CHAPTER 9

LESSON 1

Energy and Life

READING TOOL **Main Idea** As you read the lesson, complete the main idea table for each heading. The first one has been completed for you.

Heading	Main Idea
Chemical Energy and ATP	Chemical energy is contained in the bonds between atoms. ATP is the molecule that organisms use to temporarily store energy.
• Storing Energy	
• Releasing Energy	
• How Cells Use ATP	
Heterotrophs and Autotrophs	

Lesson Summary

As you read, circle the answers to each Key Question. Underline any words you do not understand.

Chemical Energy and ATP

KEY QUESTION *Why is ATP useful to cells?*

Cells require energy to perform work, and energy makes life possible. We humans cannot use sunlight as a source of energy, but must take in food made by other organisms, plant or animal, to acquire energy. We are heterotrophs.

Energy comes in many forms, including light, heat, and electricity. Energy can be stored in chemical compounds, too. For example, when you light a candle, the wax melts, soaks into the wick, and is burned. As the candle burns, chemical bonds between carbon and hydrogen atoms in the wax are broken. New bonds then form between these atoms and oxygen, producing CO_2 and H_2O (carbon dioxide and water). These new bonds are at a lower energy state than the original chemical bonds in the wax. The energy is released as heat and light in the glow of the candle's flame.

Storing Energy All living cells store energy in the chemical bonds of certain compounds. Of these compounds, one of the most important is adenosine triphosphate **(ATP)**. ATP consists of adenine, a 5-carbon sugar called ribose, and three phosphate groups. The phosphate groups are the key to ATP's ability to store and release energy. Adding a phosphate group to adensosine diphosphate (ADP) adds energy to the molecule and changes it to ATP. When a cell requires this energy, it removes the third phosphate group from ATP, changing it to ADP again.

Releasing Energy ATP can release energy by breaking the bonds between its phosphate groups. This characteristic of ATP makes it exceptionally useful as a basic energy source for all cells. ATP is the most immediate source of energy for cells.

How Cells Use ATP Cells use the energy provided by ATP to carry out active transport. Many cell membranes contain sodium-potassium pumps, which are membrane proteins that pump sodium ions (Na^+) out of the cell and potassium ions (K^+) into the cell. ATP provides the energy that keeps this pump working, which involves maintaining a carefully-regulated balance of ions on both sides of the cell membrane. The energy stored in ATP also enables cells to move, providing power for motor proteins that contract muscles and generate the wavelike movement of cilia and flagella.

Energy from ATP can be transferred to other molecules in the cell to power processes such as protein synthesis. The chemical energy from ATP can even be converted to light. In fact, the blink of a firefly comes from an enzyme that is powered by ATP!

Most cells have only enough ATP to last for a few seconds of activity. ATP is not a good molecule for storing large amounts of energy over the long term. A single molecule of the sugar glucose, for example, stores more than 90 times the energy required to add a phosphate group to ADP to produce ATP. Therefore, it is more efficient for cells to keep only a small supply of ATP on hand. Cells regenerate ATP from ADP as needed by using the energy in sugars and other sources.

BUILD Vocabulary

adenosine triphosphate (ATP) compound used by cells to store and release energy

Word Origins The name photosynthesis comes from the Greek words *phós* (light) and *synthesis* (putting together).

☑ **What other words do you know that begin with the prefix *photo-*?**

BUILD Vocabulary

photosynthesis process used by plants and other autotrophs to capture light energy and store it in energy-rich carbohydrates such as sugars and starches

READING TOOL

Compare and Contrast

Heterotrophs cannot make their own energy, so they obtain it from eating other living organisms, such as autotrophs. ☑ **What are the two different types of autotrophs, and which is more common on our planet?**

Heterotrophs and Autotrophs

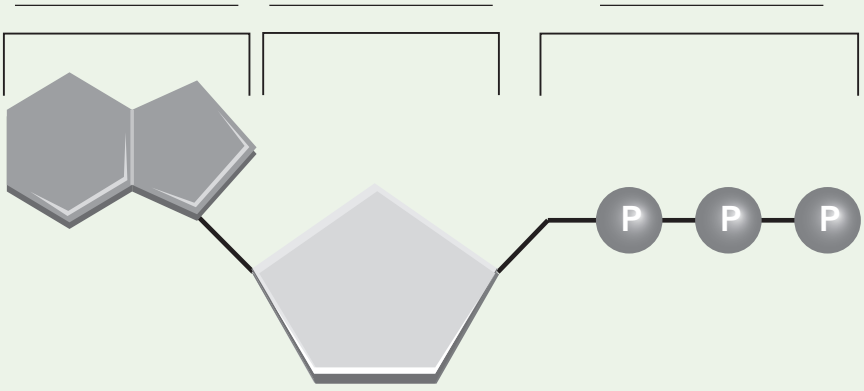
KEY QUESTION *What happens during the process of photosynthesis?*

All animals obtain the chemical energy they need from the food they consume. Animals are known as heterotrophs, which are organisms that obtain energy by consuming other organisms.

Some heterotrophs eat plants and are known as herbivores. Others, such as the heron, consume other animals and are known as carnivores. Animals that eat both plants and other animals are known as omnivores. Decomposers are heterotrophs that consume dead organisms and the wastes of living organisms. A mushroom is one example of a decomposer.

Autotrophs are organisms that make their own food using an external source of energy. Most autotrophs use sunlight as a source of energy and are known as photoautotrophs. Chemoautotrophs use chemicals as a source of energy, and are found only near vents on the ocean floor. **Photosynthesis** is the process by which photoautotrophs convert light energy into chemical energy. Photosynthetic organisms include plants, algae, and bacteria known as cyanobacteria. Nearly all life on Earth depends on autotrophs that capture sunlight energy and synthesize high-energy carbohydrates—sugars and starches—that can be used as food.

Visual Reading Tool: Adenosine Triphosphate



1. Label the ATP shown above.

2. Which part of the structure is a type of sugar? _____

3. Which part contains important bonds that store energy? _____

4. How does ADP get converted to ATP? _____

_____

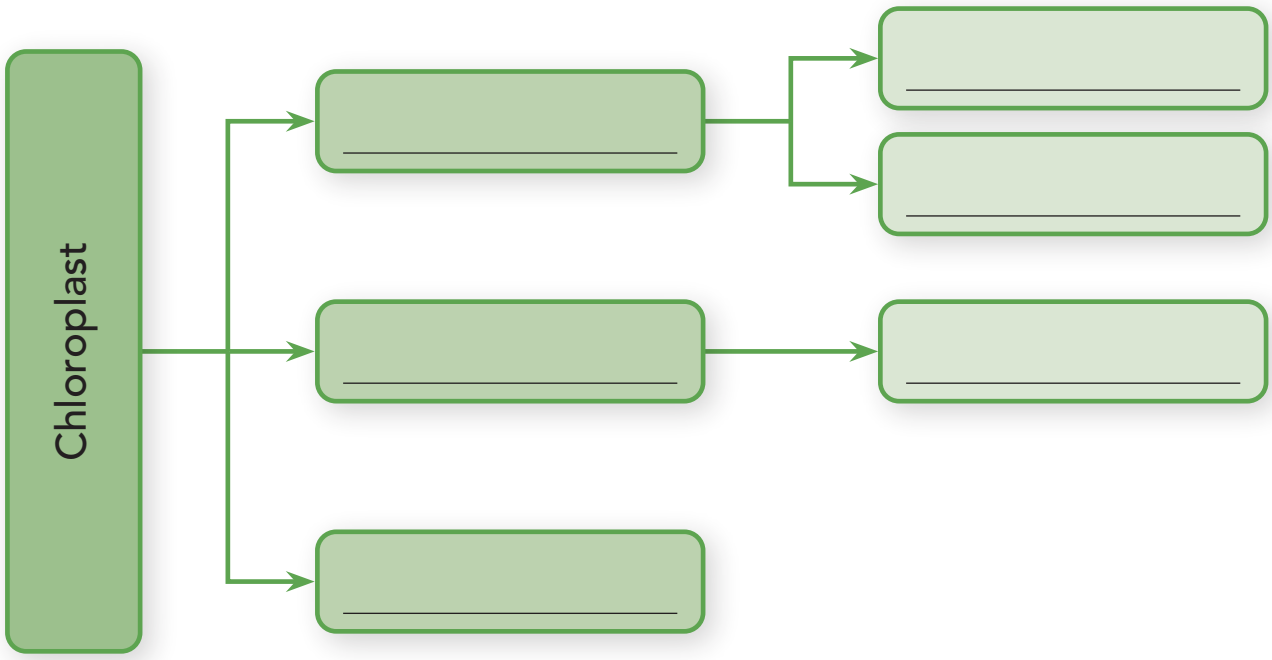
5. Which molecule has a higher potential energy. ADP or ATP? _____

CHAPTER 9

LESSON 2

Photosynthesis: An Overview

READING TOOL **Make Connections** Fill in the concept map to show the organization of a chloroplast. Then below, answer the questions to describe how the different parts are related to each other.



Complete each of the following sentences.

Saclike membranes that contain chlorophyll are known as _____.

_____ is a stack of thylakoids.

_____ is the fluid portion of the chloroplast outside of the thylakoids.

Two _____ surround and enclose the chloroplasts.

Lesson Summary

Chlorophyll and Chloroplasts

KEY QUESTION *What role do pigments play in the process of photosynthesis?*

As you read, circle the answers to each Key Question. Underline any words you do not understand.

Our lives, and the lives of nearly every living thing on the surface of Earth, are made possible by the sun and the process of photosynthesis. In order for photosynthesis to occur, light energy from the sun must somehow be captured.

BUILD Vocabulary

pigment light-absorbing molecules used by plants to gather the sun's energy

chlorophyll principal pigment of plants and other photosynthetic organisms

thylakoid saclike membranes found in chloroplasts, the location of the light-dependent reactions

stroma fluid portion of the chloroplasts; outside of the thylakoids, location of the light-independent reactions (Calvin cycle)

$NADP^+$ (nicotinamide adenine dinucleotide phosphate) carrier molecule that transfers high-energy electrons from chlorophyll to the Calvin cycle

Word Origins The word "thylakoid" comes from the Greek word *thylakos*, meaning sac or pouch. There once was a species of marsupials called the thylacine that went extinct in the 1930's.

☑ **Based upon what you know about the Greek word *thylakos*, how do you think the thylacines carried their young?**

Light The sun's energy travels to Earth in the form of light. Sunlight, which our eyes perceive as "white" light, is actually a mixture of different wavelengths. Our eyes see the different wavelengths of the visible spectrum as different colors: shades of red, orange, yellow, green, blue, indigo, and violet.

Pigments Light-absorbing compounds are known as **pigments**. Photosynthetic organisms primarily use the pigment chlorophyll to capture the energy in sunlight. The principal pigment of green plants is known as **chlorophyll**. Two types of chlorophyll, *a* and *b*, are found in plants, and are available to absorb different parts of the visible light spectrum, primarily blue-violet and red. Chlorophyll does not absorb the color green. Leaves appear green because they reflect these wavelengths. Plants also have red and orange carotene pigments, which we can only see when leaves begin to die during the fall.

Chloroplasts The plant organelle known as a chloroplast is where photosynthesis takes place. Within chloroplasts are grana, which are stacks of **thylakoids** that contain chlorophyll. The rest of the fluid outside of this is called **stroma**. The number of chloroplasts per cell varies across different plants. Chloroplasts can sometimes move within plants, as well as duplicate themselves.

Energy Collection The light energy collected by a cluster of pigments, including chlorophyll, is transferred to the reaction center in the center of the cluster where a particular chlorophyll molecule is excited and releases energized electrons. These high-energy electrons are vital to later steps of photosynthesis.

High-Energy Electrons

KEY QUESTION *What are electron carrier molecules?*

Specific molecules called electron carriers are necessary to convey the highly reactive and high-energy electrons that are produced by chlorophyll. The electron carrier moves the electrons with their energy to other molecules where they are needed.

Nicotinamide adenine dinucleotide phosphate, or **$NADP^+$**, is one such electron carrier. When it accepts two high-energy electrons, $NADP^+$ also bonds a hydrogen ion, which turns it into NADPH. Now the captured energy can be moved to the location in the chloroplast where sugars are manufactured.

An Overview of Photosynthesis

KEY QUESTION *What are the reactants and products of photosynthesis?*

Photosynthesis uses the energy of sunlight to convert water and carbon dioxide (low-energy reactants) into high-energy sugars and oxygen (products).

BUILD Vocabulary

light-dependent reactions set of reactions in photosynthesis that use energy from light to produce ATP and NADPH

light-independent reactions set of reactions in photosynthesis that do not require light; energy from ATP and NADPH is used to build high-energy compounds such as sugar

Light-Dependent Reactions

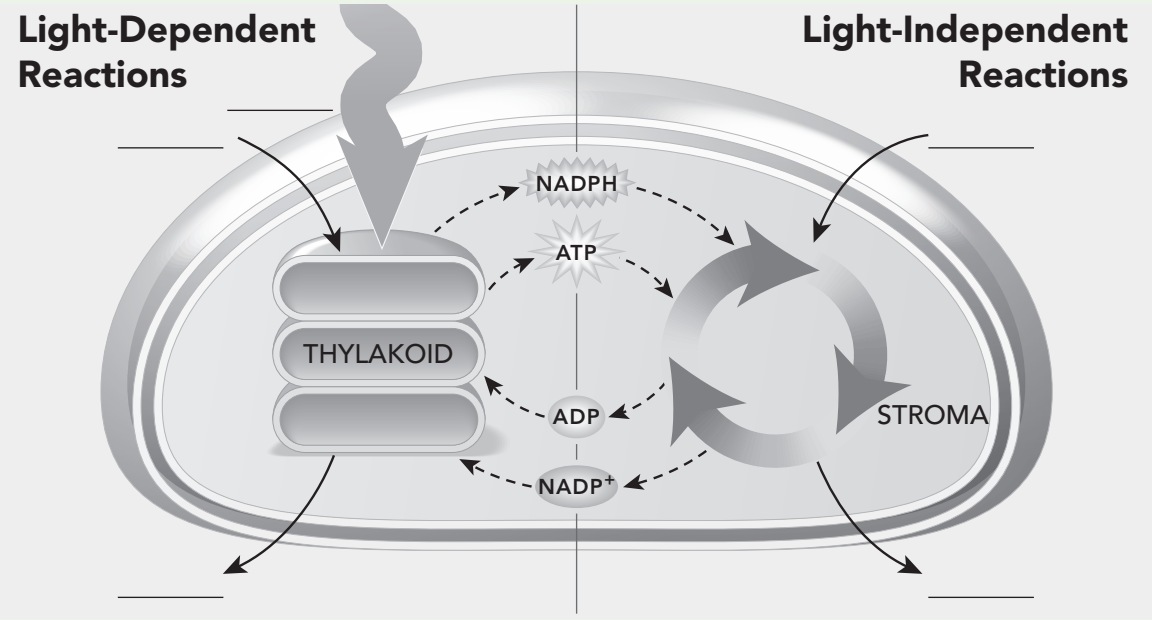
The **Light-dependent Reactions** need sunlight. The sunlight energy is captured by pigments in the thylakoid membrane. The energy is used to convert ADP into ATP and $NADP^+$ into NADPH. These sources of energy are important for other steps in photosynthesis. Also, water is split apart, which makes more electrons available, and produced oxygen (O_2) and hydrogen ions (H^+).

Light-Independent Reactions

The **Light-independent Reactions** (Calvin cycle) occur in the stroma and do not use sunlight. The energy in ATP and NADPH, produced in the light-dependent reactions, is used to "fix" carbon dioxide. That is, carbon dioxide (CO_2) is combined with H^+ to produce sugars, primarily glucose ($C_6H_{12}O_6$). The plant makes these sugars as food for itself.

Visual Reading Tool: Inside a Chloroplast

1. Fill in the reactants and products of the light-dependent and light-independent reactions of photosynthesis.



2. What is the NADPH responsible for? _____

_____

3. Where do the "light" reactions (light-dependent) take place? _____

CHAPTER 9

LESSON 3

The Process of Photosynthesis

READING TOOL **Main Idea** As you read the lesson, complete the main idea table for the primary headings below.

Heading	Main Idea
The Light-Dependent Reactions: Generating ATP and NADPH	
The Light-Independent Reactions: Producing Sugars	
Factors Affecting Photosynthesis	

Lesson Summary

As you read, circle the answers to each Key Question. Underline any words you do not understand.

BUILD Vocabulary

photosystem cluster of chlorophyll and proteins found in thylakoids

The Light-Dependent Reactions: Generating ATP and NADPH

KEY QUESTION *What happens during the light-dependent reactions?*

The light-dependent reactions use solar energy to convert ADP and $NADP^+$ into the energy and electron carriers ATP and NADPH. Oxygen is produced as a by-product of this reaction.

The light-dependent reactions occur across the thylakoids of chloroplasts. Thylakoids are saclike membranes that contain most of the machinery needed to carry out photosynthesis, including clusters of chlorophyll and proteins known as **photosystems**.

Photosystem II The light-dependent reactions begin in photosystem II. Chlorophyll molecules in the photosystem absorb light. This absorption of light raises electrons in chlorophyll to a higher energy level, and these high-energy electrons (e^-) are passed from chlorophyll to the electron transport chain.

Electron Transport Chain The **Electron Transport Chain** (ETC) uses energy from the electrons to pump protons (H^+) through the proteins in the chain from the stroma to the inside of the thylakoid sac. At the end of the electron transport chain, the electrons themselves pass to a second photosystem called photosystem I.

Photosystem I In Photosystem I the low-energy electrons from the ETC are passed to chlorophyll molecules and re-energized using light energy. The energized electrons are passed on to an enzyme that facilitates the production of NADPH from NADP+ and hydrogen ions. The NADPH can now move on to the light-independent reactions.

Hydrogen Ion Movement and ATP Formation All of the prior steps involved some increasing of H^+ concentration inside the thylakoids. Now there is a concentration gradient between the inside and outside of the thylakoid. Because molecules tend to move from a high to low concentration, the H^+ ions will move back across the thylakoid, if given the opportunity. **ATP synthase** provides a pathway for the hydrogen ions. As H^+ ions move across the thylakoid, through the ATP synthase protein, ADP is converted into ATP by the addition of a phosphate group.

Summary of Light-Dependent Reactions Light energy is used to convert ADP to ATP, and $NADPH^+$ to NADPH. Water is split apart to make electrons available to PS II, which produces O_2 and hydrogen ions.

The Light-Independent Reactions

KEY QUESTION *What happens during the light-independent reactions?*

During the light-independent reactions, ATP and NADPH from the light-dependent reactions are used to synthesize high-energy sugars. The light-independent reactions are commonly referred to as the **Calvin cycle**. The Calvin cycle occurs in the stroma of the chloroplast.

Carbon Dioxide Enters the Cell Carbon dioxide that has entered the leaves through the stomata is used in the Calvin cycle to produce higher energy sugars. An enzyme called RuBisCO "grabs" the CO_2 and brings it into the cycle where the energy from ATP and NADPH is used, through a series of steps, to produce a simple 3-carbon sugar for every 3 carbon dioxides that enter the cycle.

Sugar Production The two 3-carbon compounds are vital later on, helping to make other carbon-based compounds. One glucose molecule is a 6-carbon compound and would require 6 "turns" of the Calvin cycle.

BUILD Vocabulary

electron transport chain series of electron carrier proteins that shuttle high-energy electrons in preparation for ATP-generating reactions

ATP synthase enzyme that spans the thylakoid membrane and produces ATP from ADP when hydrogen ions (H^+) pass through it

Calvin Cycle the light-independent reactions of photosynthesis in which energy from ATP and NADPH is used to build high-energy compounds such as sugar

Suffixes When words end in *-ase* this usually indicates an enzymatic protein. ATP synthase is an enzymatic protein that creates ATP.

☑ **What molecules need to travel through ATP synthase to help it create ATP?**

READING TOOL

Apply Prior Knowledge Think about how you would care for a houseplant. It needs water, access to sunlight, and a supply of air.

☑ **Now that you know more about the specific processes of photosynthesis, explain exactly why a plant needs carbon dioxide from the air.**

Summary of the Calvin Cycle Six carbon dioxide molecules are needed to produce a 6-carbon sugar molecule, glucose. ATP and NADPH provided energy for these reactions to occur. The plant uses the sugars for growth and maintenance. Animals access the sugars when they eat the plant.

The End Results High energy sugars and O_2 gas are the end products of photosynthesis. The basic photosynthetic steps consisting of the light reactions and Calvin cycle is known as the C3 photosynthetic pathway. It is labeled as C3 because the first molecule generated during the Calvin cycle contains 3 carbon atoms.

Factors Affecting Photosynthesis

KEY QUESTION *What factors affect photosynthesis?*

Many factors affect the rate of chemical reactions, including those that occur during photosynthesis.

Temperature, Light, and Water The reactions of photosynthesis function best within a certain range of environmental conditions. The enzymes that carry out the Light-Dependent and Light-Independent reactions function best between 0°C and 35°C. Above or below that, it slows the rate of photosynthesis and can even stop it completely. Plants also need access to sunlight. High intensity light increases the rate of photosynthesis up to a certain point where plants reach their maximum photosynthetic rate. The last factor that affects photosynthesis is water availability. A shortage of water can halt photosynthesis. Some plants that live in dry conditions, such as desert plants and conifers, have waxy coatings on their leaves that reduce water loss.

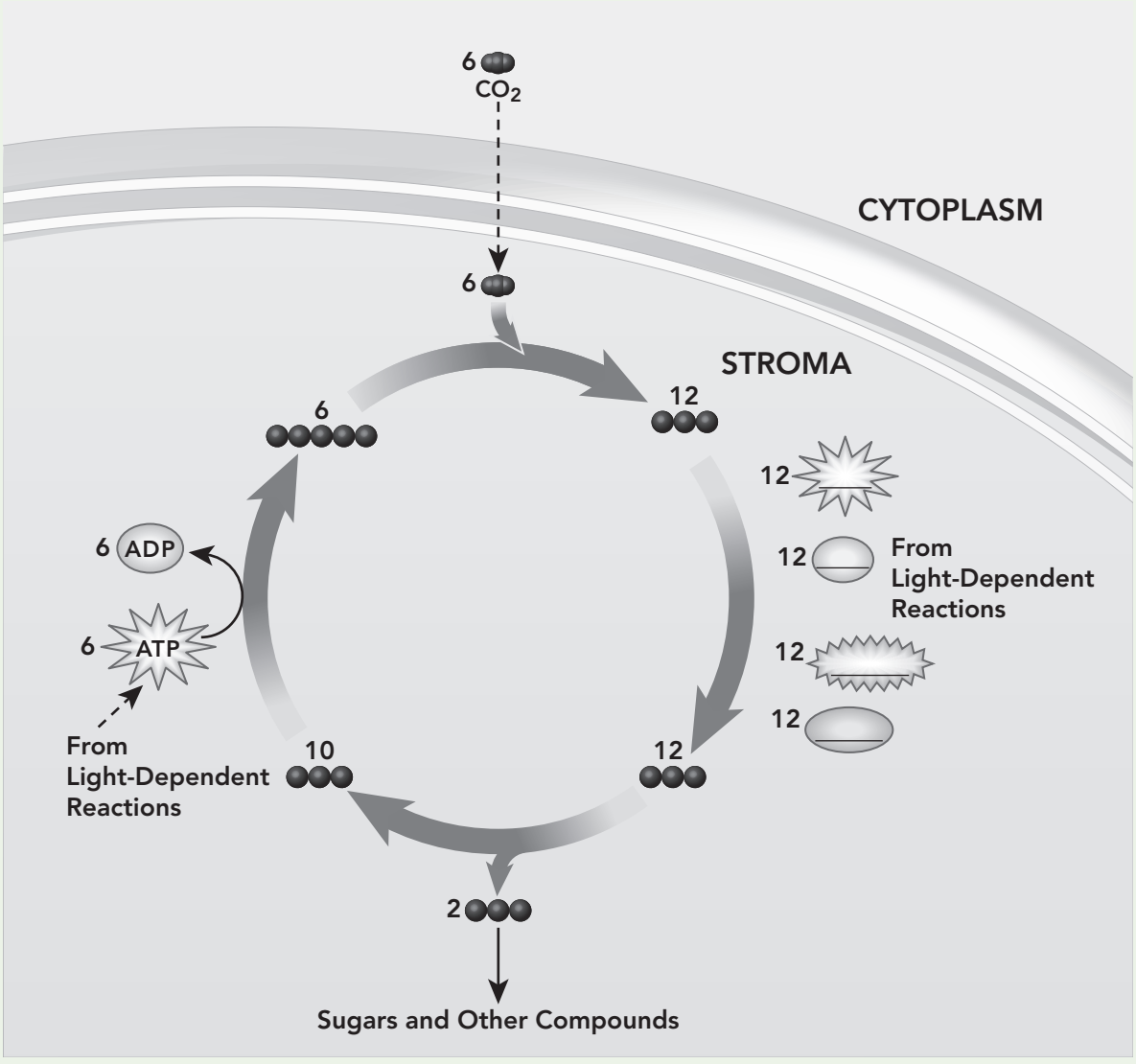
Photosynthesis Under Extreme Conditions Plants have openings on the underside of their leaves that are called stomata. They allow for CO_2 to enter the leaf and excess O_2 to leave. Unfortunately these openings also allow water to leave the leaf. Under hot and dry conditions the rate of water loss can be very high and the plant can run low on water. Plants have many adaptations to conserve water, including the physiological adaptations of C4 plants and CAM photosynthesis.

C4 Plants Dry conditions force plants to close their stomata in order to conserve water. Photosynthesis in C3 plants quickly comes to a stop because there is not enough CO_2 inside the leaves. However, C4 plants are able to fix CO_2 at much lower concentrations because they have an extra enzyme that assists RuBisCO. The name "C4" comes from the fact that the first compound formed in this pathway contains four carbon atoms instead of three. C4 plants include important crop plants like corn, sugar cane, and sorghum.

CAM Plants Crassulacean acid metabolism (CAM) plants open their stomata at night to allow for gas exchange when water loss will be minimized. They store the CO_2 that they collect at night as in an organic acid. When day comes, they then release the CO_2 in order to perform photosynthesis as usual. This evolved in some plants as an adaptation to arid conditions. The jade plant is one example of the Crassulacea family.

Visual Reading Tool: The Light-Independent Reactions

1. Label the diagram with the four molecules that carry energy through photosynthesis.



2. Where does the ATP and NADPH get created? _____

3. How many molecules of carbon dioxide are required to produce a 6-carbon sugar? _____

9 Chapter Review

Review Vocabulary

Choose the letter of the best answer.

1. The main pigment of green plants is:

A. thylakoid

B. carotene

C. chlorophyll

D. chloroplast

2. What concentration gradient powers ATP synthase?

A. O_2

B. CO_2

C. H^+

D. H_2O

Match the vocabulary term to its definition.

3.	material that absorbs light energy	a. stroma
4.	source of temporary energy	b. pigment
5.	reactions that occur in the thylakoid membrane	c. ATP
6.	fluid matrix of chloroplasts	d. light-dependent

Review Key Questions

Provide evidence and details to support your answers.

7. What is the importance of photosynthesis for all life?

8. How is energy captured from the sun?

9. In what stages are carbon dioxide and oxygen involved in photosynthesis ATP production?