATP and NADPH
- **Light-independent reactions**: Use ATP and NADPH *(from the light reactions)* plus CO_2 to produce carbohydrates (carbon fixation or Dark rxn's)

*Both pathway reactions stop in the dark because ATP synthesis and $NADP^+$ reduction require light.

→ **Reactions of both pathways proceeds through the chloroplast**

1. Light reactions

2. Light-independent reactions



LIFE 9e, **Figure 10.3**

Properties of light:

Light is a form of energy that can produce **electromagnetic radiation**.

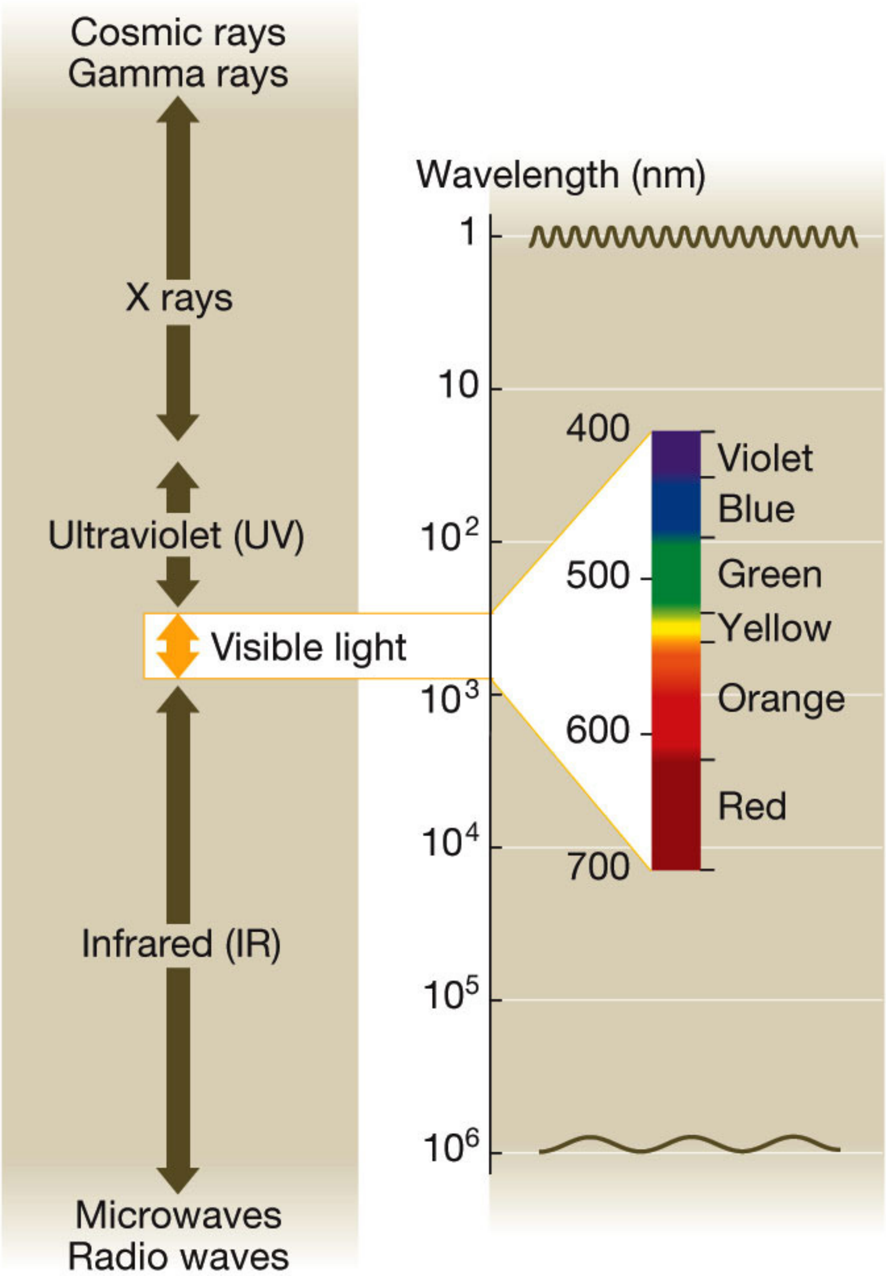
- Light is propagated as waves—the energy of light is inversely proportional to its **wavelength**;

AND

- Light also behaves as particles, called **photons**.

Figure 10.4 The Electromagnetic Spectrum

Receptor molecules absorb only specific wavelengths of light for photons to have the correct amount of energy



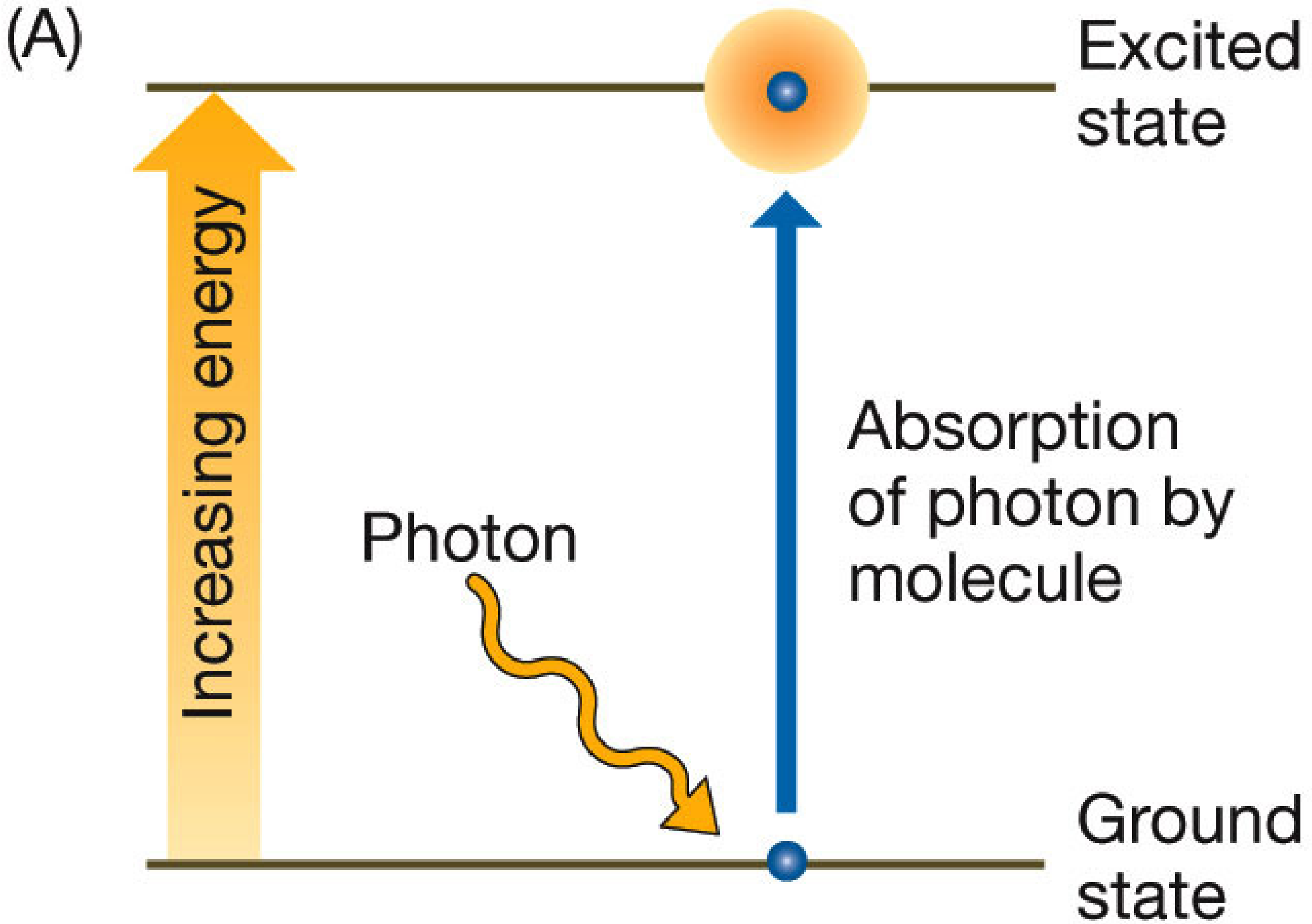
LIFE 9e, Figure 10.4

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

When a photon meets a receptive molecule it can be:

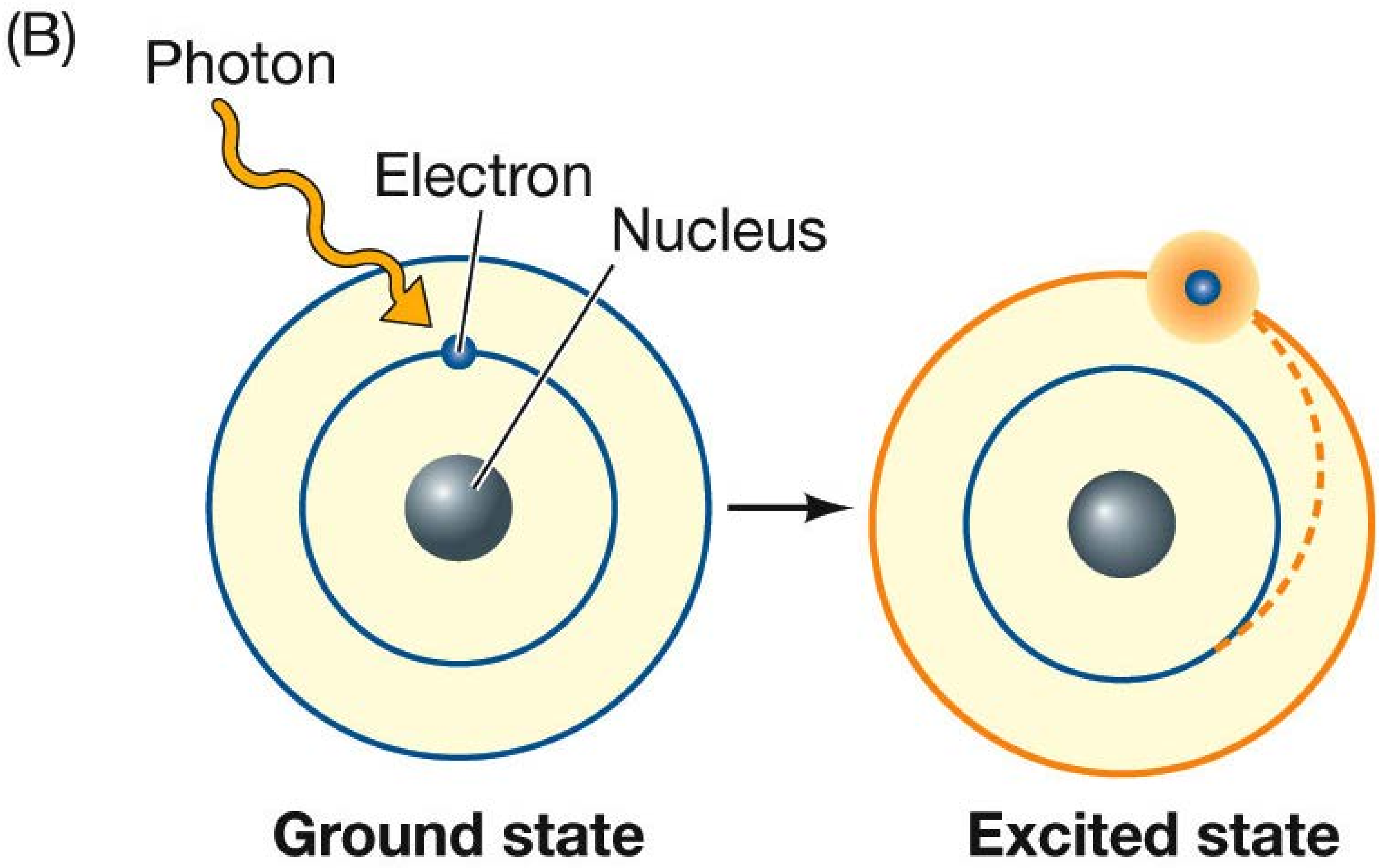
- Scattered—photon bounces off the molecule
- Transmitted—photon is passed through the molecule
- Absorbed— a molecule acquires the energy of the photon. The receptive molecule is energized and goes from ground state to an excited state

Figure 10.5 Exciting a Molecule (A)



→When a receptive molecule absorbs a photon, it is raised to an energized state

Figure 10.5 Exciting a Molecule (B)



→The absorbed energy of the photon boosts an electron to a shell farther from its atomic nucleus

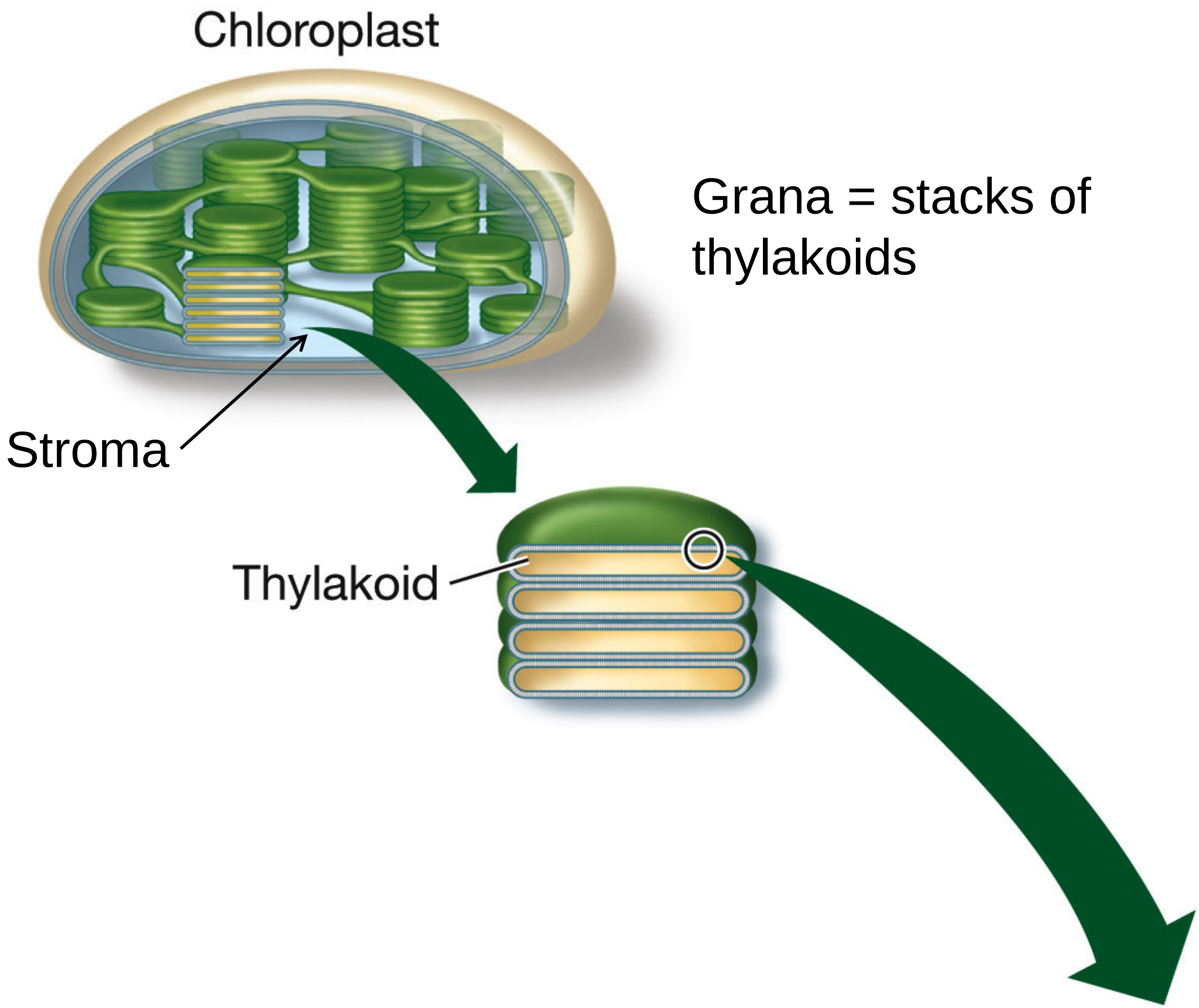
Photons can have a wide range of wavelengths and energy levels.

Molecules that absorb specific wavelengths in the visible range of the spectrum are called **pigments**.

Several types of pigments absorb light energy used in photosynthesis:

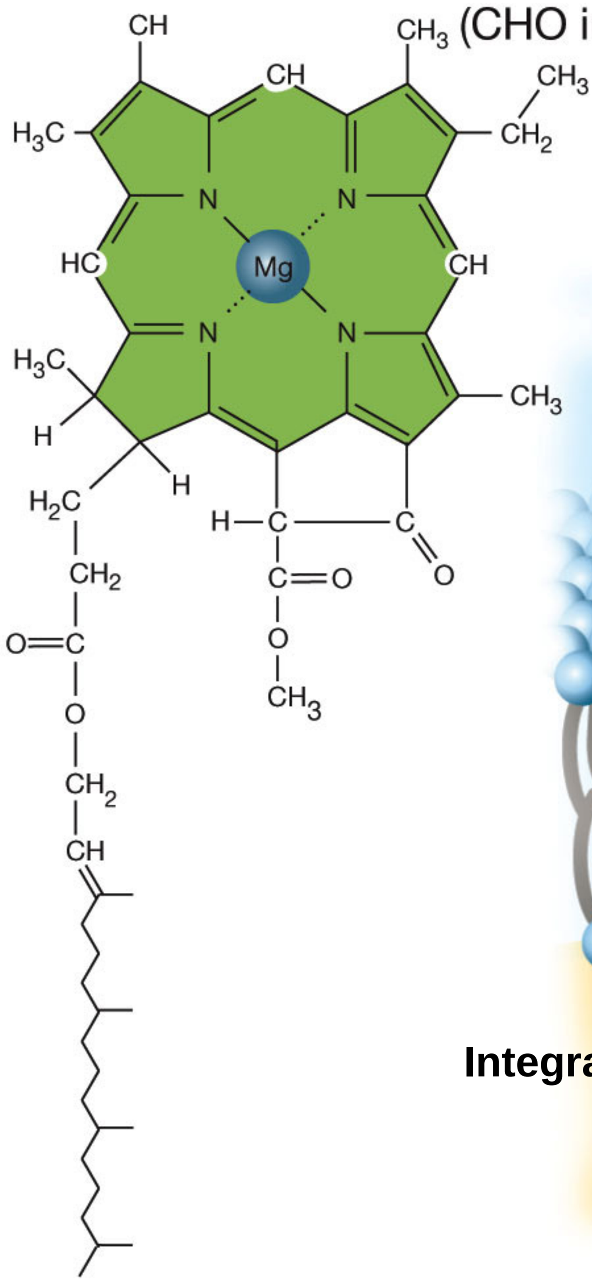
- **Chlorophylls *a*** and ***b***
  - *Absorbs blue & red light*
  - *Remaining light we see is green*
- **Accessory pigments**: Absorb in red and blue regions, transfer the energy to chlorophylls—**carotenoids** and **phycobilins**

Figure 10.7 The Molecular Structure of Chlorophyll (Part 1)

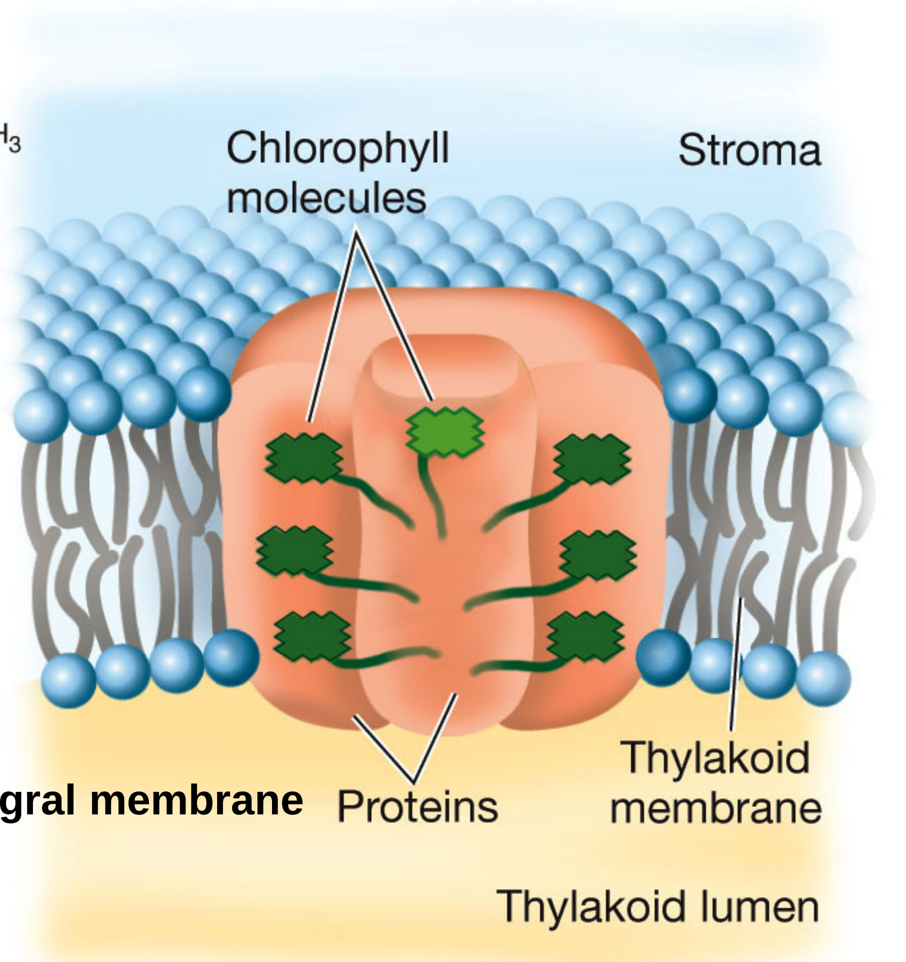


Grana = stacks of thylakoids

Figure 10.7 The Molecular Structure of Chlorophyll (Part 2)



→Light is absorbed by the complex ring structure of a chlorophyll molecule



Integral membrane Proteins

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

When a pigment molecule absorbs a photon the energy can be:

- Released as heat and/or light (fluorescence)
- Transferred to another molecule
- Used for a chemical reaction

When a pigment gives up it's energy it returns to ground state.

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

Energy can be transferred to another molecule if -

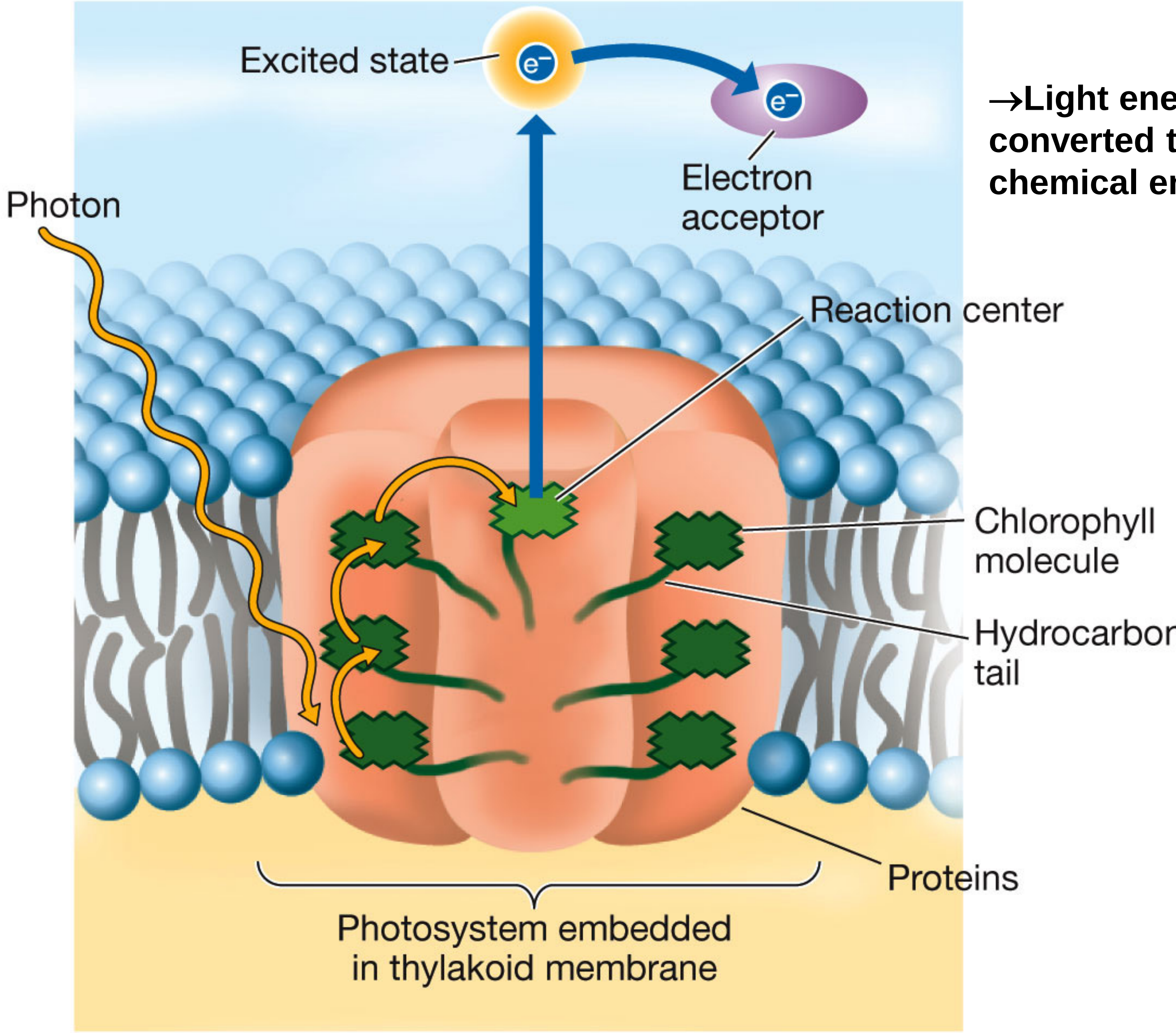
- ✓ Target molecule is very near
- ✓ Orientation is correct
- ✓ Has appropriate structure

This occurs in photosynthesis.

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

Pigments are arranged in **antenna systems**, or *light-harvesting complexes*.

- A **photosystem** consists of a large multi-protein complex with multiple antenna systems and their pigments and surrounds a **reaction center** (300:1 ratio)
- Pigments are packed together on thylakoid membrane proteins.
- Excitation energy passes from pigments that absorb short wavelengths to those that absorb longer wavelengths, and ends up in the **reaction center** pigment.



→Light energy is converted to chemical energy

LIFE 9e, Figure 10.8

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

The reaction center converts light energy into chemical energy.

- The excited chlorophyll *a* molecule (Chl*) is a reducing agent (electron donor).
- A is an acceptor molecule (oxidizing agent).

$$Chl^{*} + A \rightarrow Chl^{+} + A^{-}$$

10.2 How Does Photosynthesis Convert Light Energy into Chemical Energy?

Chlorophyll a is the first in a chain of electron carriers on the thylakoid membrane –

- a process called *Electron Transport* –
  - a series of redox reactions.

- Where the final electron acceptor is $NADP^+$

$$NADP^+ + H^+ + 2e^- \rightarrow NADPH$$

- NADPH is a reduced stable coenzyme

There are two systems of **Electron Transport**:

- **Noncyclic electron transport**—produces NADPH and ATP
- **Cyclic electron transport**—produces ATP only

Noncyclic electron transport:

- Requires participation of two different Photosystems in the thylakoid membrane – Photo I & Photo II

➢ Light energy is used to oxidize (photolysis)

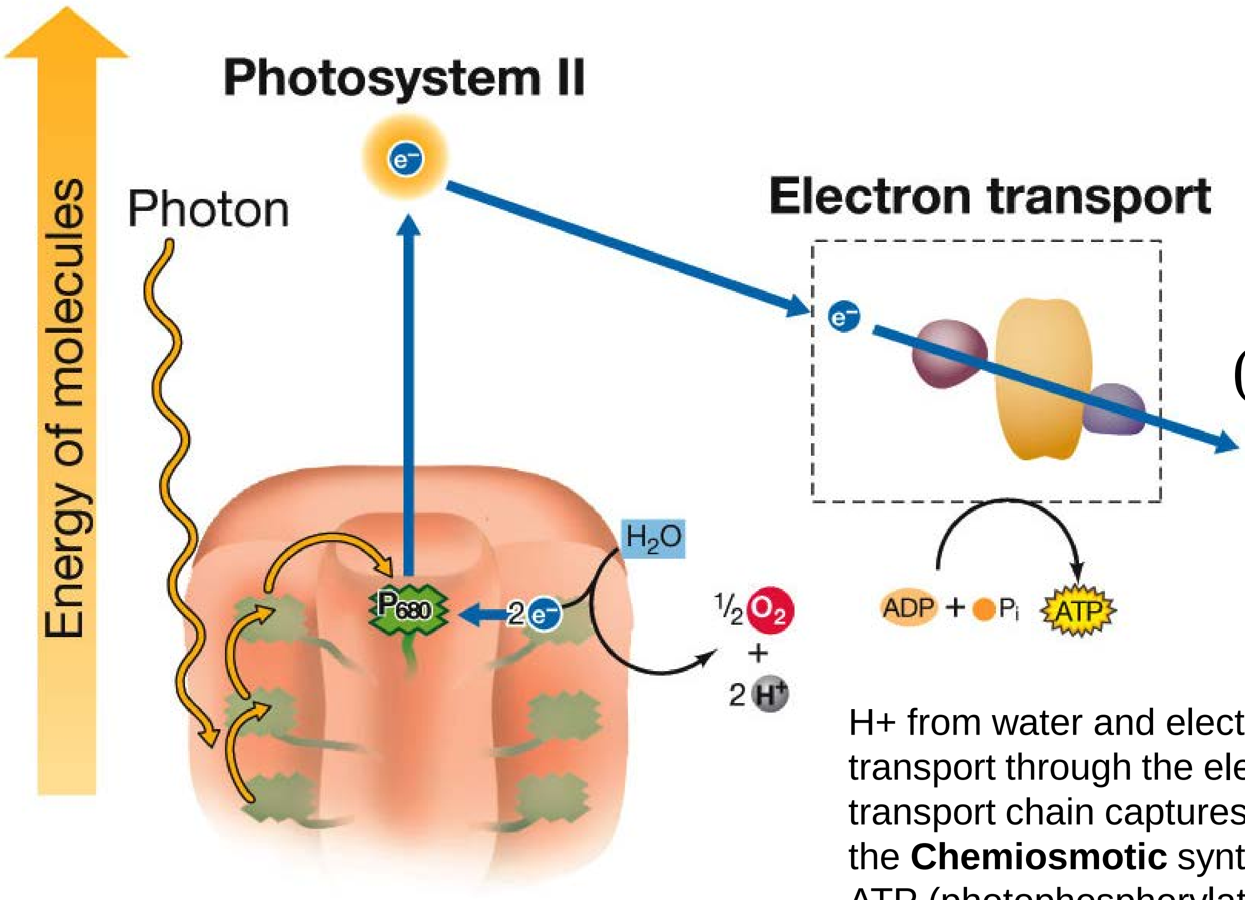
$$H_2O + \text{enzyme} \rightarrow O_2, H^+, \text{and electrons.}$$

1. After excitation by light, Chl^+ is an unstable molecule and seeks electrons.
2. Chl^+ is a strong oxidizing agent and takes electrons from H_2O, splitting the water molecule with the aid of an enzyme.

Photosystem II

- Light energy oxidizes water → O_2, H^+, and electrons.
- Reaction center has a pair of chlorophyll *a* molecules P_{680}—absorb at 680nm.
- 1 ATP is produced by Chemiosmosis

Noncyclic Electron Transport begins with Photosystem II



(Exergonic)

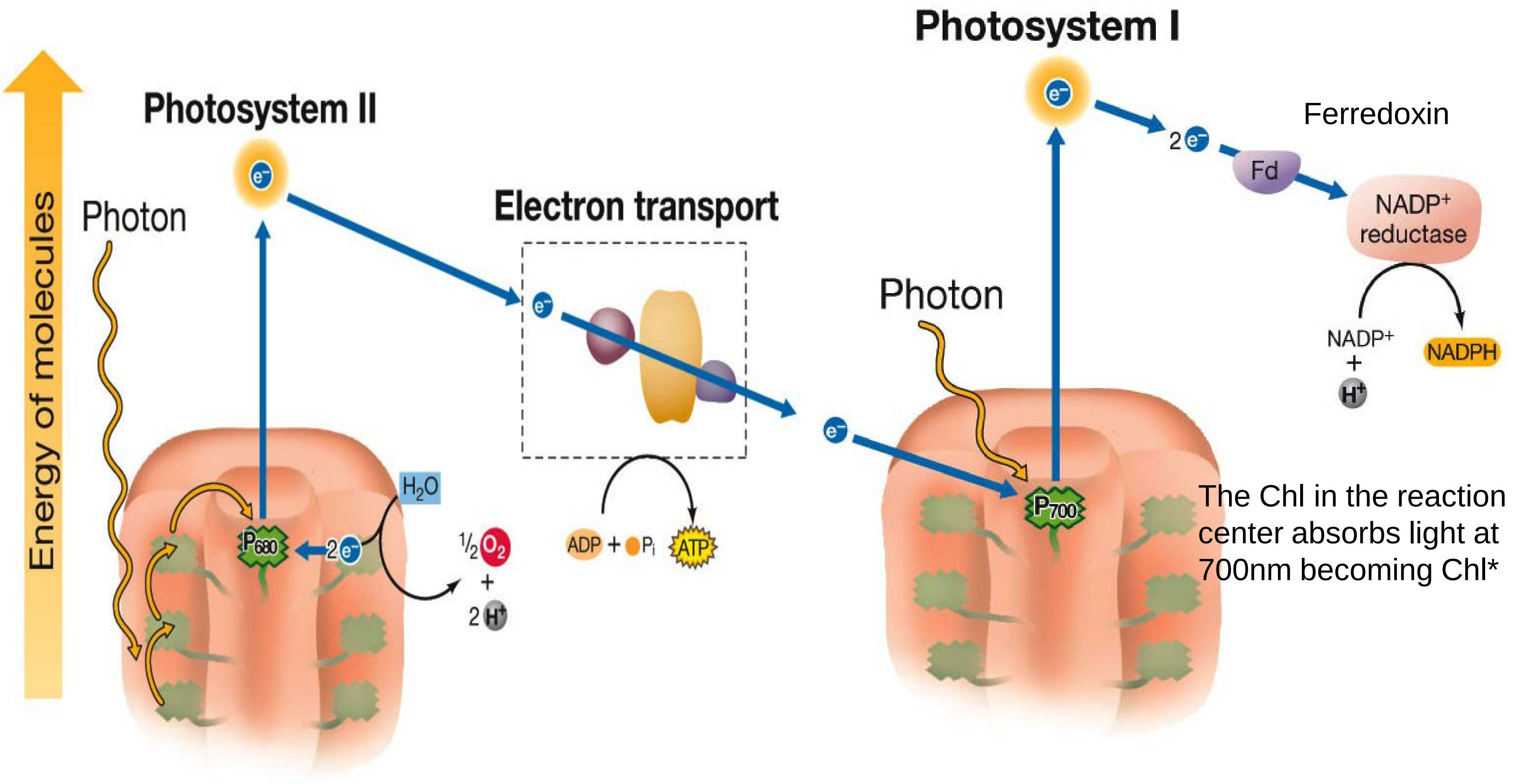
H+ from water and electron transport through the electron transport chain captures energy for the **Chemiosmotic** synthesis of ATP (photophosphorylation)

Photosystem I & II complement each other and enhance photosynthesis.

Photosystem I

- Light energy reduces $NADP^+$ to NADPH
- **Reaction center** has a pair of chlorophyll *a* molecules: P_{700}—absorb in the 700nm range

Figure 10.10 Noncyclic Electron Transport Uses Two Photosystems (Part 2)



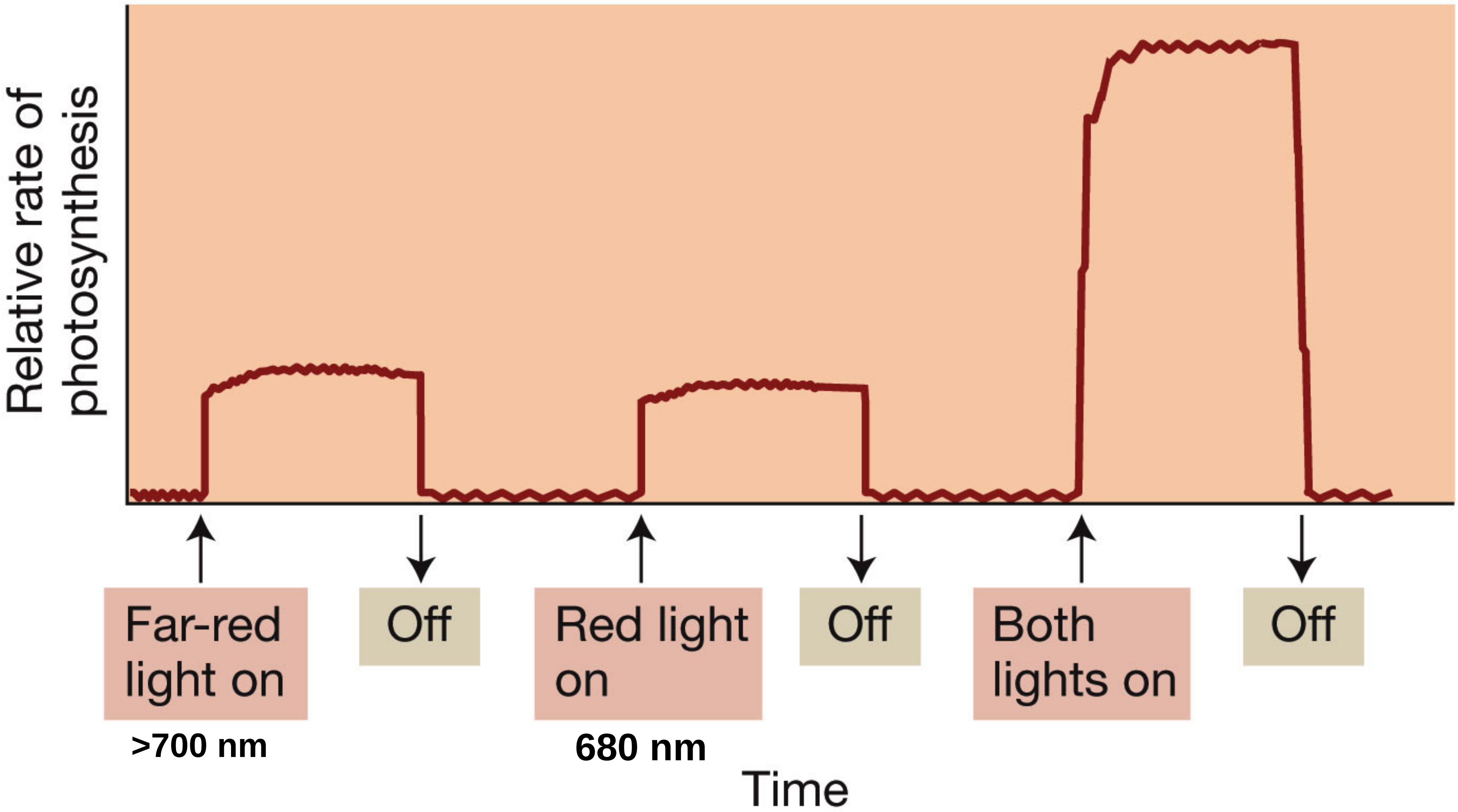
The Chl in the reaction center absorbs light at 700nm becoming Chl*

Z scheme

The "Z scheme" model of noncyclic electron transport:

- Extracts electrons from water and transfers them to NADPH, using energy from photosystems I and II and resulting in ATP synthesis
- Yields NADPH, ATP and O_2

Figure 10.9 Two Photosystems



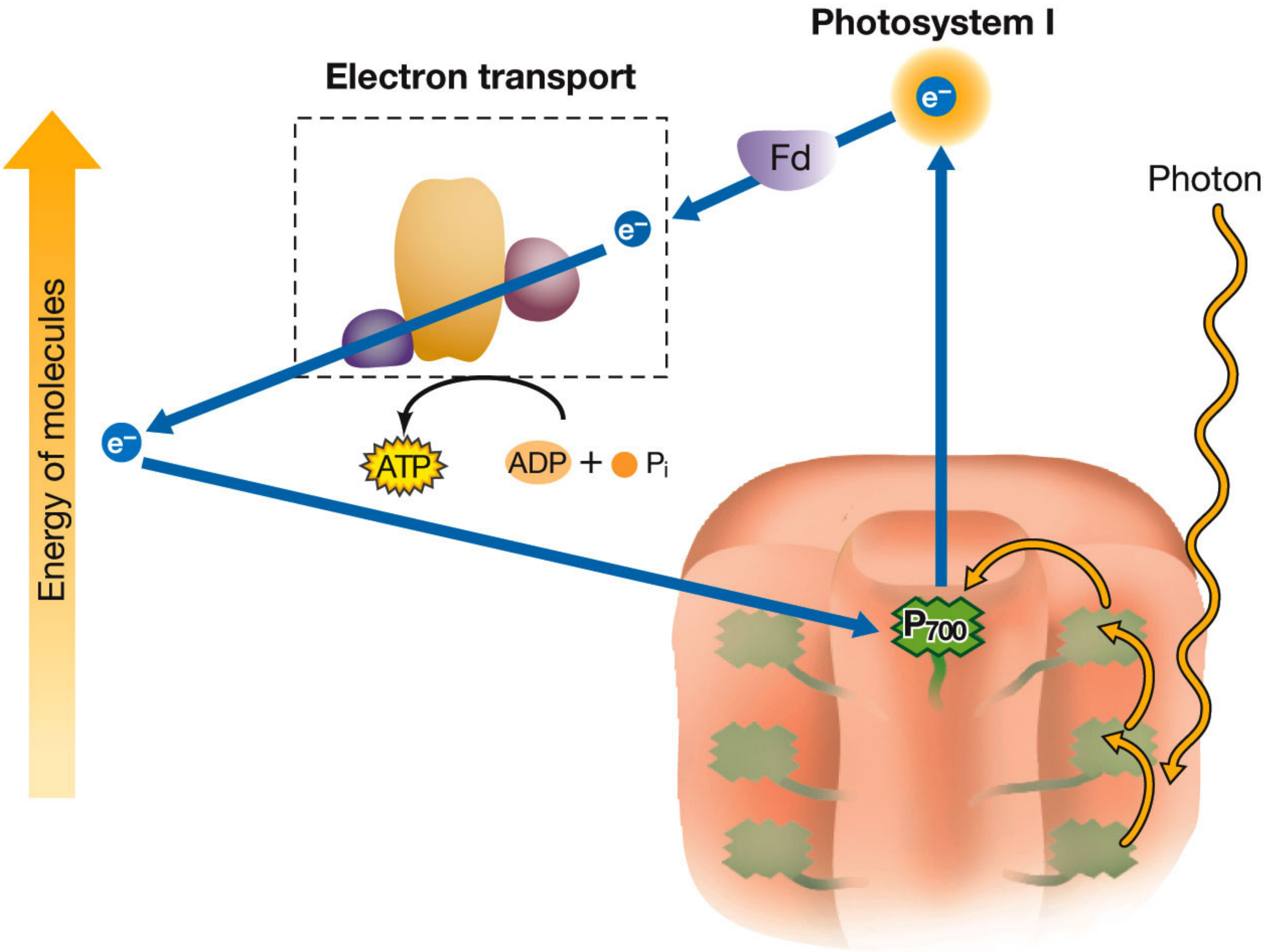
Cyclic electron transport

- only makes ATP—an electron from an excited chlorophyll molecule cycles back to the same chlorophyll molecule.

Cyclic electron transport begins and ends in photosystem I.

Released energy is stored and can be used to form ATP.

Figure 10.11 Cyclic Electron Transport Traps Light Energy as ATP

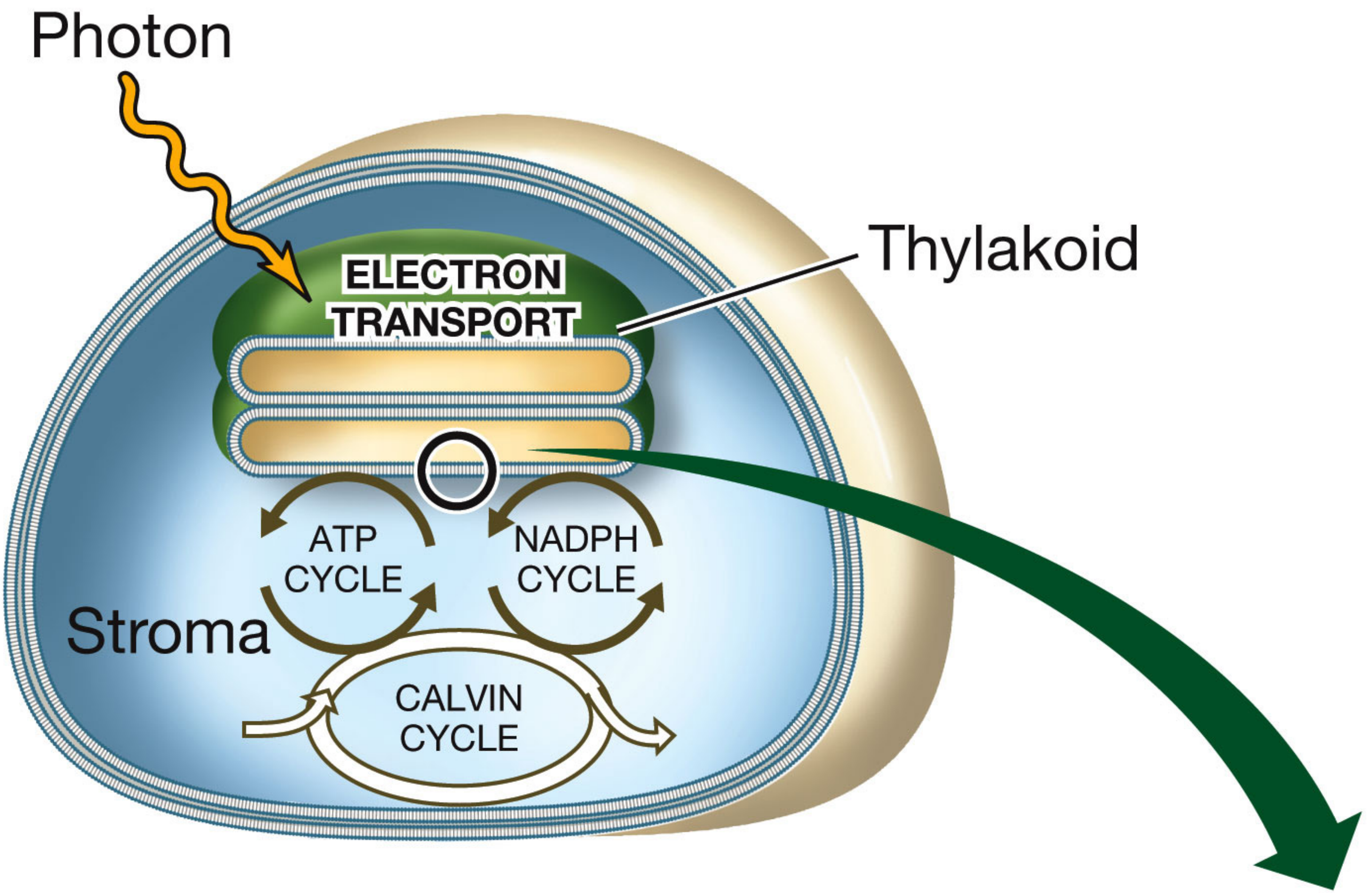


LIFE 9e, Figure 10.11

Photophosphorylation:

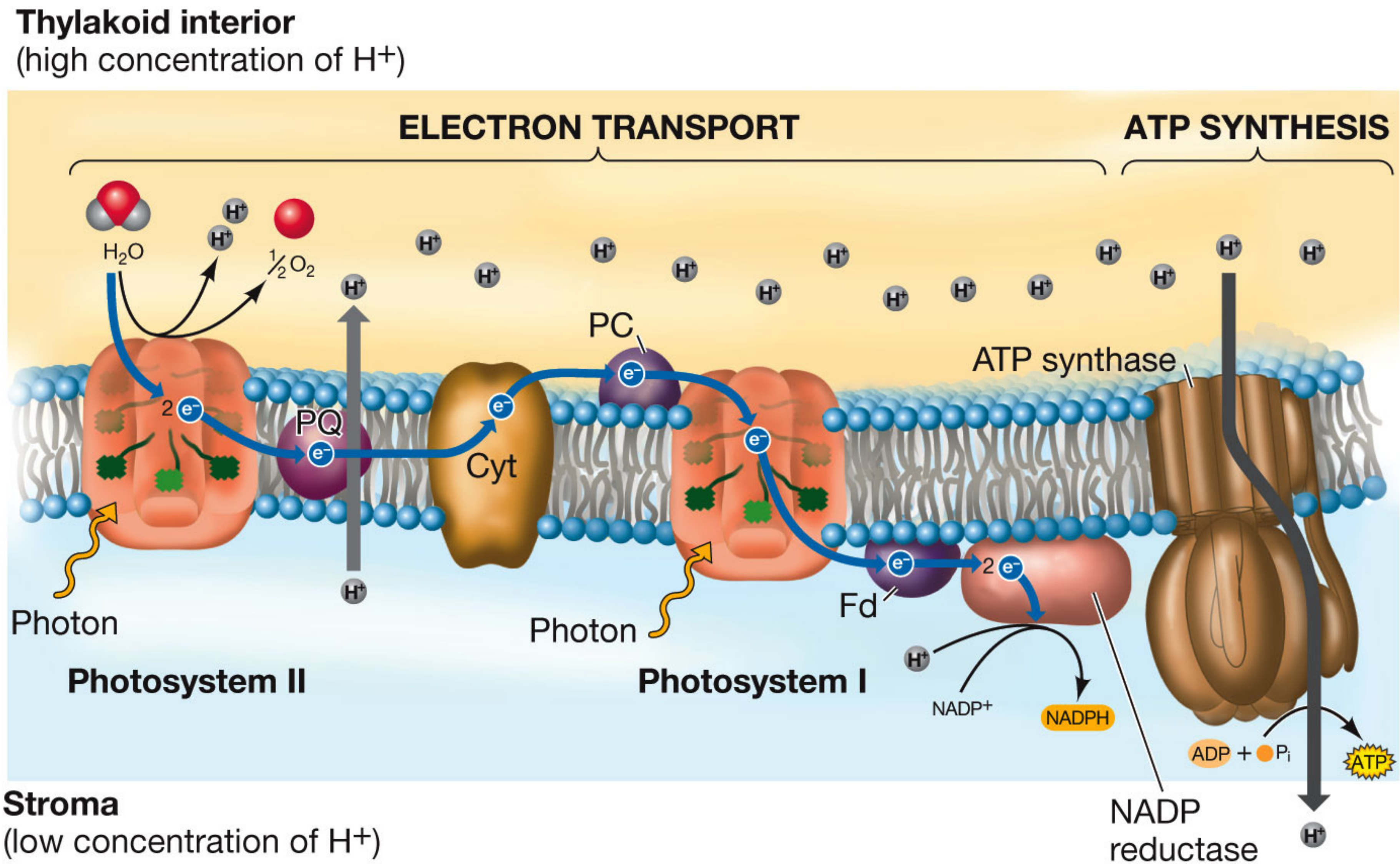
- Light-driven production of ATP—a chemiosmotic mechanism

H^+ is transported via electron carriers across the thylakoid membrane into the lumen—creating an electrochemical gradient – Proton Motive gradient



***LIFE* 9e, Figure 10.12 (Part 1)**

Figure 10.12 Chloroplasts Form ATP Chemiosmotically (Part 2)



LIFE 9e, Figure 10.12 (Part 2)

10.3 How Is Chemical Energy Used to Synthesize Carbohydrates?

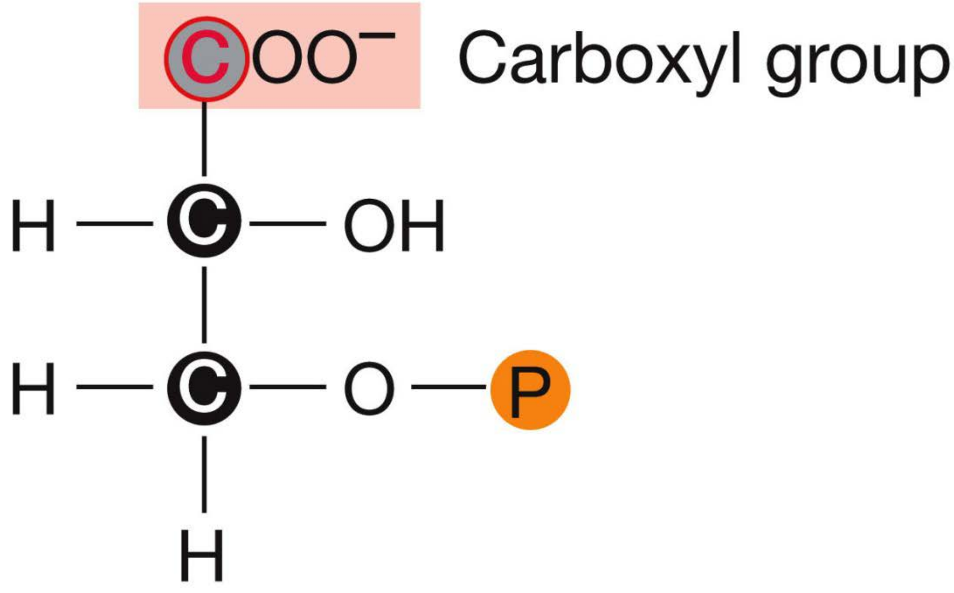
CO_2 fixation:

- CO_2 is reduced to carbohydrates.

Enzymes in the stroma use the energy in ATP and NADPH to reduce CO_2.

Production of ATP and NADPH is light-dependent; therefore CO_2 fixation must also take place in the light.

$^{14}CO_2$ fixation experiments revealed that the first compound to be formed is 3PG, a 3-carbon sugar phosphate.



3-Phosphoglycerate (3PG)

10.3 How Is Chemical Energy Used to Synthesize Carbohydrates?

The pathway of CO_2 fixation is called the **Calvin cycle**.

CO_2 is first added to an acceptor molecule—5-C RuBP (ribulose biphosphate)

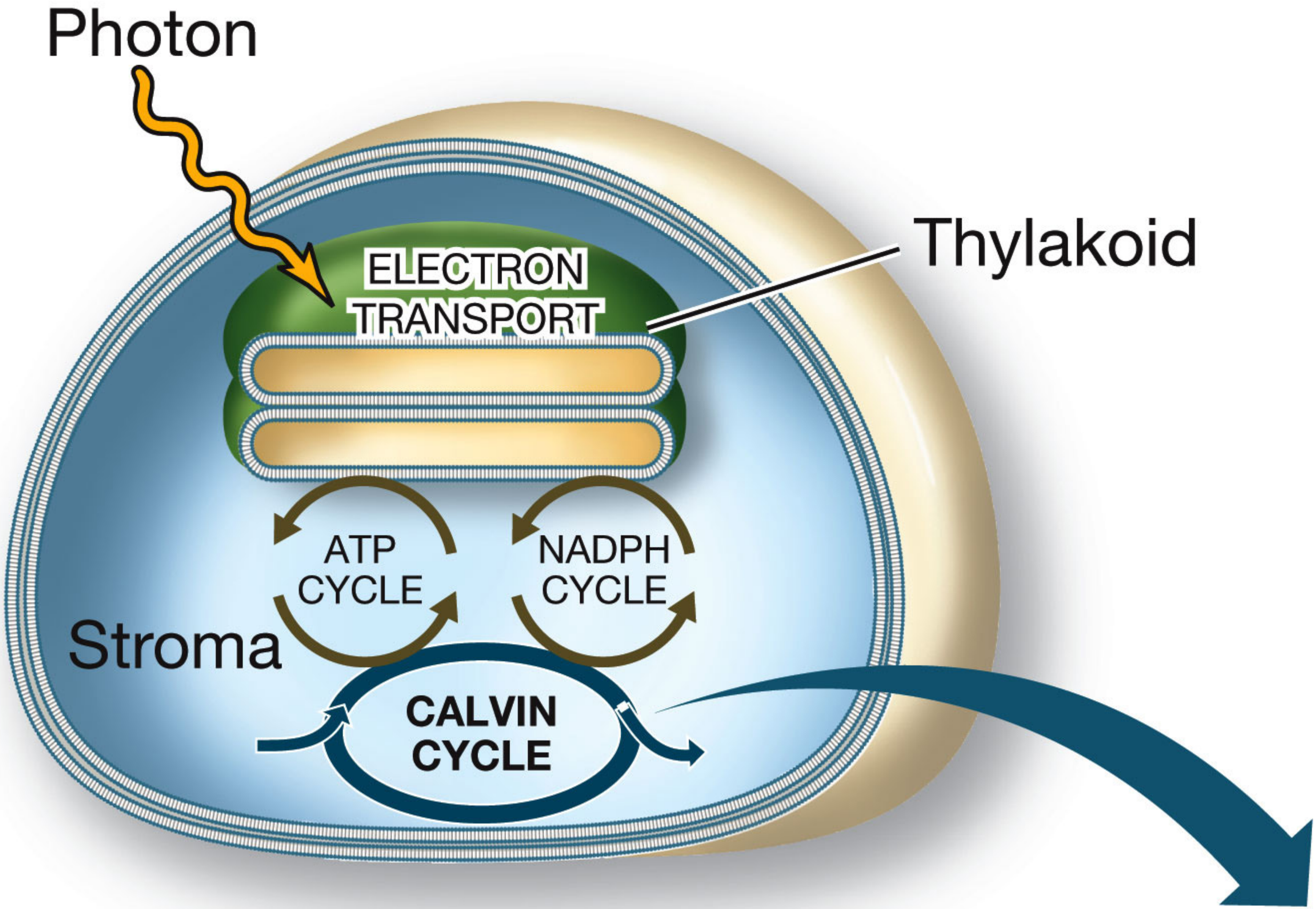
- the 6-C compound immediately breaks down into two molecules of 3PG.

The enzyme catalyzing the intermediate formation is **rubisco**—**ribulose bisphoshate carboxylase/oxygenase**—the most abundant protein in the world.

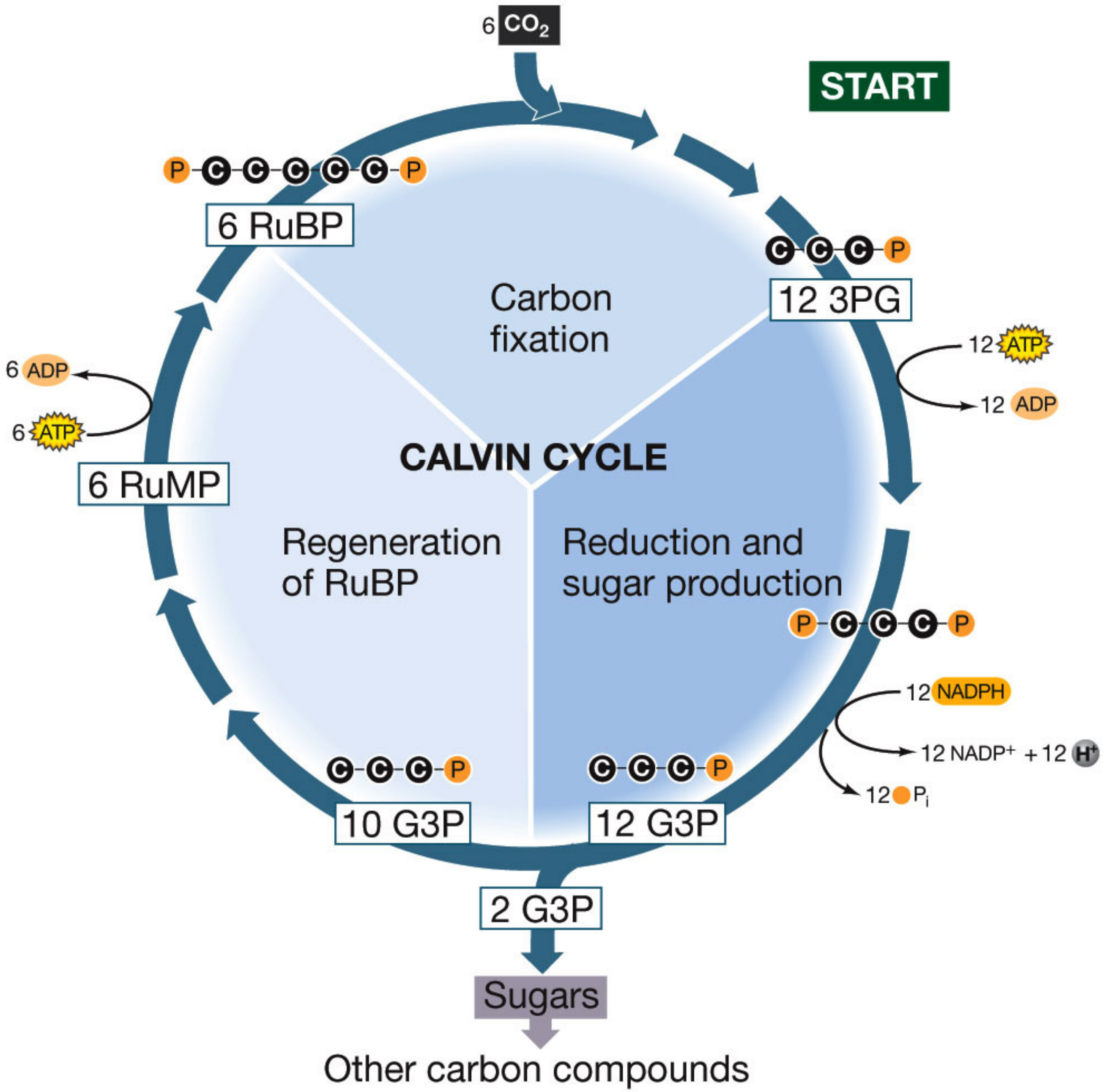
10.3 How Is Chemical Energy Used to Synthesize Carbohydrates?

The Calvin cycle consists of 3 processes:

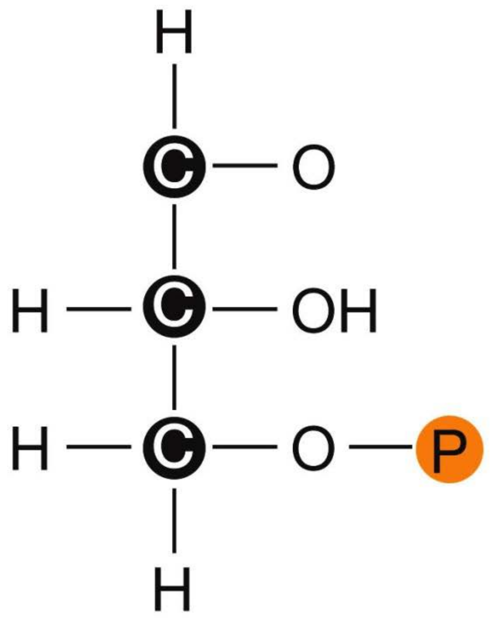
- *Fixation* of CO_2 catalyzed by rubisco
- *Reduction* of 3PG to G3P
- *Regeneration* of RuBP, the CO_2 acceptor



LIFE 9e, Figure 10.15 (Part 1)



LIFE 9e, **Figure 10.15 (Part 2)**



G3P: Glyceraldehyde 3-phosphate is the product of the Calvin cycle.

Most is recycled into RuBP; the rest is used to make sugars or stored starch.

10.3 How Is Chemical Energy Used to Synthesize Carbohydrates?

Covalent bonds in carbohydrates produced in the Calvin cycle represent the total energy yield of photosynthesis.

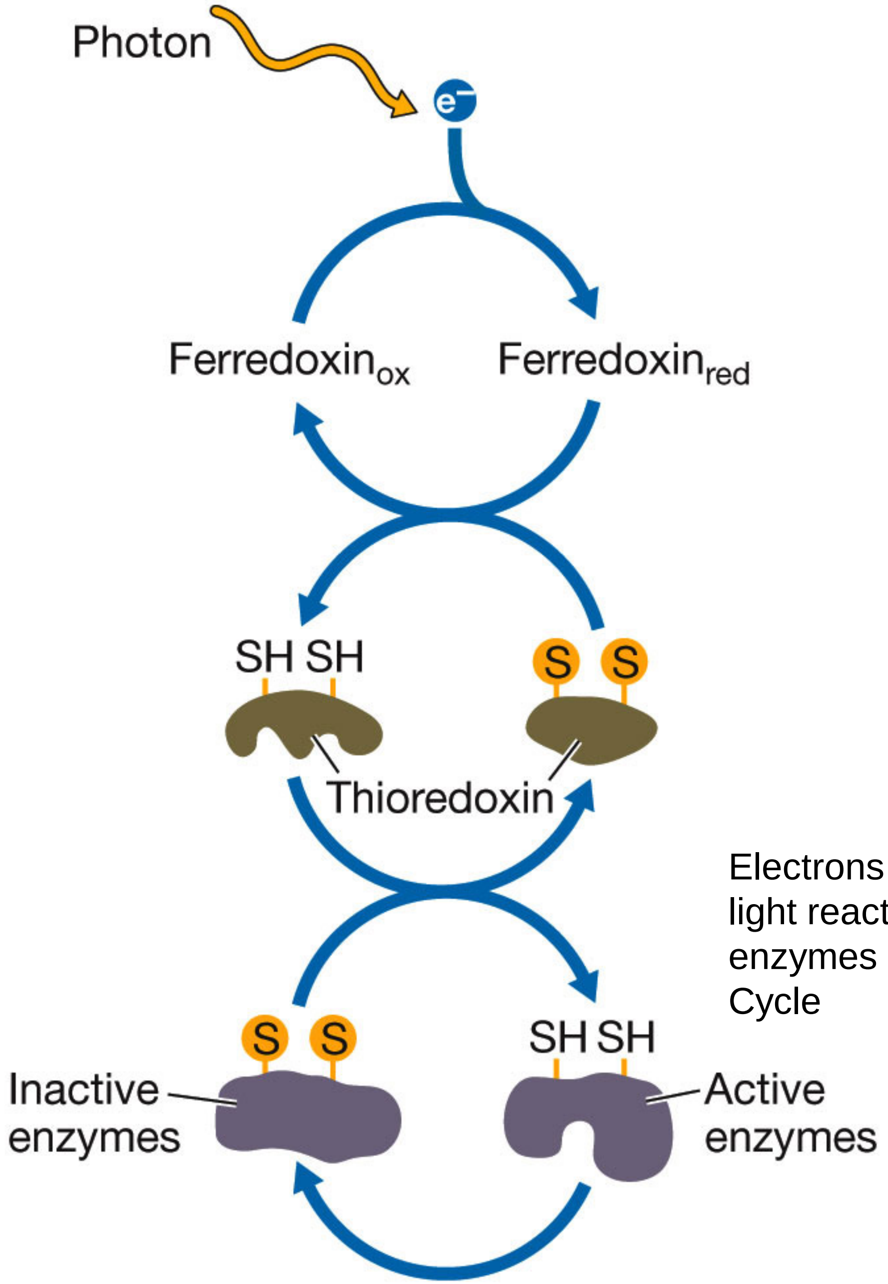
Photosynthetic **autotrophs** (“self-feeders”) can release this energy themselves.

Heterotrophs (“other-feeders”)—cannot photosynthesize and must consume plants.

10.3 How Is Chemical Energy Used to Synthesize Carbohydrates?

The Calvin cycle is stimulated by light:

- Protons pumped from stroma into thylakoids increase the pH which favors the activation of rubisco
- Electron flow from photosystem I reduces disulfide bonds to activate Calvin cycle enzymes



Electrons from the light reactions activate enzymes of the Calvin Cycle

Rubisco is an **oxygenase** as well as a **carboxylase**.

It can add O_2 to RuBP instead of CO_2; may reduce the amount of CO_2 converted to carbohydrates may limit plant growth.

Products of RuBP + O_2 is 3PG and phosphoglycolate

The phosphoglycolate forms glycolate—moves into peroxisomes—converted to glycine

Glycine diffuses into mitochondria, two glycines are converted into glycerate + CO_2

This is called Photorespiration: Consumes O_2, releases CO_2, and takes place in light.

Photorespiration is more likely at high temperatures, such as hot days when **stomata** (leaf pores) are closed.

Rubisco has ten times more affinity for CO_2.

In the leaf, if O_2 concentration is high, photorespiration occurs. If CO_2 concentration is high, CO_2 is fixed.

10.4 How Do Plants Adapt to the Inefficiencies of Photosynthesis?

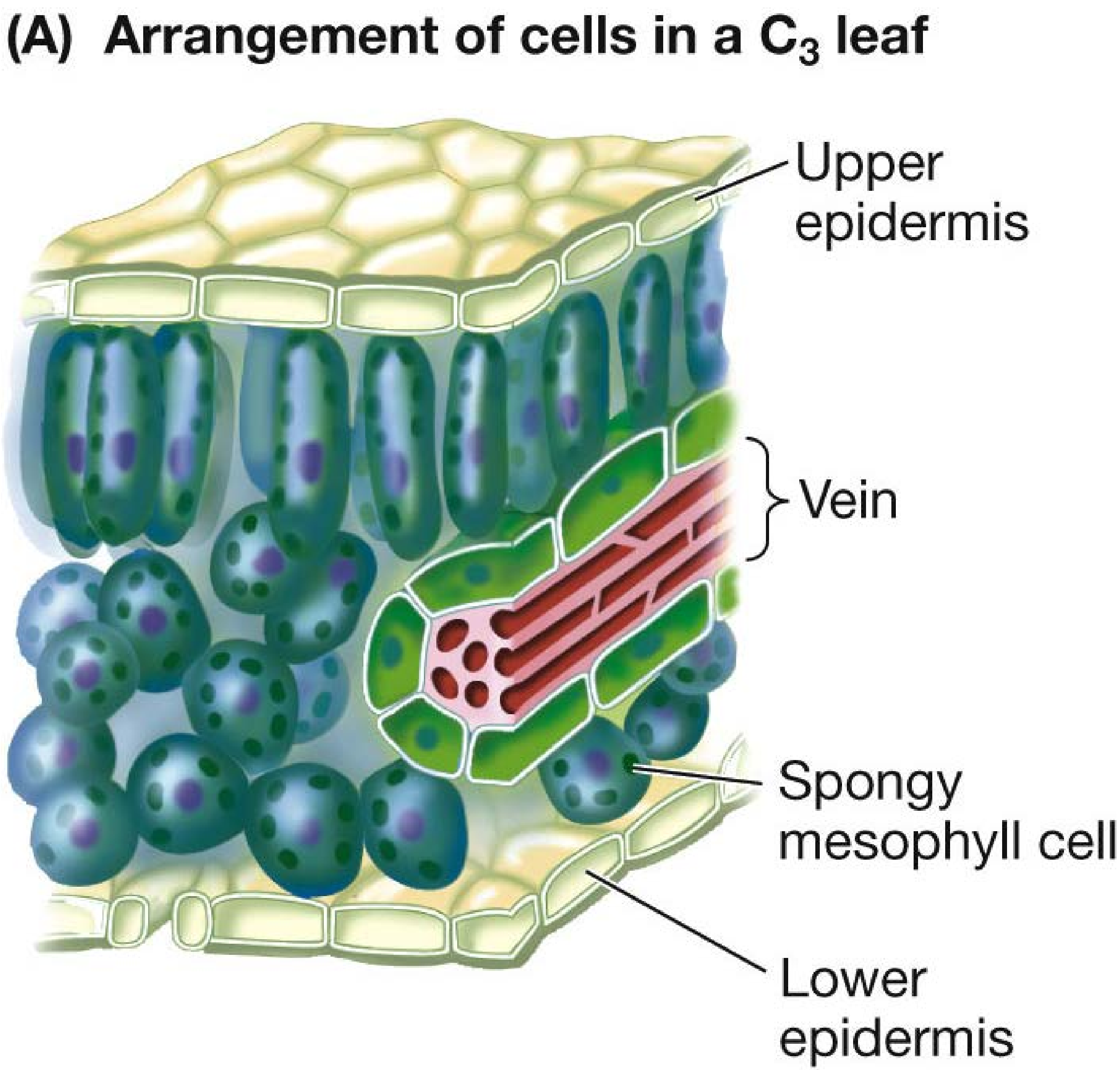
Plants differ in how they fix CO_2:

C_3 plants: First product of CO_2 fixation is the 3-C compound 3PG. Cells in the mesophyll have abundant rubisco.

- Roses, wheat, rice

On hot days, plants close stomata to conserve water but limits entry of CO_2.

Rubisco acts as an oxygenase, and photorespiration occurs.


(A) Arrangement of cells in a C3 leaf
Upper epidermis
Vein
Spongy mesophyll cell
Lower epidermis

10.4 How Do Plants Adapt to the Inefficiencies of Photosynthesis?

C_4 plants have two separate enzymes for CO_2 fixation:

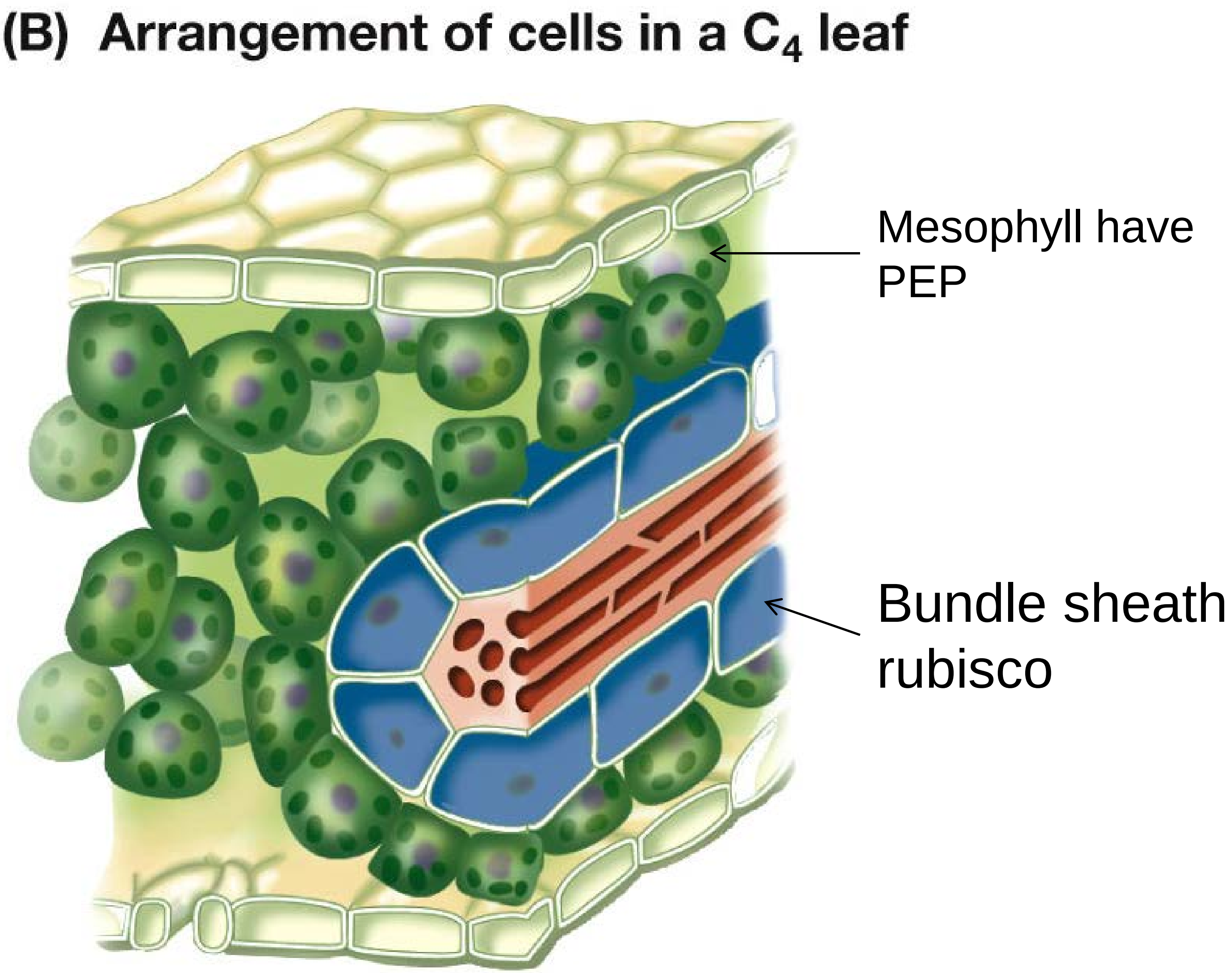
- Corn, sugarcane, tropical grasses

- Rubisco is in **bundle sheath cells**

- **PEP carboxylase** in mesophyll cells—fixes CO_2 to **PEP (phosphoenolpyruvate)** to produce **oxaloacetate**, a 4-C compound

PEP carboxylase has no affinity for O_2 and fixes CO_2 even at very low CO_2 levels. On hot days with stomata partly closed, photorespiration does not occur

Figure 10.18 Leaf Anatomy of C_3 and C_4 Plants (B)



CAM plants—**crassulacean acid metabolism**

- Similar to C_4 plants, CO_2 is initially fixed into a 4-C molecule but timing differs:
- At night: CO_2 fixed by PEP carboxylase; stomata open with less water loss. Oxaloacetate is converted to malic acid for storage.

Day: Stored malic acid goes to chloroplasts and is decarboxylated—supplies CO_2 for the Calvin cycle and light provides ATP and NADPH.

TABLE 10.1

Comparison of Photosynthesis in C_3, C_4, and CAM Plants

	C_3 PLANTS	C_4 PLANTS	CAM PLANTS
Calvin cycle used?	Yes	Yes	Yes
Primary CO_2 acceptor	RuBP	PEP	PEP
CO_2-fixing enzyme	Rubisco	PEP carboxylase	PEP carboxylase
First product of CO_2 fixation	3PG (3-carbon)	Oxaloacetate (4-carbon)	Oxaloacetate (4-carbon)
Affinity of carboxylase for CO_2	Moderate	High	High
Photosynthetic cells of leaf	Mesophyll	Mesophyll and bundle sheath	Mesophyll with large vacuoles
Photorespiration	Extensive	Minimal	Minimal

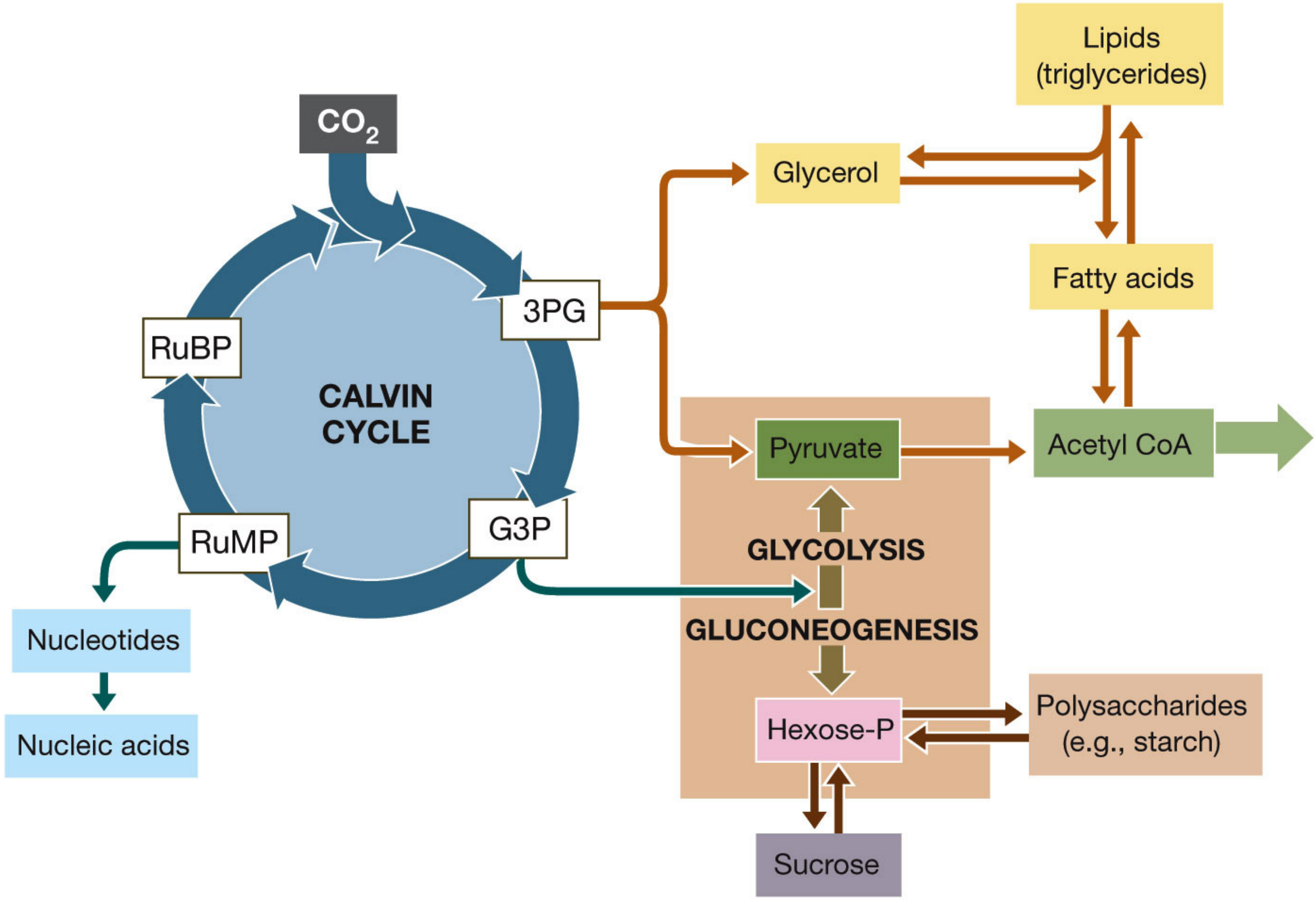
10.5 How Does Photosynthesis Interact with Other Pathways?

Photosynthesis and respiration are closely linked through the Calvin cycle.

G3P is important:

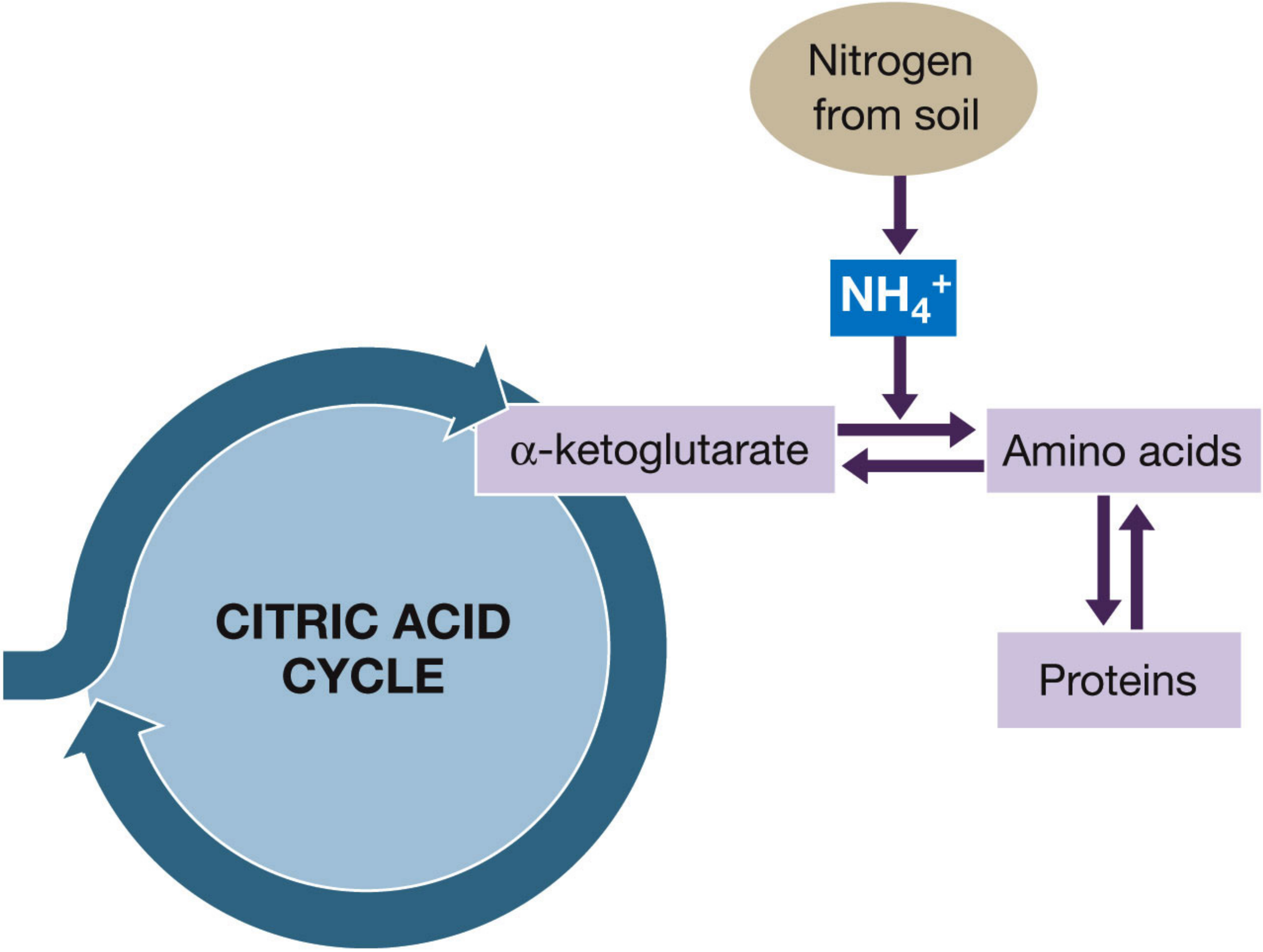
- Some takes part in glycolysis and cellular respiration for energy, or can make other compounds
- Some is involved in gluconeogenesis, the reverse of glycolysis, supplying non-photosynthetic tissues, such as roots, with sucrose

Figure 10.20 Metabolic Interactions in a Plant Cell (Part 1)



LIFE 9e, **Figure 10.20 (Part 1)**

Figure 10.20 Metabolic Interactions in a Plant Cell (Part 2)



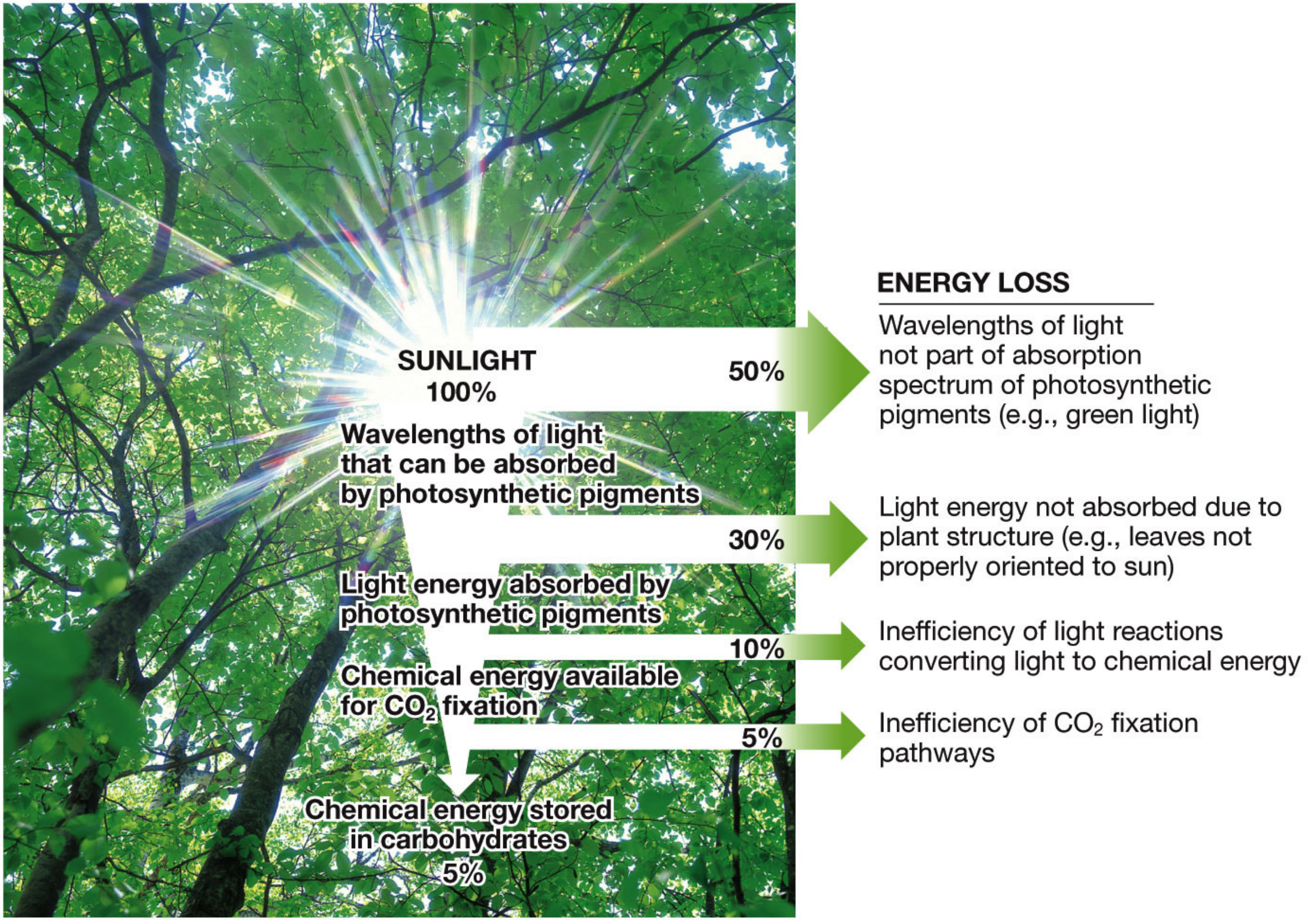
LIFE 9e, **Figure 10.20 (Part 2)**

10.5 How Does Photosynthesis Interact with Other Pathways?

Photosynthesis results in only 5 percent of total sunlight energy being transformed to the energy of chemical bonds.

Understanding the inefficiencies of photosynthesis may be important as climate change drives changes in photosynthetic activity of plants.

Figure 10.21 Energy Losses During Photosynthesis



LIFE 9e, Figure 10.21