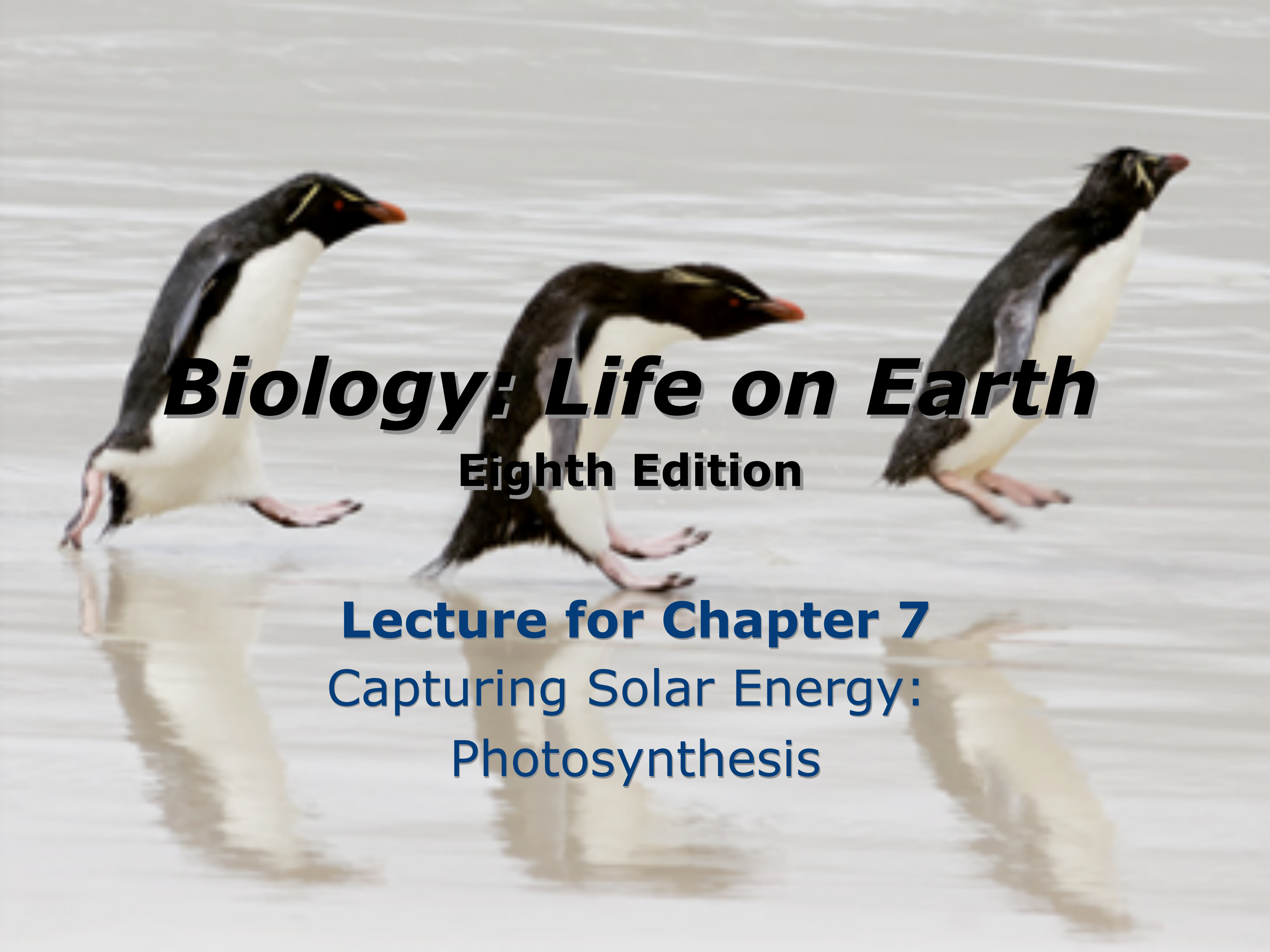


Biology: Life on Earth

Eighth Edition

Lecture for Chapter 7

Capturing Solar Energy:
Photosynthesis

Chapter 7 Outline

Section 7.1 Outline

- **7.1 What Is Photosynthesis?**
  – Leaves and Chloroplasts Are Adaptations for Photosynthesis
  – Photosynthesis Consists of Light-Dependent and Light-Independent Reactions

What Is Photosynthesis?

- Early cells evolved the ability to perform photosynthesis about 2 billion years ago
- **<u>Photosynthesis is the ability to capture sunlight energy and convert it to chemical energy</u>**
- Most forms of life on Earth depend on the chemical energy produced by photosynthetic organisms

The Photosynthetic Equation

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

carbon dioxide	water	sunlight	glucose (sugar)	oxygen

The Photosynthetic Equation

- Photosynthesis occurs in plants, algae, and some prokaryotes
- Photosynthetic organisms are **autotrophs** ("self- feeders") or **producers**.
- **Photosynthesis in plants occurs within chloroplasts**

What Is Photosynthesis?

- Photosynthesis and cellular respiration are interconnected
- Photosynthesis is the making of the food (glucose)and respiration is taking the food and getting usable energy (ATP) from it.

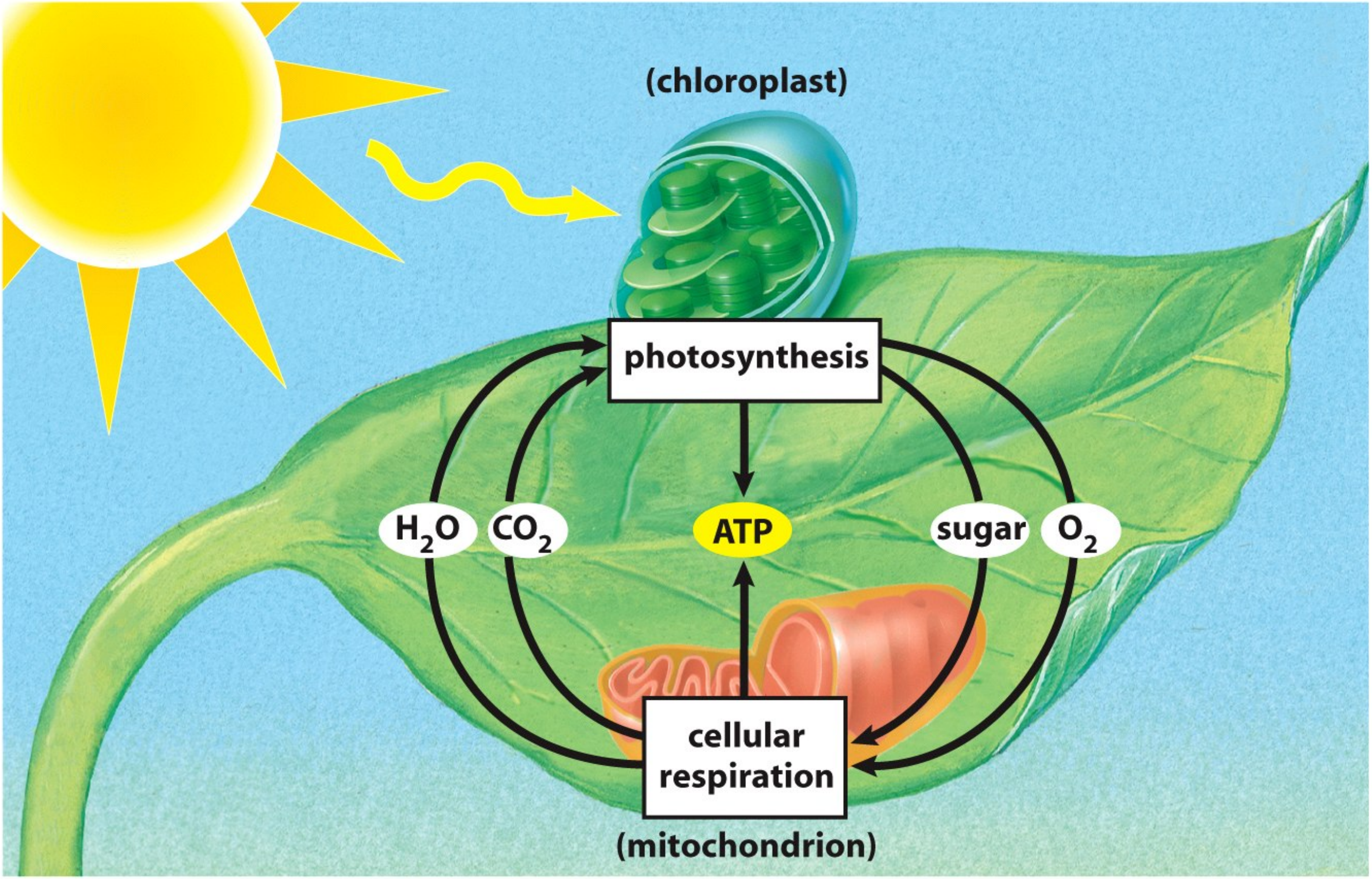


Figure 7-1 Biology: Life on Earth, 8/e

Leaves

- Leaves are adaptations used to perfrom photosynthesis.
- Flattened leaf shape exposes large surface area to catch sunlight
- Upper and lower leaf surfaces of a leaf comprise the **epidermis**
- Waxy, waterproof **cuticle** on outer surfaces reduces water evaporation

Leaf Anatomy

- Adjustable pores called **stomata** allow for entry of air with CO_2
- Inner **mesophyll** cell layers contain majority of chloroplasts
- **Vascular bundles** (veins) supply water and minerals to the leaf while carrying sugars away from the leaf
- Internal leaf structure is crucial to photosynthesis since photosynthesis occurs primarily in the leaves of land plans

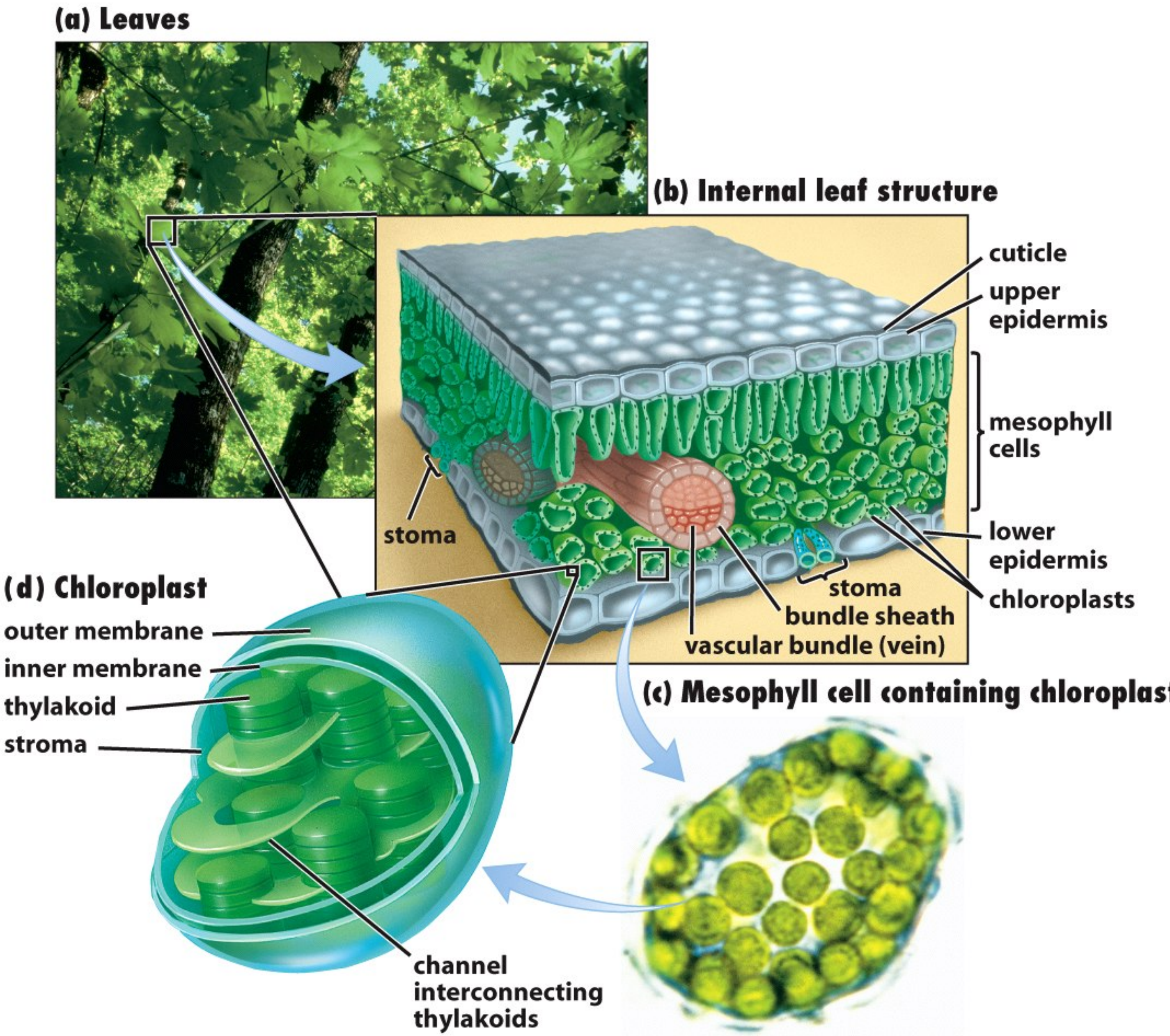


Figure 7-2 Biology: Life on Earth, 8/e

Leaves

Figure 7-2a Biology: Life on Earth, 8/e

Internal leaf structure

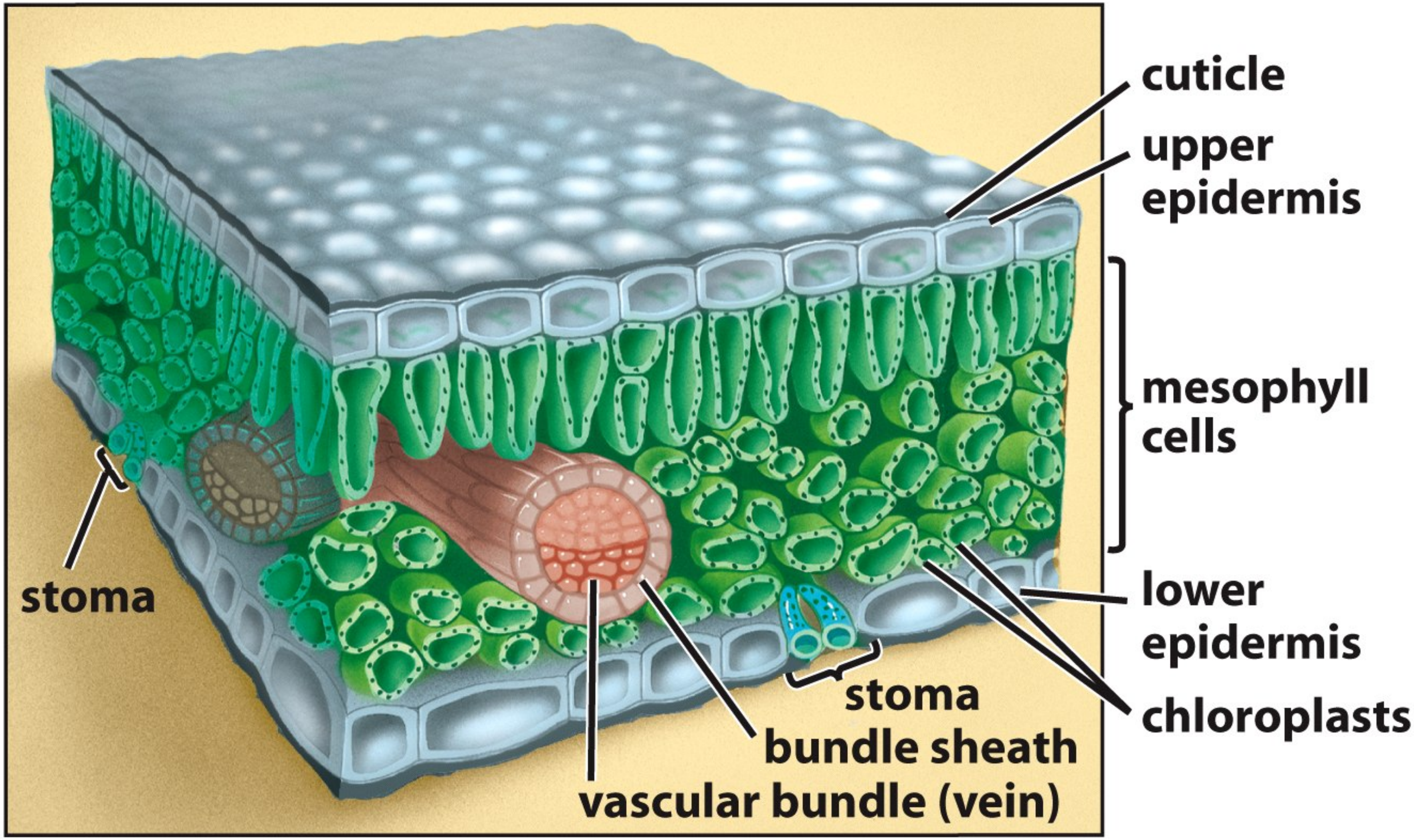


Figure 7-2b Biology: Life on Earth, 8/e

Mesophyll cell containing chloroplasts

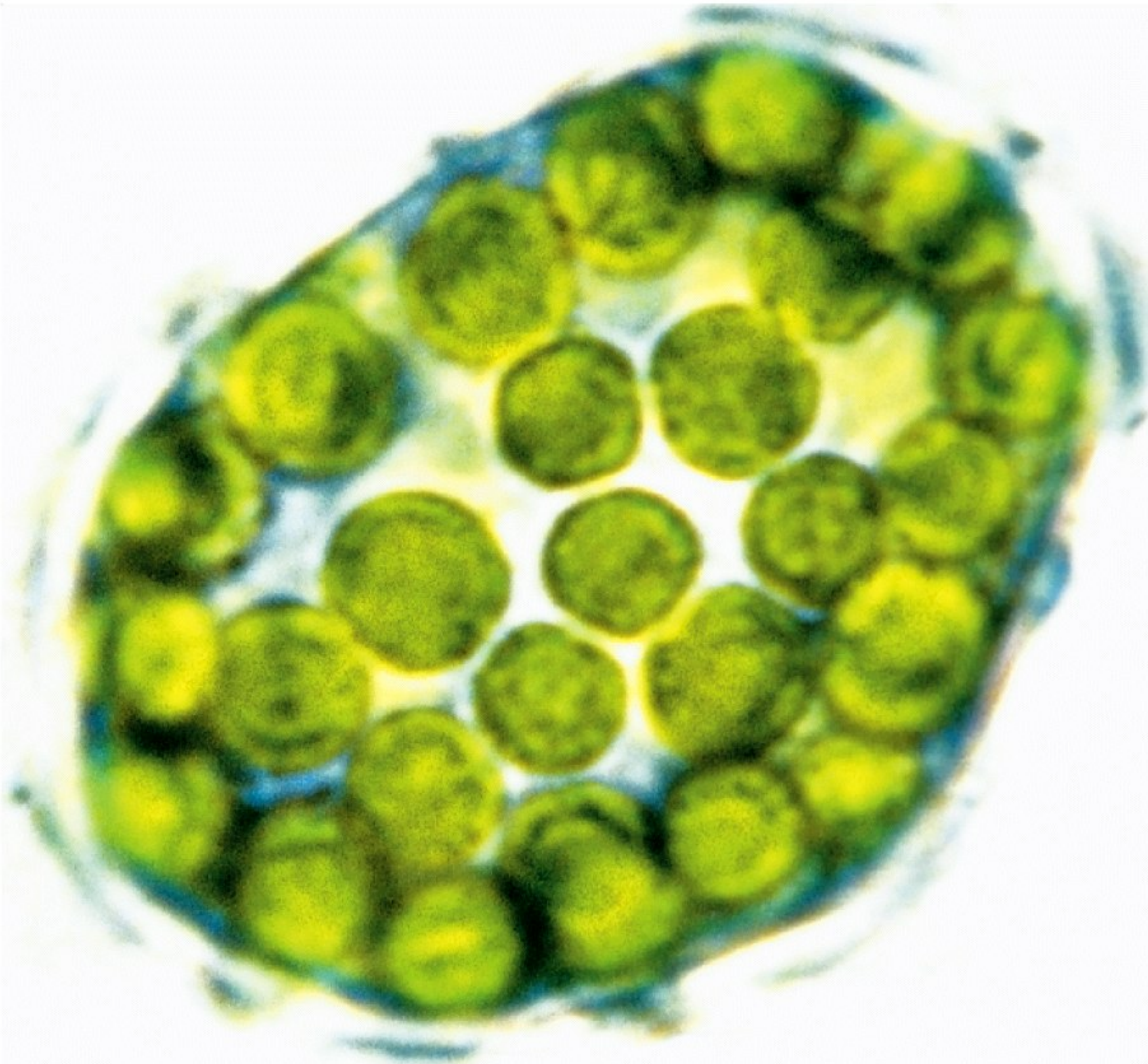


Figure 7-2c Biology: Life on Earth, 8/e

Figure 7-3 Biology: Life on Earth, 8/e

Anatomy of a Chloroplast

- Chloroplasts are adaptations that allow for photosynthesis to occur.
- Mesophyll cells have 40-200 chloroplasts each
- Chloroplasts are bounded by a double membrane composed of the **inner** and **outer membranes**
- The **stroma** is the semi-fluid medium within the inner membrane
- Disk-shaped sacs called **thylakoids** found within the stroma in stacks called **grana**

Chloroplast

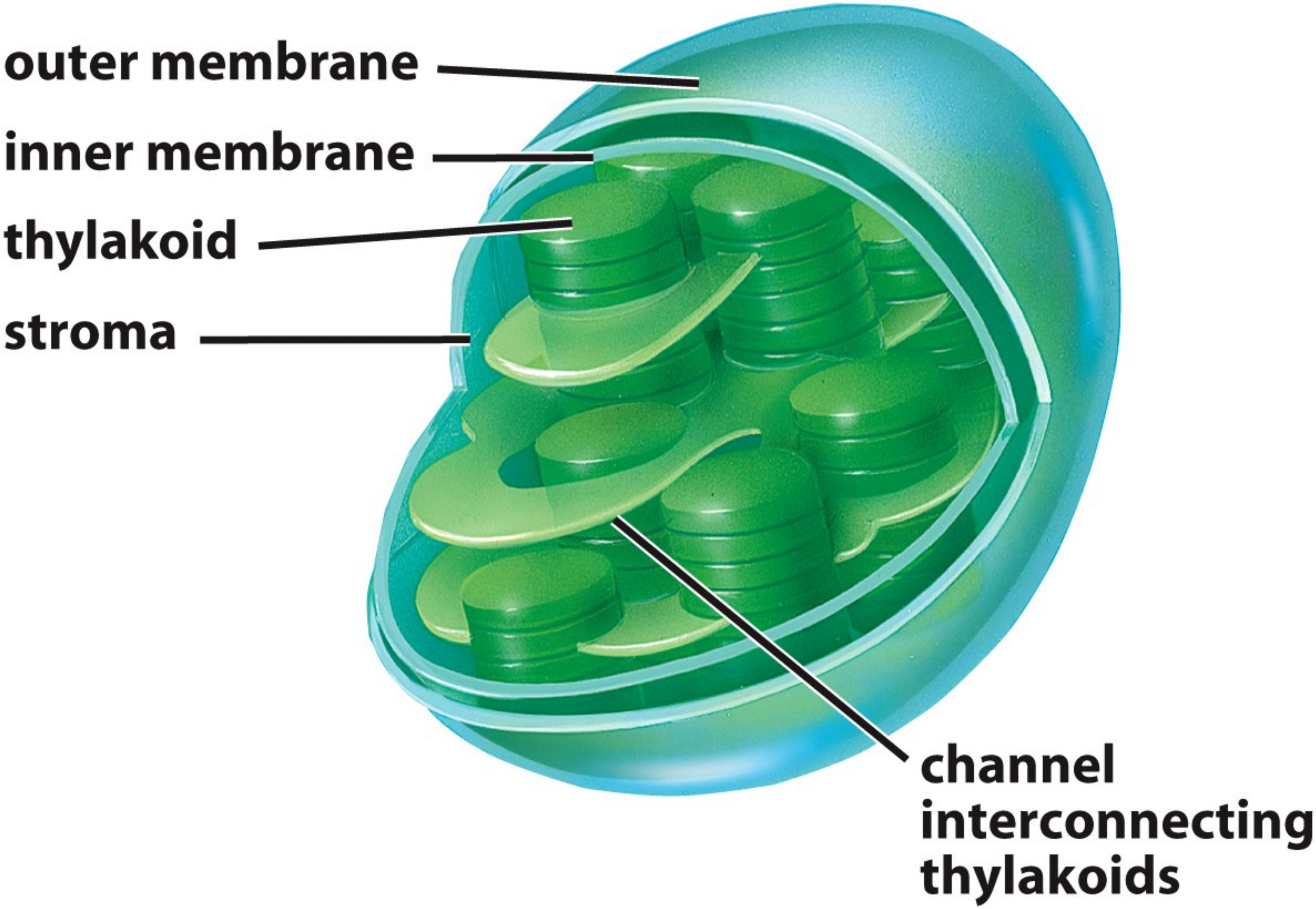


Figure 7-2d Biology: Life on Earth, 8/e

Location of Photosynthetic Reactions

- The two chemical reactions of photosynthesis are localized:
  1. The conversion of sunlight energy to chemical energy (*light-dependent reactions*) occurs on the thylakoid membranes
  2. The synthesis of glucose and other molecules (*light-independent reactions*) occurs in the surrounding stroma

Two Groups of Reactions

1. **Light-dependent** reactions
   - Chlorophyll and other molecules of the thylakoids capture sunlight energy
   - Sunlight energy is converted to the energy carrier molecules ATP and NADPH
   - Oxygen gas is released as a by-product

Two Groups of Reactions

2. **Light-independent** reactions
   - Enzymes in the stroma synthesize glucose and other organic molecules using the chemical energy stored in ATP and NADPH

Two Groups of Reactions

- Light-dependent and light-independent reactions are related

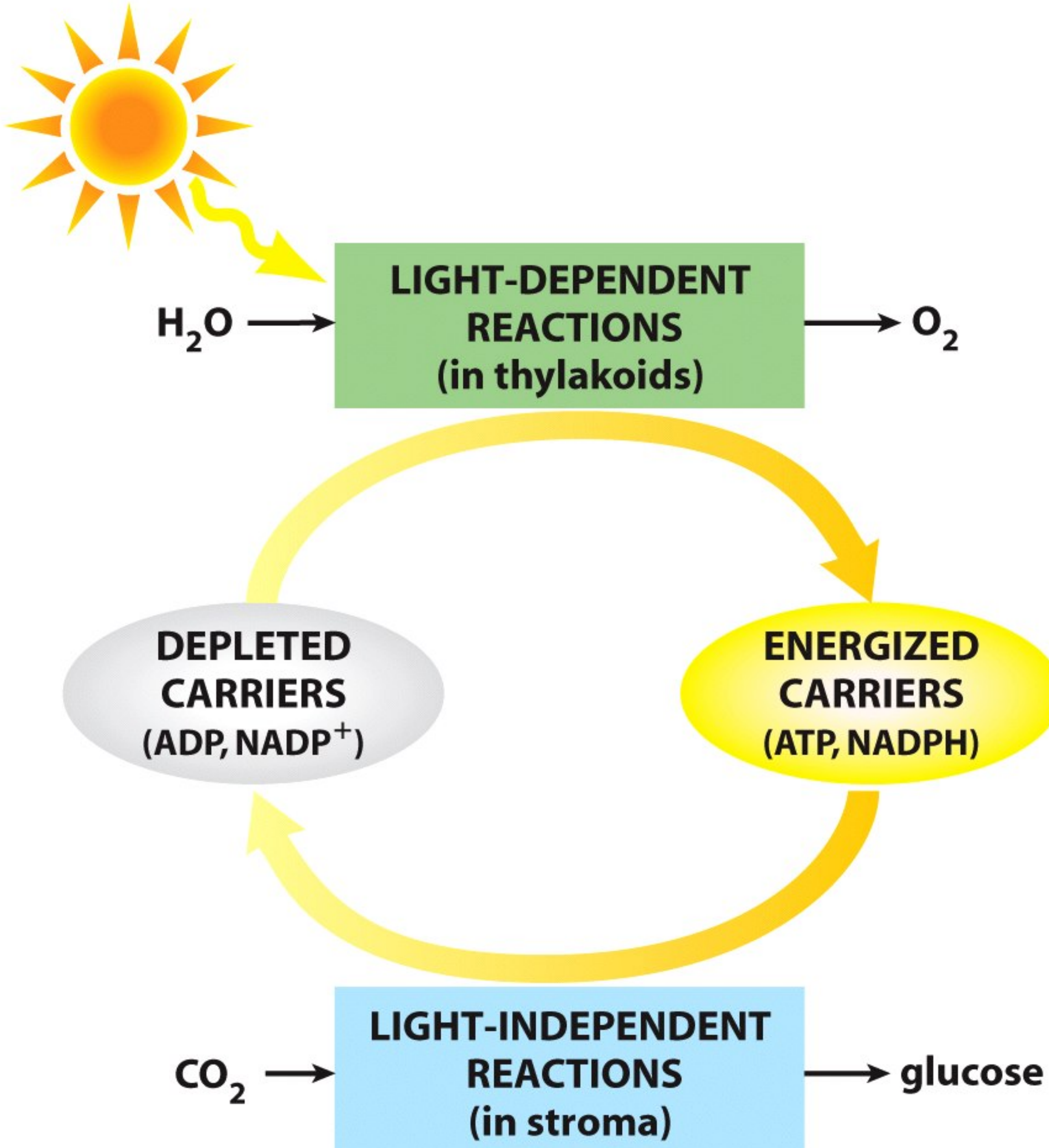


Figure 7-4 Biology: Life on Earth, 8/e

Section 7.2 Outline

- **7.2 Light-Dependent Reactions: How Is Light Energy Converted to Chemical Energy?**
  - During Photosynthesis, Light Is First Captured by Pigments in Chloroplasts
  - The Light-Dependent Reactions Occur in Association with Thylakoid Membranes
    - Photosystem II Generates ATP
    - Photosystem I Generates NADPH
    - Splitting Water Maintains the Flow of Electrons Through the Photosystems

Light Dependent Reactions

- Captured sunlight energy is stored as chemical energy in two carrier molecules
  - Adenosine triphosphate (ATP)
  - Nicotinamide adenine dinucleotide phosphate (NADPH)

Light Captured by Pigments

- Action of light-capturing pigments
  - **Absorption** of certain wavelengths (light is “trapped”)
  - **Reflection** of certain wavelengths (light bounces back)
  - **Transmission** of certain wavelengths (light passes through)

Light Captured by Pigments

- Absorbed light drives biological processes when it is converted to chemical energy
- Common pigments found in chloroplasts include:
  - **Chlorophyll a and b**
  - Accessory pigments such as **carotenoids**

Light Captured by Pigments

- **Chlorophyll a and b** absorb violet, blue, and red light but reflect green light (hence they appear green)
- **Carotenoids** absorb blue and green light but reflect yellow, orange, or red (hence they appear yellow-orange)
- Pigment absorbs visible light

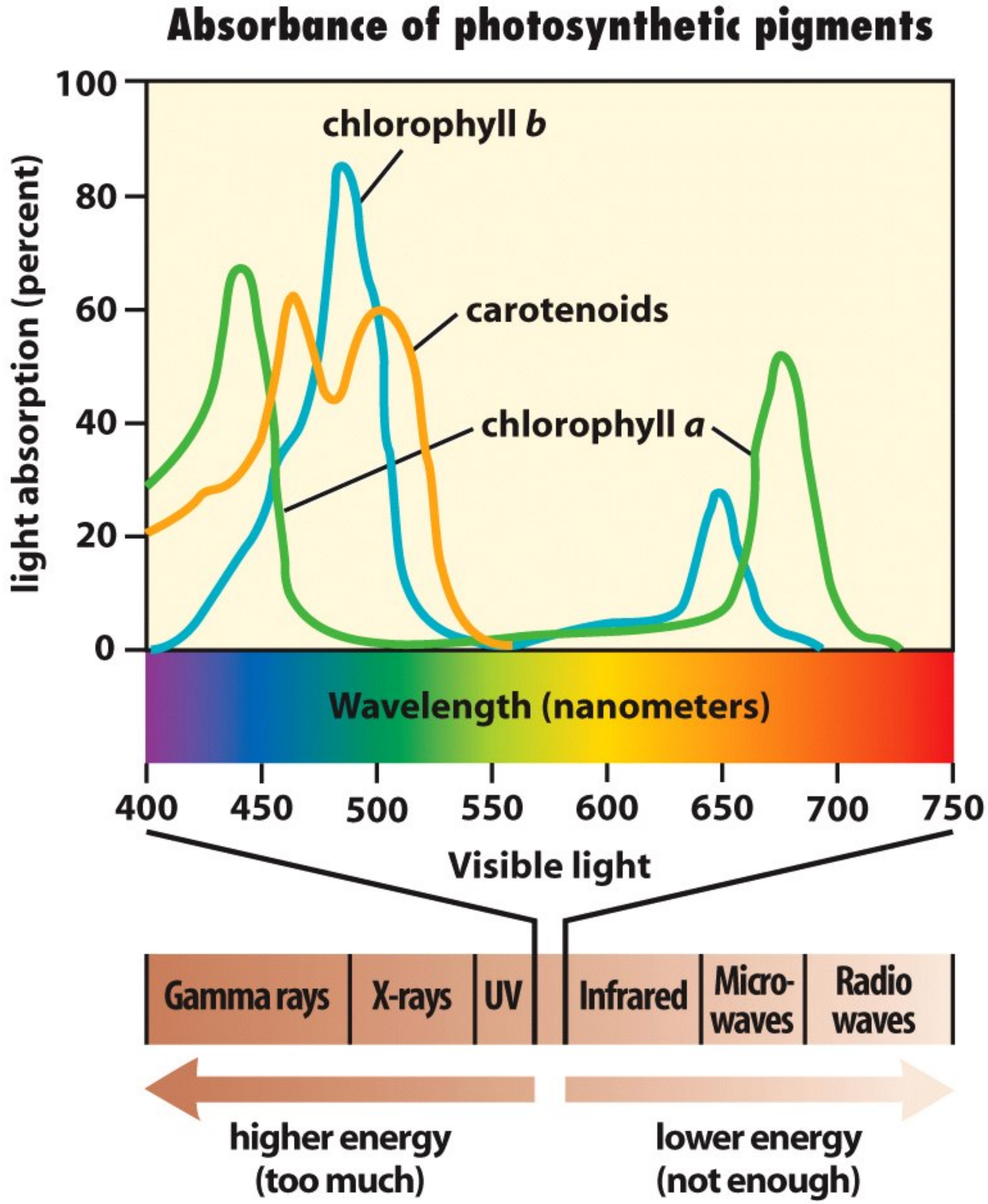


Figure 7-5 Biology: Life on Earth, 8/e

Why Autumn Leaves Turn Color

- Both chlorophylls and carotenoids are present in leaves
  - Chlorophyll breaks down before carotenoids in dying autumn leaves revealing yellow colors
  - Red fall colors (anthocyanin pigments) are synthesized by some autumn leaves, producing red colors

Figure 7-6 Biology: Life on Earth, 8/e

Light-Dependent Reactions

- Photosystems within thylakoids ***Figure 7-8 8e***:
  - Photosystems are assemblies of proteins, chlorophyll, & accessory pigments
  - Two Photosystems (PSI and PSII) in thylakoids
  - Each Photosystem is associated with a chain of electron carriers

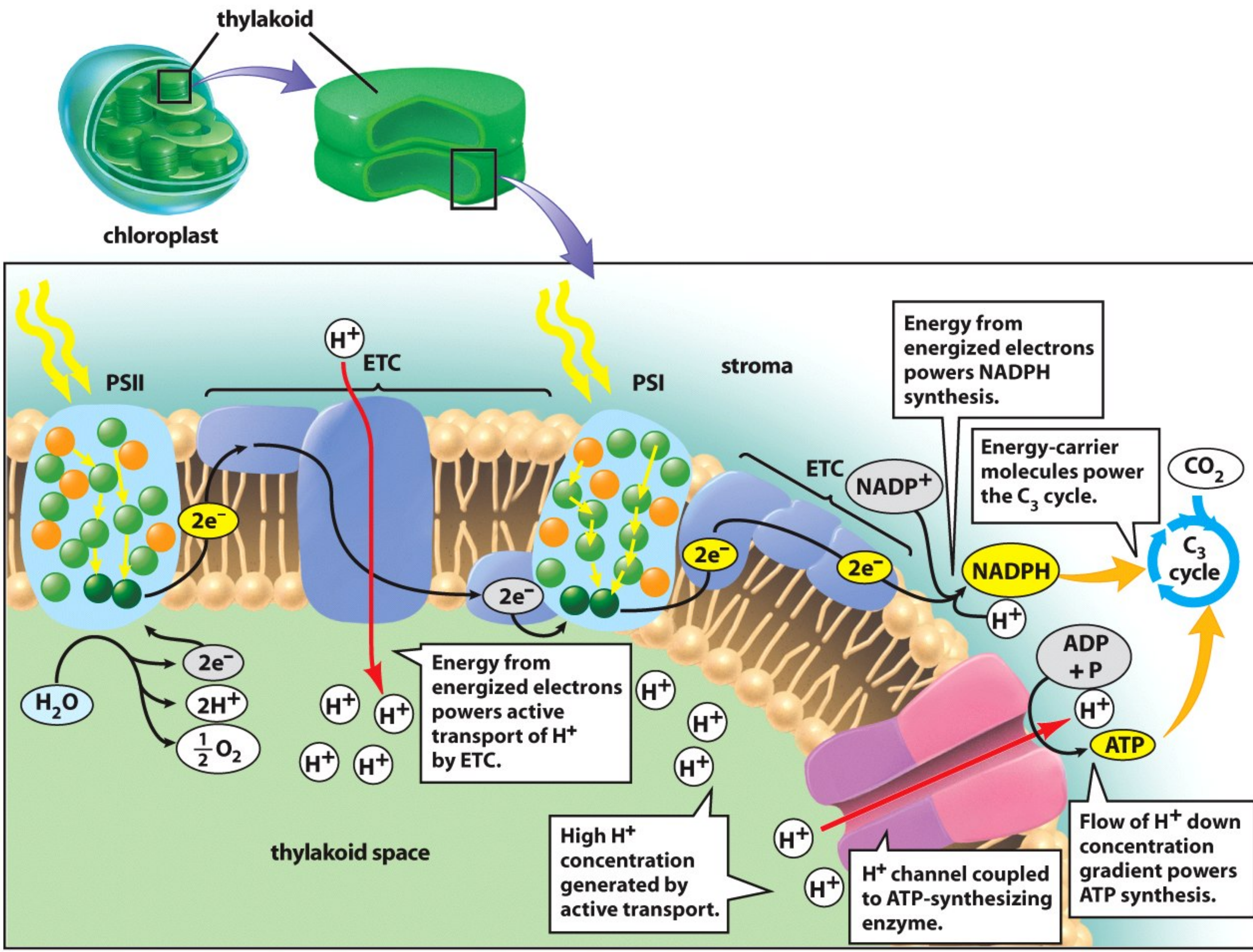


Figure 7-8 Biology: Life on Earth, 8/e

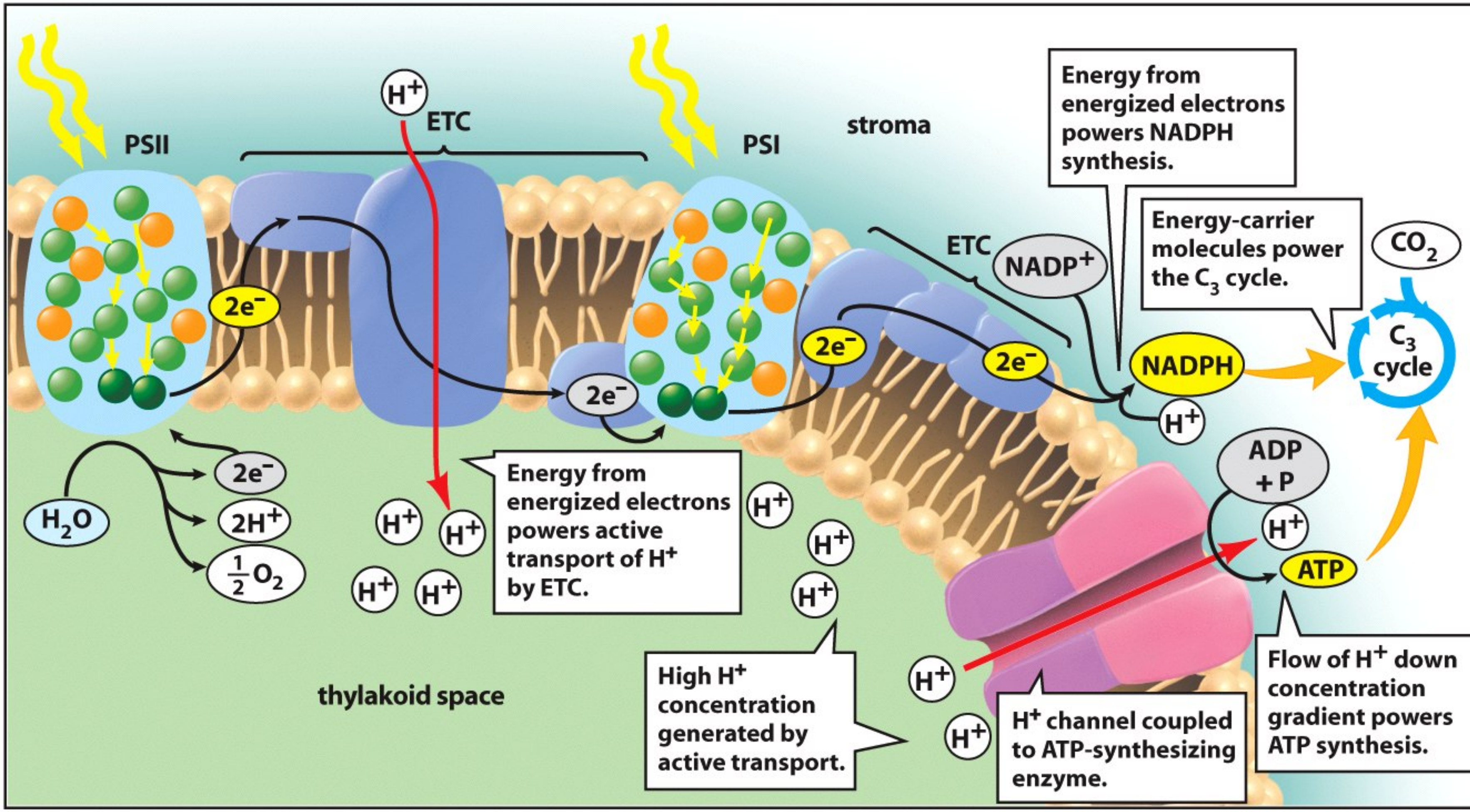


Figure 7-8 part 2 Biology: Life on Earth, 8/e

Light-Dependent Reactions

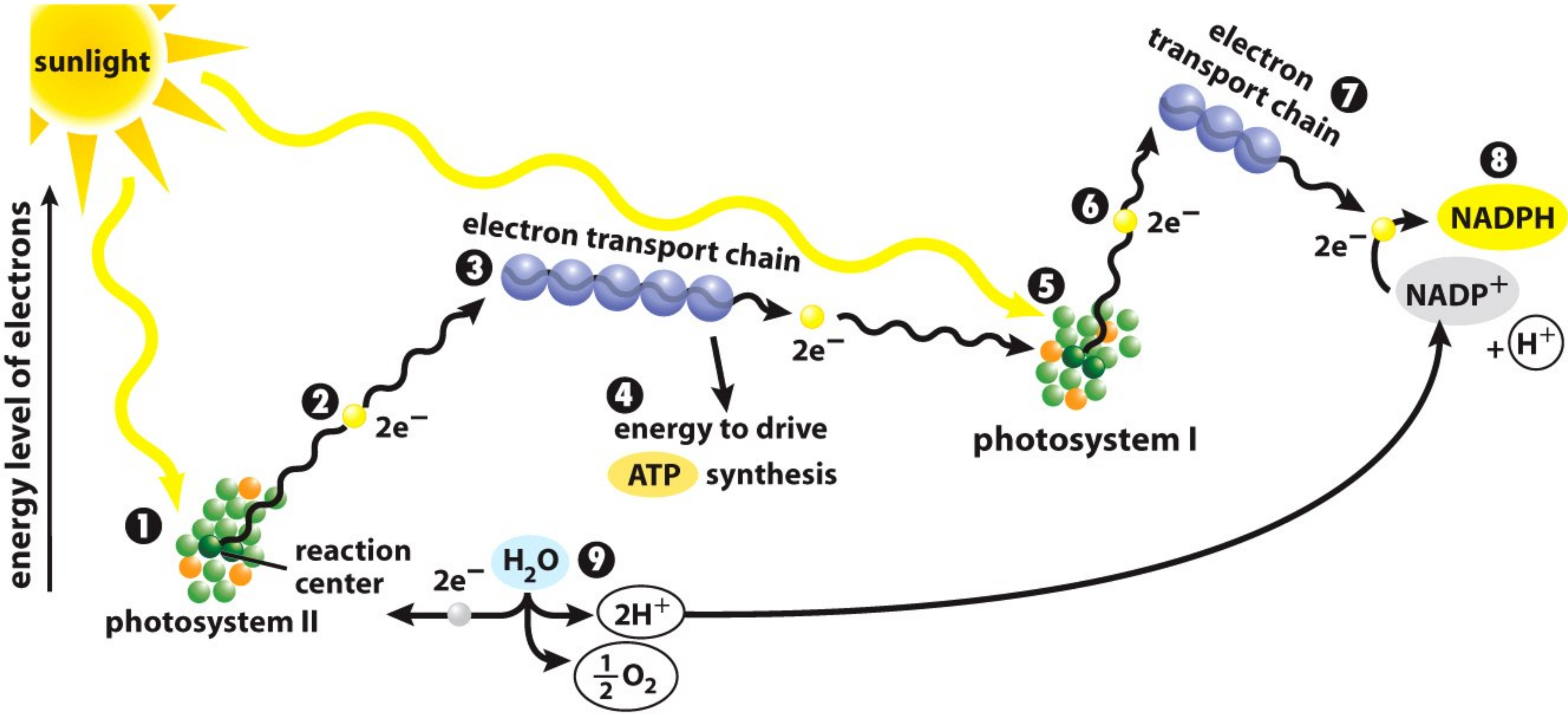
Steps of the light reactions:

1. Accessory pigments in Photosystems absorb light and pass energy to **reaction centers** containing chlorophyll
2. Reaction centers receive energized electrons…
3. Energized electrons then passed down a series of electron carrier molecules (**Electron Transport Chain**)

Light-Dependent Reactions

4. Energy released from passed electrons used to synthesize **ATP** from ADP and phosphate
5. Energized electrons also used to make **NADPH** from NADP+ + H+

Light-dependent reactions resemble a pinball game


sunlight
energy level of electrons
1
photosystem II
reaction center
2
2e⁻
3
electron transport chain
2e⁻
4
energy to drive
ATP synthesis
5
photosystem I
6
2e⁻
electron transport chain
7
8
NADPH
2e⁻
NADP+
+ H+
2e⁻
H_2O
9
2H+
$\frac{1}{2}O_2$

Photosystem II Generates ATP

- Photosystem II positioned before PS I in thylakoids
- There are four steps in ATP generation by PSII…

Photosystem II Generates ATP

Steps of ATP generation by PSII:

1. Two photons absorbed by Photosystem II
   - Light energy passed between pigment molecules
2. At reaction center, two electrons boosted out of two chlorophyll molecules when energy arrives…

Photosystem II Generates ATP

3. First electron carrier accepts two energized electrons
   – Electrons then passed between carrier molecules
   – Energy released from electrons used to pump H+ into thylakoid compartment from stroma
4. H+ ion concentration gradient used to drive ATP synthesis (chemiosmosis)

Photosystem I Generates NADPH

5. Photons of light absorbed by Photosystem I
    - Energy passed to reaction center chlorophyll
6. Two high energy electrons boosted and ejected from reaction center
7. Electrons passed down electron transport chain for PS I…

Photosystem I Generates NADPH

8. Two electrons, $NADP^+$, and H^+ ion used to form 1 NADPH molecule
9. H^+ ion obtained from the splitting of H_2O into 2 H^+ and $\frac{1}{2}O_2$

Electrons from PSII flow one-way into PS I

Maintaining Electron Flow

- Electrons leaving PS II replaced when H_2O is split:
  - $H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$
  - Two electrons from water replace those lost when 2 photons boost 2 electrons out of PSII
  - Two hydrogen ions used to form NADPH
  - Oxygen atoms combine to form O_2

Oxygen

- May be used by plant or released into atmosphere

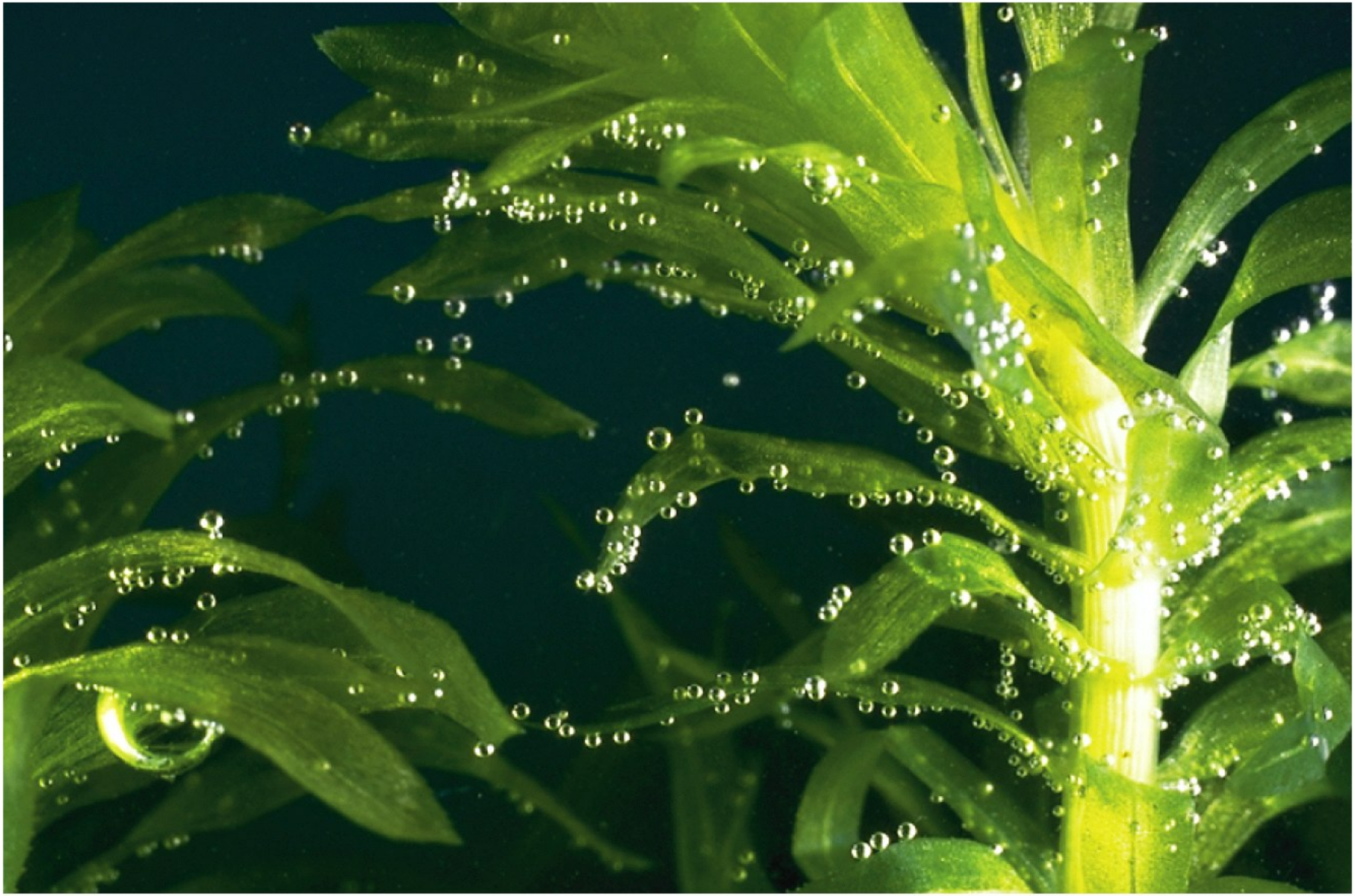


Figure 7-9 Biology: Life on Earth, 8/e

Section 7.3 Outline

- **7.3 Light-Independent Reactions: How Is Chemical Energy Stored in Glucose Molecules?**
  - The C_3 Cycle Captures Carbon Dioxide
  - Carbon Fixed During the C_3 Cycle Is Used to Synthesize Glucose

Light-*In*dependent Reactions

- NADPH and ATP from light-dependent reactions used to power glucose synthesis
- Light not *directly* necessary for light-independent reactions if ATP & NADPH available
- Light-independent reactions called the **Calvin-Benson Cycle** or **C_3 Cycle**

The C_3 Cycle

- 6 CO_2 used to synthesize 1 glucose ($C_6H_{12}O_6$)
- Carbon dioxide is captured and linked to ribulose bisphosphate (RuBP)
- ATP and NADPH from light dependent reactions used to power C_3 reactions

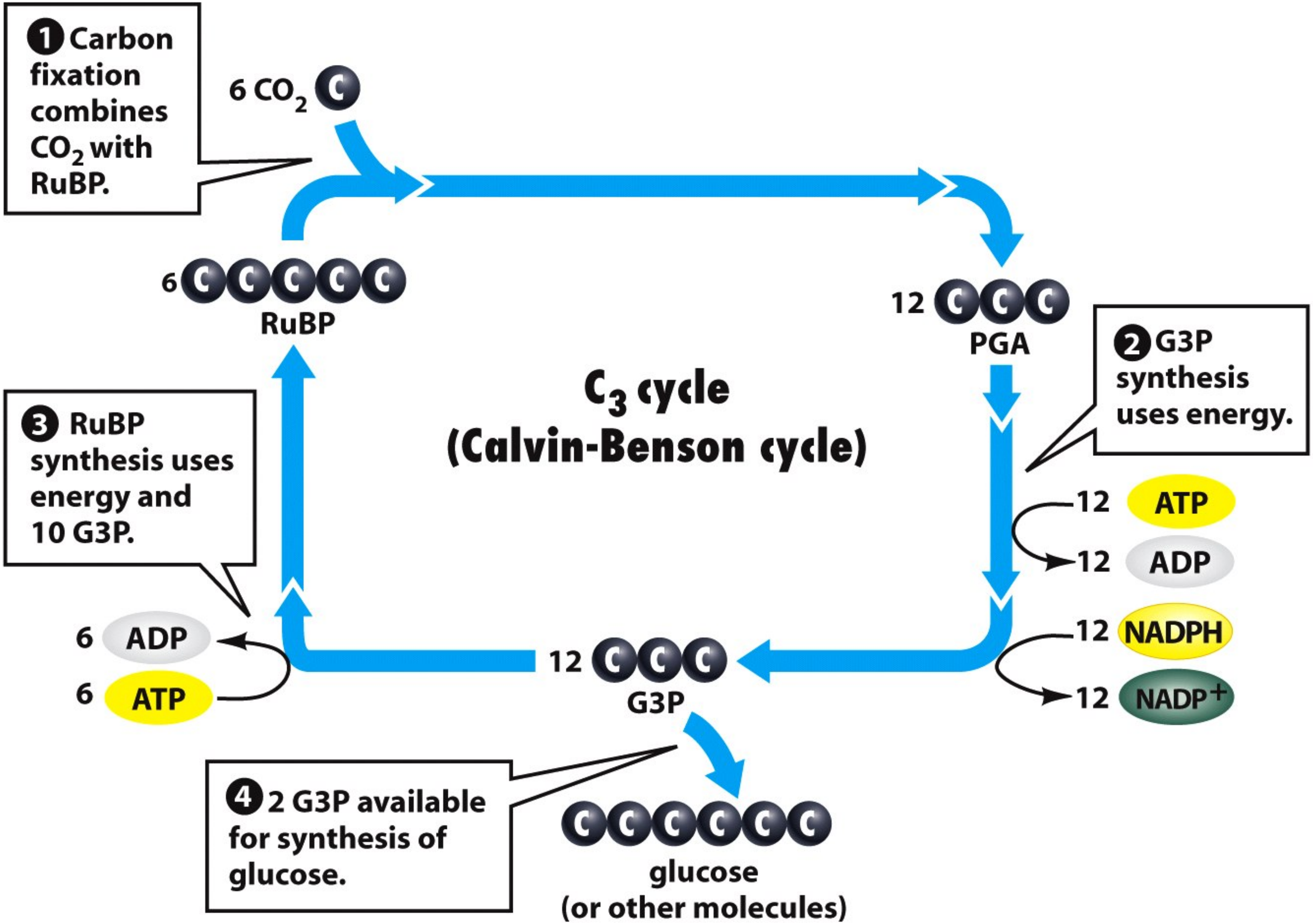


Figure 7-10 Biology: Life on Earth, 8/e

C_3 Cycle Has Three Parts

1. Carbon fixation (carbon capture)
   - 6 Ribulose bisphosphate (RuBP) molecules combine with $6CO_2$
   - Fixation step and subsequent reactions yield twelve 3-carbon phosphoglyceric acid (PGA) molecules…

C_3 Cycle Has Three Parts

2. Synthesis of Glyceraldehyde 3-Phosphate (G3P)
   - Energy is donated by ATP and NADPH
   - Phosphoglyceric acid (PGA) molecules are converted into glyceraldehyde 3-Phophate (G3P) molecules …

C_3 Cycle Has Three Parts

3. Regeneration of Ribulose bis-phosphate (RuBP)
   - 10 of 12 G3P molecules converted into 6 RuBP molecules
   - 2 of 12 G3P molecules used to synthesize 1 glucose
   - ATP energy used for these reactions

Glucose Synthesis

- One cycle of the C3 Cycle produce two "left over" G3P molecules
- Two G3P molecules (3 carbons each) used to form 1 glucose (6 carbons)
- Glucose may later be broken down during cellular respiration or stored in chains as starch or cellulose

Section 7.4 Outline

- **7.4 What Is the Relationship Between Light-Dependent and Light-Independent Reactions?**

Relationship Between Reactions

- The "photo" part of photosynthesis refers to the capture of light energy (light dependent reactions)
- The "synthesis" part of photosynthesis refers to glucose synthesis (light-*in*dependent reactions)

Relationship Between Reactions

- Light dependent reactions produce ATP and NADPH which is used to drive light-independent reactions
- Depleted carriers (ADP and $NADP^+$) return to light-dependent reactions for recharging

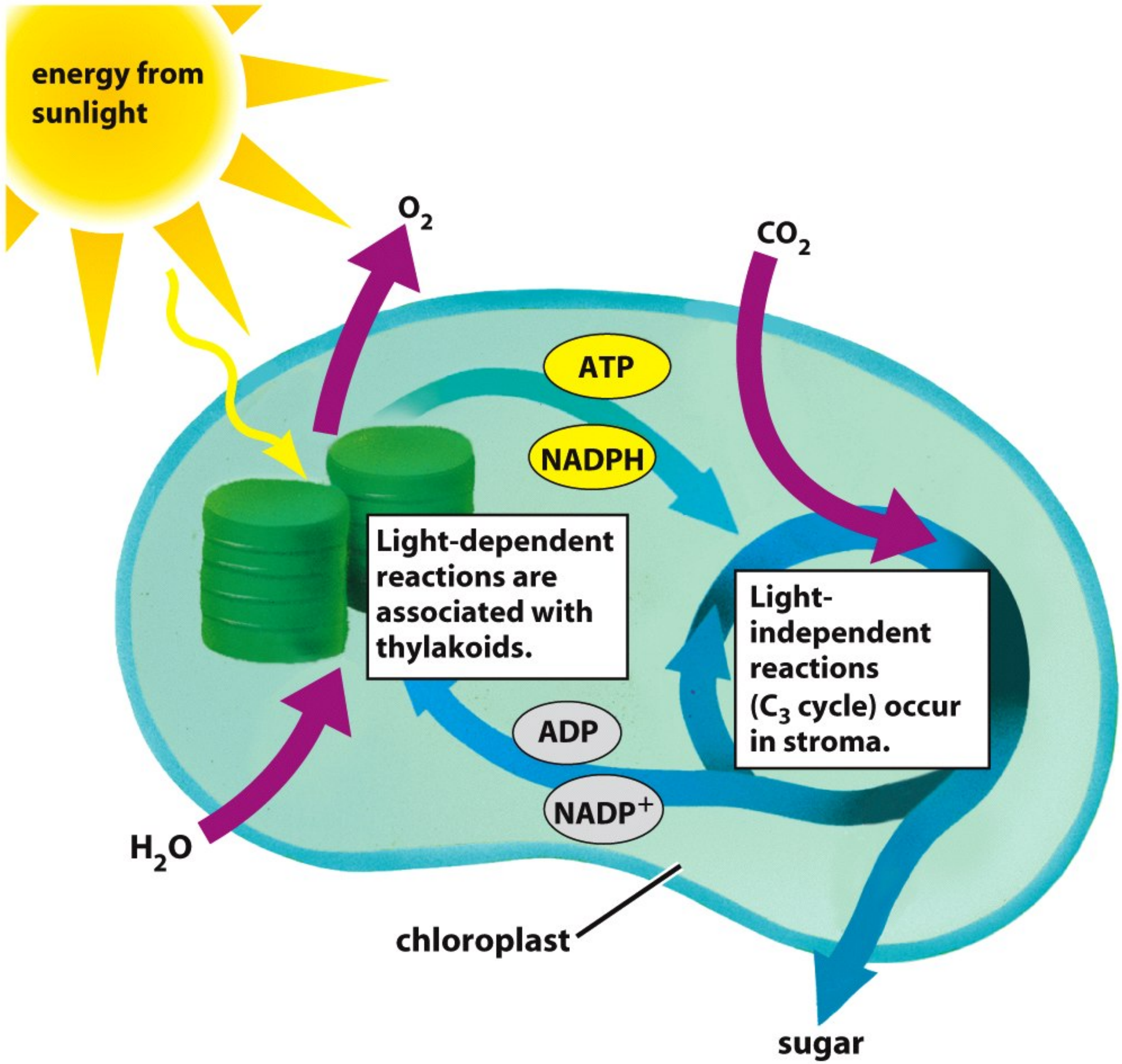


Figure 7-11 Biology: Life on Earth, 8/e

Section 7.5 Outline

- **7.5 Water, CO_2, and the C_4 Pathway**
  - When Stomata Are Closed to Conserve Water, Wasteful Photorespiration Occurs
  - C_4 Plants Reduce Photorespiration by Means of a Two-Stage Carbon-Fixation Process
  - C_3 and C_4 and Plants Are Each Adapted to Different Environmental Conditions

Water, CO_2, and the C_4 Pathway

- The ideal leaf:
  - Ideal leaves have large surface area to intercept sunlight
  - Ideal leaves are very porous to allow for CO_2 entry from air

Water, CO_2, and the C_4 Pathway

- Problem: Substantial leaf porosity leads to substantial water evaporation, causing dehydration stress on the plant
- Plants evolved waterproof coating and adjustable pores (stomata) for CO_2 entry

When Stomata Are Closed

- When stomata close, CO_2 levels drop and O_2 levels rise
- Carbon fixing enzyme combines O_2 instead of CO_2 with RuBP (called **photorespiration**)

When Stomata Are Closed

- Photorespiration:
  - O_2 is used up as CO_2 is generated
  - No useful cellular energy made
  - No glucose produced
  - Photorespiration is unproductive and wasteful

When Stomata Are Closed

- Hot, dry weather causes stomata to stay closed
- Oxygen levels rise as carbon dioxide levels fall inside leaf
- Photorespiration very common under such conditions
- Plants may die from lack of glucose synthesis

C_4 Plants Reduce Photorespiration

- "C_4 plants" have chloroplasts in bundle sheath cells as well as mesophyll cells
  - Bundle sheath cells surround vascular bundles deep within mesophyll
  - C_3 plants lack bundle sheath cell chloroplasts
- C_4 plants utilize the C_4 pathway
  - Two-stage carbon fixation pathway

The C_4 Pathway

1. Outer mesophyll cells contain phosphoenolpyruvate (PEP) instead of RuBP
2. Carbon dioxide-specific enzyme links CO_2 with PEP (unaffected by high O_2)
3. 4 carbon molecule then shuttled from mesophyll to bundle sheath cells...

The C_4 Pathway

4. CO_2 released in bundle sheath cells, building up high CO_2 concentration
5. CO_2 in bundle sheath cells fixed by standard C_3 pathway
6. 3 carbon shuttle molecule returns to mesophyll cells

C_3 plants use the C_3 pathway

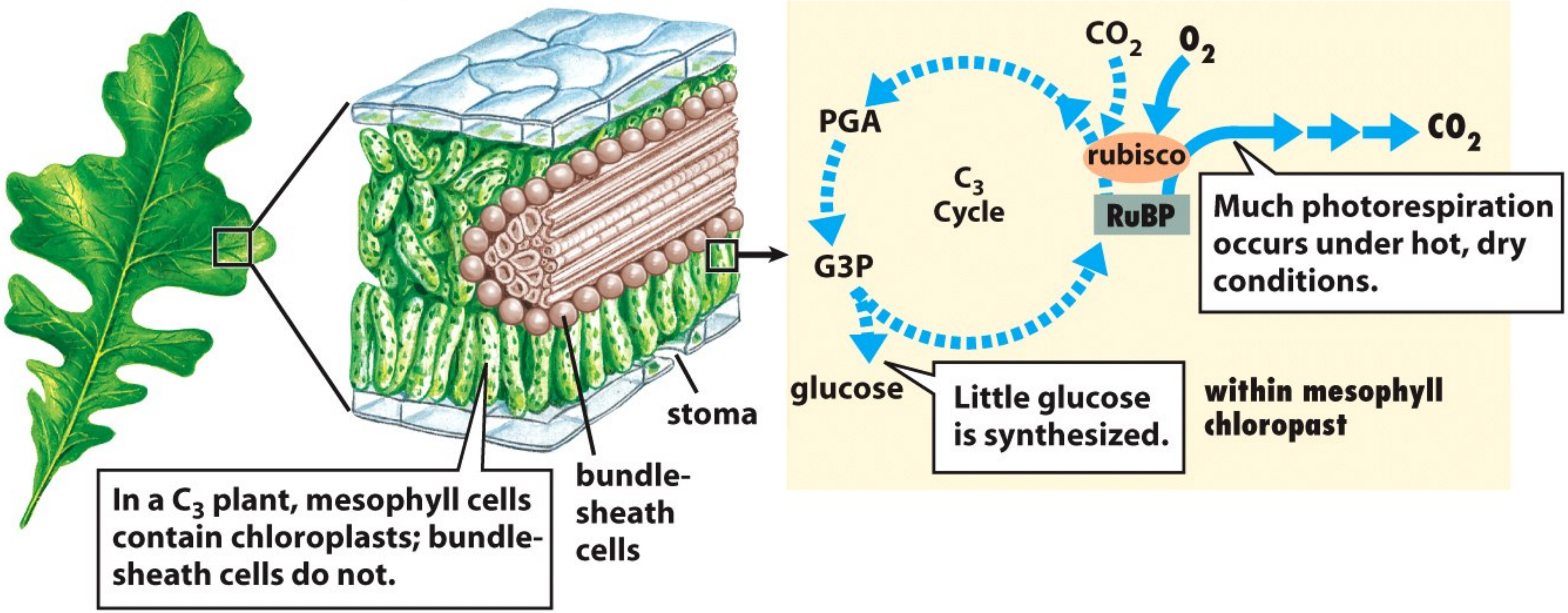


Figure 7-12a Biology: Life on Earth, 8/e

C_4 plants use the C_4 pathway

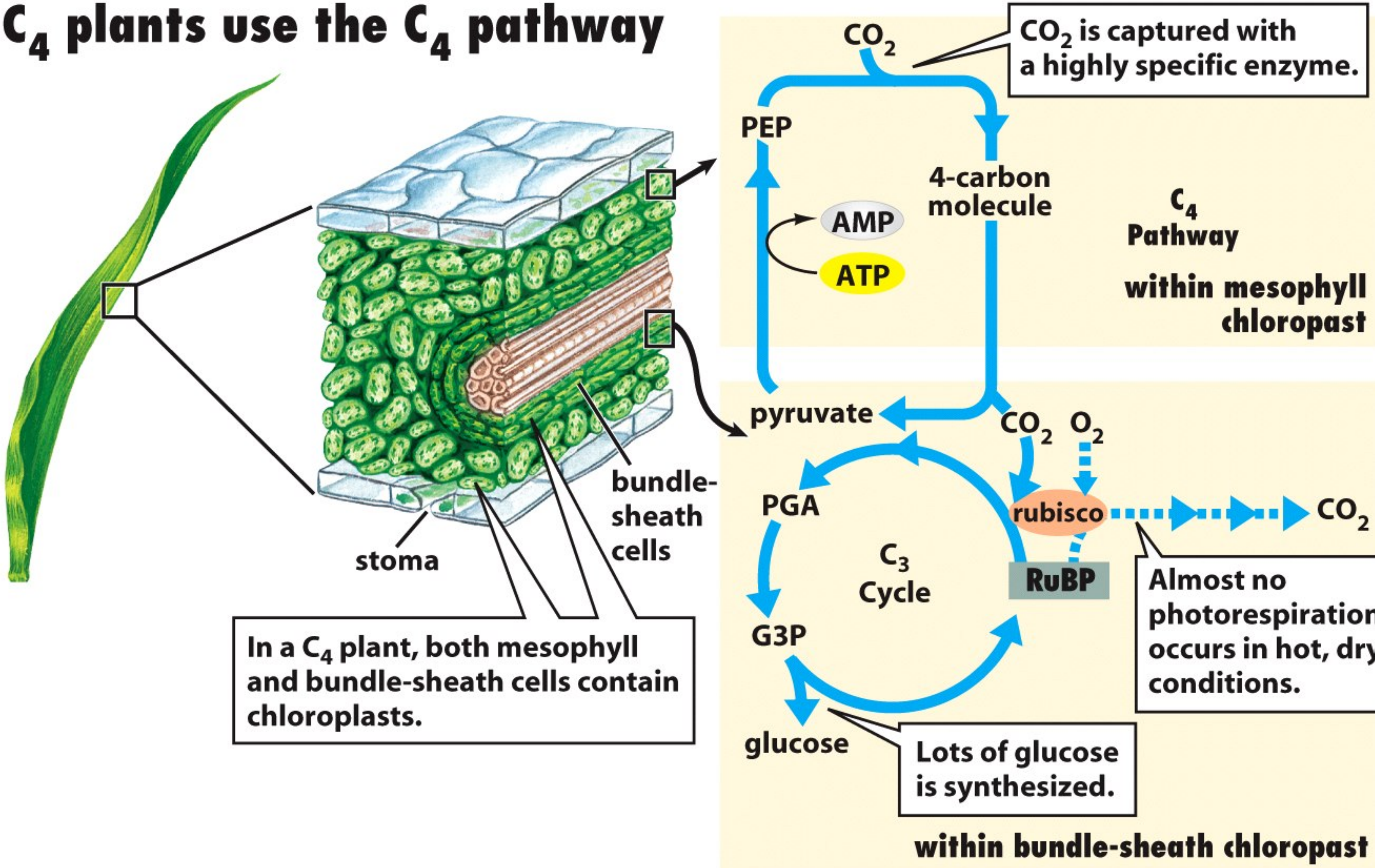


Figure 7-12b Biology: Life on Earth, 8/e

Environmental Conditions

- C_4 pathway uses up more energy than C_3 pathway
- C_4 plants thrive when *light is abundant* but *water is scarce* (deserts and hot climates)
  - C_4 plant examples: corn, sugarcane, sorghum, crabgrass, some thistles

Environmental Conditions

- C_3 plants thrive where *water is abundant* or if *light levels are low* (cool, wet, and cloudy climates)
  - C_3 plant examples: most trees, wheat, oats, rice, Kentucky bluegrass