

8

Photosynthesis

Learning Objectives

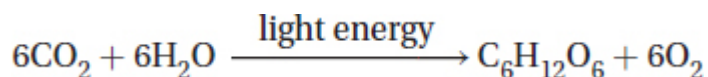
In this chapter, you will learn:

- Light-Dependent Reactions
- Light-Independent Reactions (The Calvin Cycle)

Overview

Some organisms consume other organisms to obtain organic molecules—these are called **heterotrophs**. Organisms that can produce their own organic molecules from inorganic molecules are called **autotrophs**. Autotrophs that use light energy to power this process are called **photoautotrophs**. This chapter will review the process that photoautotrophs use to produce organic molecules: photosynthesis.

Before studying all the reactions associated with photosynthesis, it is important to understand the basics of this process. Here is the overall equation for photosynthesis:



Note that during photosynthesis, the carbon atoms from carbon dioxide gain hydrogen atoms (carbon is reduced) and the oxygen atoms in water lose hydrogen atoms (oxygen is oxidized).

TIP

An easy way to remember the difference between oxidation and reduction is the mnemonic device OILRIG: Oxidation Is Losing hydrogen atoms; Reduction Is Gaining hydrogen atoms.

Photosynthesis can be divided into two main parts—the **light-dependent reactions** and the **light-independent reactions** (also known as the **Calvin cycle**), as shown in [Figure 8.1](#). The light-dependent reactions use energy from sunlight to split water, producing oxygen gas, protons, and high-energy electrons. Oxygen gas is released into the atmosphere. The protons and high-energy electrons are used to power the production of ATP and NADPH (which are sent to the light-independent reactions). The light-independent reactions use this ATP and NADPH, along with carbon dioxide, to produce sugars. The light-independent reactions then send ADP, P_i , and $NADP^+$ back to the light-dependent reactions so that photosynthesis can continue. In this way, the two parts of photosynthesis are interdependent.

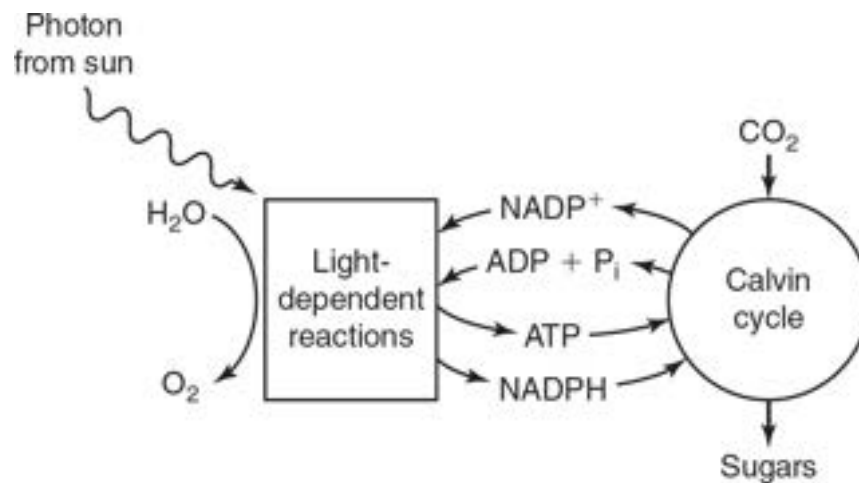


Figure 8.1 Light-Dependent Reactions and Light-Independent Reactions (The Calvin Cycle)

In plants, photosynthesis occurs in the chloroplasts. Chloroplasts have an outer membrane, which is filled with a liquid called stroma. Floating in the stroma are stacks of membranous sacs called grana, and each individual sac is called a thylakoid. The stroma is the location of the light-independent reactions, and the thylakoid is the site of the light-dependent reactions.

Some prokaryotes (for example, cyanobacteria) also perform photosynthesis. However, prokaryotes do not possess membrane-bound organelles, such as the chloroplasts. In photosynthetic prokaryotes, the light-dependent reactions of photosynthesis occur on infoldings of the plasma membrane and the light-independent reactions occur in the cytosol.

Light-Dependent Reactions

In the light-dependent reactions, light energy is used to drive the production of ATP. This is called **photophosphorylation**. Light energy excites the electrons in the chloroplast to higher energy levels. As these excited electrons move through the chloroplast, energy is released. At the end of the light-dependent reactions, NADP^+ accepts these electrons, forming NADPH, which is a source of reducing power for the light-independent reactions.

TIP

As you review the light-dependent reactions, focus on the role of light energy and the path of the excited electrons during the process.

Chlorophyll is a light-absorbing pigment that captures the energy of photons from the sun. Chlorophylls are the primary light-absorbing pigments in photosynthesis. Chlorophylls are found in photosystems I and II (PSI and PSII). A **photosystem** is composed of proteins, chlorophyll, and other light-absorbing pigments called accessory pigments. PSI and PSII contain different types of chlorophyll that absorb the most light energy at slightly different wavelengths (700 nm and 680 nm, respectively). Photosystems are located in the thylakoid membrane of the chloroplast and are connected by an electron transport chain (ETC). See [Figure 8.2](#).

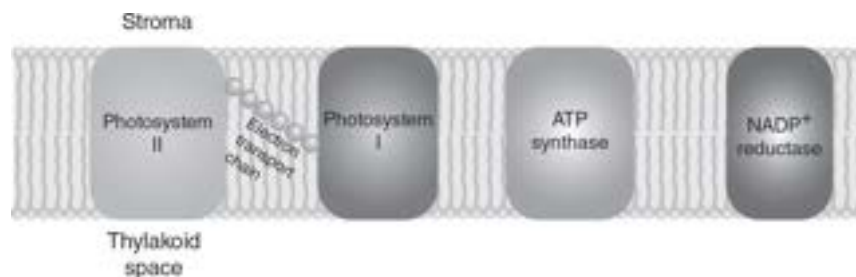


Figure 8.2 PSI, PSII, and the ETC

The energy in the photons is used to boost electrons in chlorophyll to a higher energy level in PSII. These electrons from PSII are passed from one protein carrier to another in a series of redox (reduction-oxidation) reactions that are analogous to “falling down a hill.” The final electron donor in the electron transport chain passes the electron to PSI. As the electrons pass through the carrier molecules of the ETC, the energy that is released is used to create a proton gradient, and H⁺ ions are actively transported against their concentration gradient across the thylakoid membrane.

Chemiosmosis requires a proton gradient, so a membrane is needed to separate the protons into a gradient. In eukaryotes, this gradient is generated across the thylakoid membrane. In prokaryotes, this gradient is formed in the infoldings of the plasma membrane.

The electrons from PSII that fell down the electron transport chain and are now on PSI need to be replaced on PSII. The electrons in PSII come from the splitting of water molecules. The splitting of water molecules strips electrons from the hydrogen atoms, producing the protons (the H⁺ ions), electrons for PSII, and oxygen gas. The protons will be used to form a gradient as electrons pass through the ETC. This process, which is driven by the energy from the sun (photons), is called **photolysis**. (See [Figure 8.3](#).)

The proton gradient generated by the photolysis of water and the ETC powers the production of ATP by the enzyme **ATP synthase**. (See [Figure 8.3](#).) The process of using a proton gradient and ATP synthase to produce ATP is called **chemiosmosis**. Chemiosmosis is also used in mitochondria to

generate ATP during cellular respiration, which will be reviewed in [Chapter 9](#).

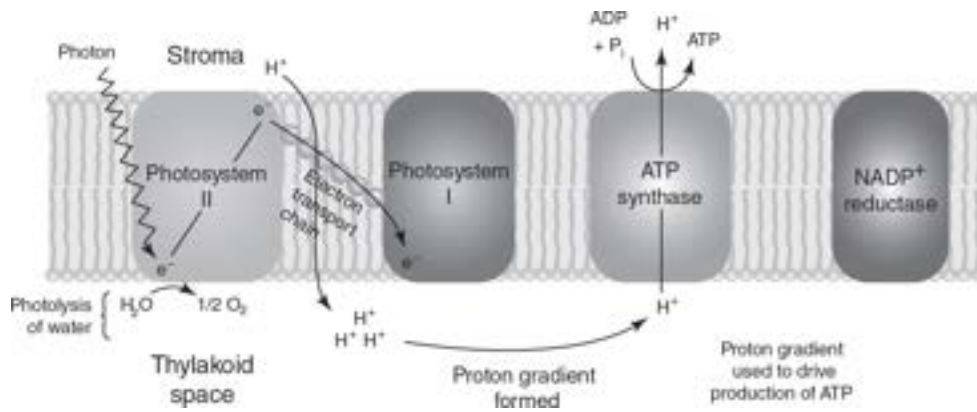


Figure 8.3 Photolysis of Water and the Production of ATP

The electron from the ETC (that is now on PSI) is boosted by another photon of light energy from the sun. The electron again passes through a series of carriers, although much shorter than that of the ETC, where it is finally transferred, along with a proton, to NADP⁺ by the enzyme NADP⁺ reductase. This produces a molecule of NADPH as shown in [Figure 8.4](#), which will provide reducing power for the light-independent reactions.

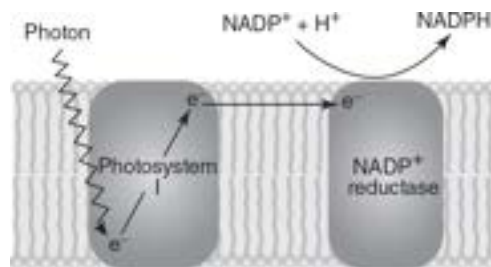


Figure 8.4 PSI and the Production of NADPH

Light-Independent Reactions (The Calvin Cycle)

The light-independent reactions (also known as the Calvin cycle) occur in the stroma of the chloroplast, which is the liquid surrounding the stacks of

thylakoids. The Calvin cycle, as shown in [Figure 8.5](#), is a complicated, multistep process that can be broken down into three main parts:

- 1. Fixation of carbon:** *Fixation* means turning a biologically unusable form into a usable form. In the fixation of carbon, the enzyme ribulose-bisphosphate-carboxylase (Rubisco, for short) adds one molecule of carbon dioxide to the five-carbon molecule ribulose-bisphosphate (RuBP, for short). This produces a six-carbon intermediate that is unstable, which then breaks down further into two three-carbon molecules.
- 2. Reduction:** Now the ATP and NADPH from the light-dependent reactions are used to reduce the three-carbon molecules. The energy to do this comes from the ATP, and the NADPH provides the hydrogen atoms (reducing power). A three-carbon molecule called glyceraldehyde-3-phosphate (simply known as G3P) is produced at the end of this process. G3P can be used to make sugars, but some of the G3P is used in the final part of the Calvin cycle: regeneration.
- 3. Regeneration of RuBP:** In order for the Calvin cycle to continue, the five-carbon RuBP must be regenerated. For every five molecules of G3P (a three-carbon molecule), there are 15 carbon atoms present. Using ATP from the light-dependent reactions, these five G3P molecules rearrange and form three molecules of RuBP (a five-carbon molecule), which also contain 15 carbon atoms. This process requires energy, which comes from the light-dependent reactions.

TIP

C4 and CAM photosynthesis occurs in plants in warmer climates, but that is beyond the scope of the AP Biology exam. Focus on the light-dependent reactions and the Calvin cycle when preparing for test day.

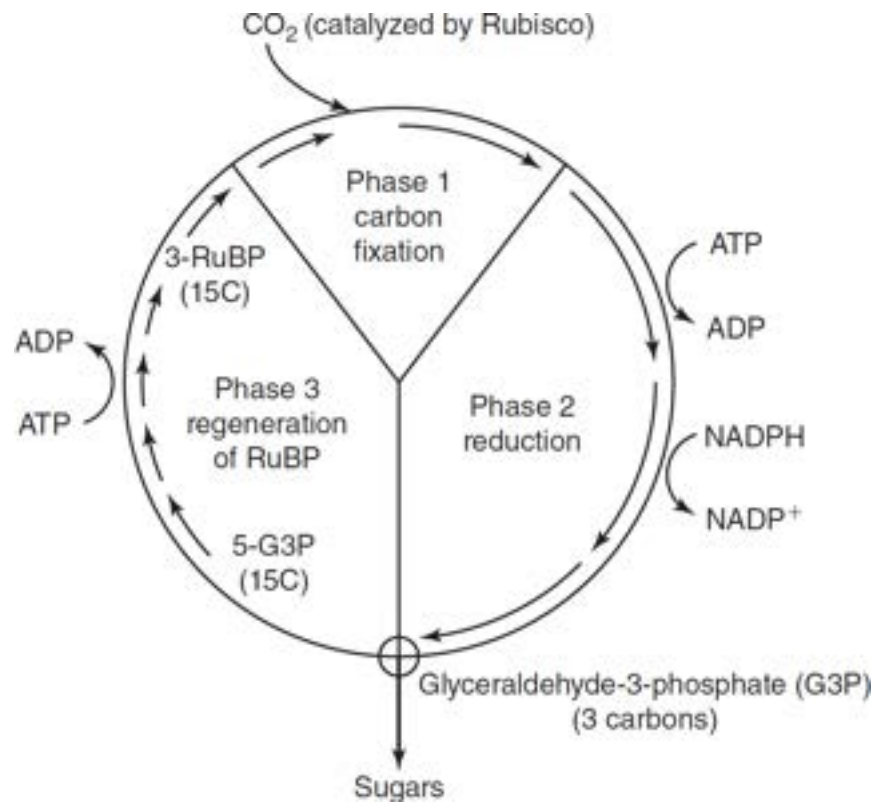


Figure 8.5 The Calvin Cycle

Practice Questions

Multiple-Choice

1. In prokaryotes, where in the cell do the light-dependent reactions of photosynthesis occur?
 - (A) on the thylakoid membrane
 - (B) on the plasma membrane
 - (C) in the cytoplasm
 - (D) in the nucleoid region

Questions 2 and 3

A scientist, who is studying photosynthesis, places a plant in an environment where the oxygen atoms in carbon dioxide are labeled with radioactive ^{18}O but the oxygen atoms in water have nonradioactive ^{16}O .

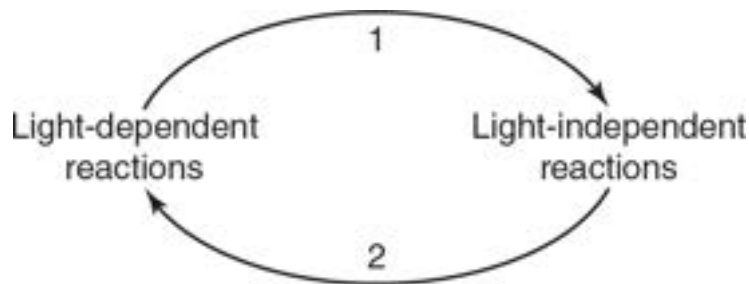
2. Based on this scenario, predict which product of photosynthesis will contain radioactive ^{18}O .
 - (A) NADPH
 - (B) glucose
 - (C) oxygen gas
 - (D) ATP
 3. Based on this scenario, predict which product of photosynthesis will contain nonradioactive ^{16}O .
 - (A) NADPH
 - (B) glucose
 - (C) oxygen gas
 - (D) ATP
-

4. Which of the following lists the three major parts of the light-independent reactions (the Calvin cycle)?
- (A) carbon fixation, electron transport chain, reduction
 - (B) carbon fixation, reduction, production of ATP
 - (C) carbon fixation, reduction, regeneration of RuBP
 - (D) reduction, regeneration of RuBP, electron transport chain
5. Which of the following correctly lists the products of the light-dependent reactions?
- (A) ADP, NADP⁺, oxygen
 - (B) ATP, NADPH, oxygen
 - (C) G3P, ADP, NADP⁺
 - (D) G3P, ATP, NADPH
6. Which of the following correctly lists the products of the Calvin cycle?
- (A) ADP, NADP⁺, oxygen
 - (B) ATP, NADPH, oxygen
 - (C) G3P, ADP, NADP⁺
 - (D) G3P, ATP, NADPH
7. Which of the following statements correctly identifies the locations of the major parts of photosynthesis in plant cells?
- (A) Light-dependent reactions occur in the stroma; light-independent reactions occur in the thylakoid.
 - (B) Light-dependent reactions occur in the matrix; light-independent reactions occur in the thylakoid.
 - (C) Light-dependent reactions occur in the thylakoid; light-independent reactions occur in the matrix.
 - (D) Light-dependent reactions occur in the thylakoid; light-independent reactions occur in the stroma.

8. If a thylakoid membrane is punctured so that molecules can freely flow between the thylakoid and the stroma, which of the following processes of photosynthesis will be most directly affected?
- (A) the formation of G3P
 - (B) the generation of a proton gradient
 - (C) the absorption of light
 - (D) the fixation of carbon
9. Which of the following best describes a relationship between the light-dependent reactions and the Calvin cycle?
- (A) The light-dependent reactions supply the Calvin cycle with oxygen, and the Calvin cycle returns carbon dioxide to the light-dependent reactions.
 - (B) The light-dependent reactions supply the Calvin cycle with ATP, and the Calvin cycle returns ADP to the light-dependent reactions.
 - (C) The light-dependent reactions supply the Calvin cycle with carbon dioxide, and the Calvin cycle returns oxygen to the light-dependent reactions.
 - (D) The light-dependent reactions supply the Calvin cycle with NADP^+ , and the Calvin cycle returns NADPH to the light-dependent reactions.
10. In the light-dependent reactions, the final electron acceptor in the electron transport chain is
- (A) oxygen.
 - (B) water.
 - (C) NAD^+ .
 - (D) NADP^+ .

Short Free-Response

11. The sea slug *Elysia crispata* eats photosynthetic algae. However, after consuming the algae, the chloroplasts from the algae are incorporated into the sea slug's own cells, give the sea slug a green color, and remain functional for up to four months. This phenomenon is called kleptoplasty.
- (a) **Describe** the role of photosynthetic algae in ecosystems.
 - (b) **Explain** why kleptoplasty would give *Elysia crispata* a survival advantage.
 - (c) An oil spill on the surface of the water reduces the intensity of light in *Elysia crispata*'s habitat. **Predict** the effect this would have on *Elysia crispata*'s survival.
 - (d) **Justify** your prediction from part (c).
12. The light-dependent and light-independent reactions of photosynthesis exchange materials and are interdependent, as shown in the following figure.

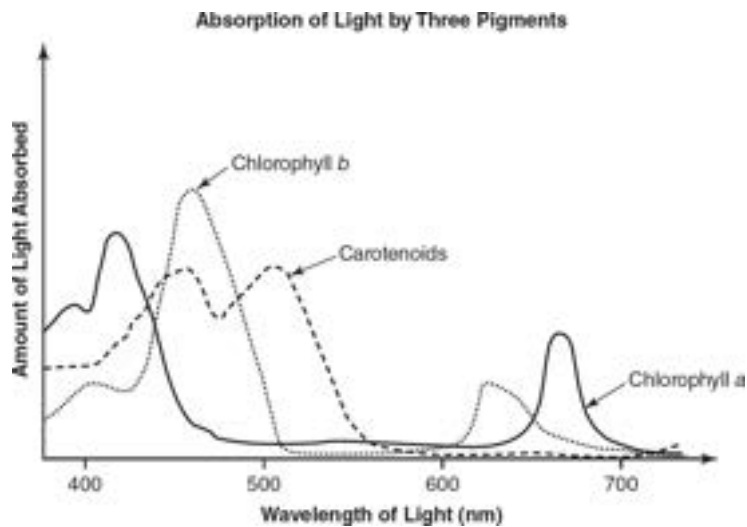


- (a) **Identify** the molecules the light-dependent reactions provide to the light-independent reactions. Label arrow 1 with those molecules.
- (b) **Identify** the molecules the light-independent reactions return to the light-dependent reactions. Label arrow 2 with those molecules.
- (c) An inhibitor of the enzyme Rubisco is added to a plant cell. **Explain** which part of photosynthesis would be most directly affected by this inhibitor.
- (d) A student claims that the light-independent reactions of photosynthesis would stop if a plant was kept in the dark for a long

period of time. Use your knowledge about photosynthesis to support the student's claim.

Long Free-Response

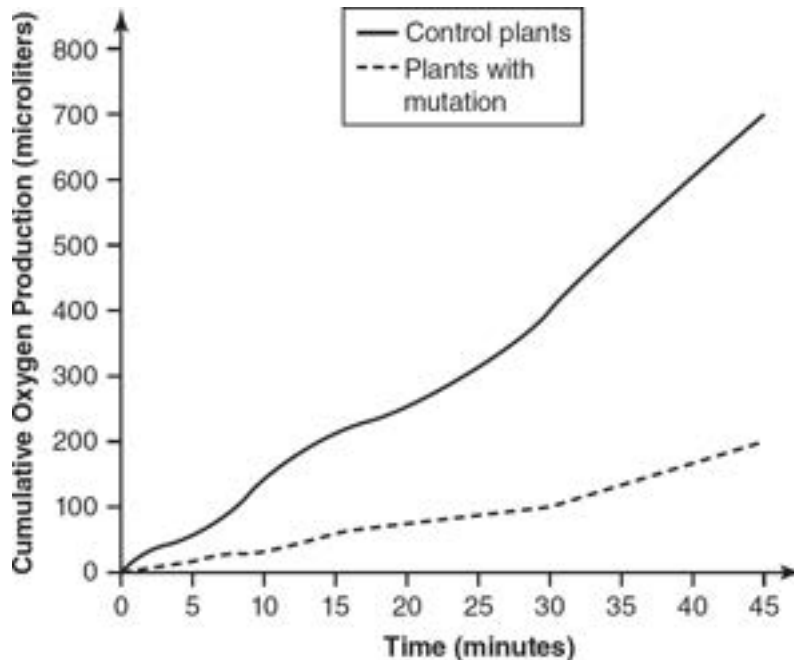
13. The following graph shows the absorption spectrum for the pigments chlorophyll *a*, chlorophyll *b*, and carotenoids.



The following table shows the wavelengths of different colors of visible light.

Color	Wavelength (nm)
Violet	380–450
Blue	450–495
Green	495–570
Yellow	570–590
Orange	590–620
Red	620–750

- (a) For each of the three pigments, **identify** the color of light that will be most absorbed by that pigment. Use the graph to **justify** your answer.
- (b) A mutation causes a plant to lose its ability to produce the pigments chlorophyll *a* and *b*. A student wants to design an experiment to study the rate of photosynthesis in the plant with this mutation. **Identify** an appropriate control for the experiment. **Identify** the independent and dependent variables in the experiment.
- (c) The following figure graphs the rate of photosynthesis (as measured by oxygen production) in control plants and in plants with the mutation described in part (b).



Calculate the rate of photosynthesis in both sets of plants during the first 30 minutes of the experiment.

- (d) Plants that use carotenoids as their primary photosynthetic pigment are grown under three different wavelengths of light: 450 nm, 500 nm, and 550 nm. **Predict** which group of plants will perform the least amount of photosynthesis, and **justify** your prediction.

Answer Explanations

Multiple-Choice

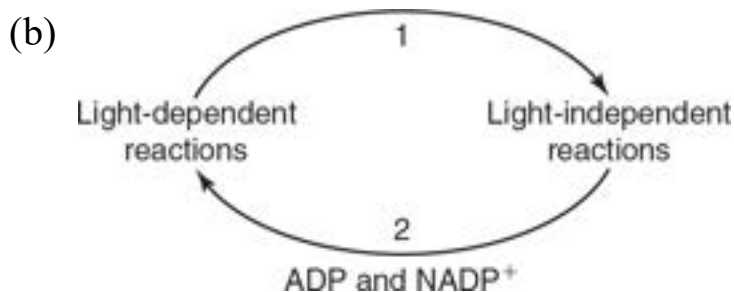
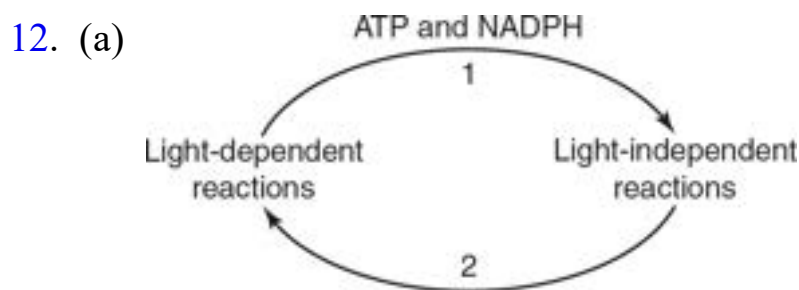
1. **(B)** In prokaryotes, the light-dependent reactions of photosynthesis occur on infoldings of the plasma membrane. Choice (A) is incorrect because prokaryotes do not have chloroplasts, so they do not have a thylakoid membrane. The light-dependent reactions require a membrane so that a proton gradient may be formed; no gradient can be formed in the liquid cytosol, so choice (C) is incorrect. The nucleoid contains the DNA of a prokaryotic cell and is not involved in the process of photosynthesis, so choice (D) is incorrect.
2. **(B)** The oxygen atoms in carbon dioxide are incorporated into glucose during photosynthesis. Choices (A) and (D) are incorrect because no oxygen atoms are incorporated into NADPH or ATP during photosynthesis. The oxygen gas released by photosynthesis is a result of the photolysis of water, so choice (C) is also incorrect.
3. **(C)** The oxygen gas released by photosynthesis is a product of the photolysis of water. Choices (A) and (D) are incorrect because no oxygen atoms are incorporated into NADPH or ATP during photosynthesis. Choice (B) is incorrect because the oxygen atoms in carbon dioxide are incorporated into glucose during photosynthesis.
4. **(C)** The three main parts of the light-independent reactions (the Calvin cycle) are carbon fixation, reduction, and regeneration of RuBP. Choices (A) and (D) are incorrect because there is no electron transport chain involved in the Calvin cycle. ATP is consumed, not produced, in the Calvin cycle, so choice (B) is also incorrect.
5. **(B)** The products of the light-dependent reactions are ATP, NADPH, and oxygen gas. Choices (A) and (C) are incorrect because ADP and NADP^+ are consumed, not produced, in the light-dependent reactions. G3P is a product of the light-independent reactions, which further rules out choice (C) and eliminates choice (D).

6. **(C)** The products of the Calvin cycle are ADP, NADP^+ , and G3P. Choice (A) is incorrect because oxygen is not produced by the Calvin cycle. Choice (B) is incorrect because ATP and NADPH are consumed, not produced, by the Calvin cycle, and oxygen is not produced by the Calvin cycle. Choice (D) is incorrect because while G3P *is* produced by the Calvin cycle, ATP and NADPH are consumed, not produced, by the Calvin cycle.
7. **(D)** This statement correctly identifies the locations of the light-dependent reactions and the light-independent reactions of photosynthesis. Choice (A) is incorrect because the correct location of the light-dependent reactions is the thylakoid and the correct location of the light-independent reactions is the stroma. Choices (B) and (C) are incorrect because the matrix is part of mitochondria, not chloroplasts, and is not involved in photosynthesis.
8. **(B)** If the thylakoid membrane is punctured, it would not be possible to generate a proton gradient since the protons would be able to diffuse freely across the thylakoid membrane. Choices (A) and (D) occur during the Calvin cycle, so (A) and (D) would not be directly affected by the puncturing of the thylakoid membrane. The absorption of light by pigments would not be affected by the puncturing of the thylakoid membrane, so choice (C) is also incorrect.
9. **(B)** The light-dependent reactions supply ATP to the Calvin cycle, which then returns ADP back to the light-dependent reactions. Choice (A) is incorrect because the oxygen produced by the light-dependent reactions is released to the atmosphere and the Calvin cycle consumes, not produces, carbon dioxide. Choice (C) is incorrect because the carbon dioxide needed for the Calvin cycle is absorbed from the atmosphere and the Calvin cycle does not produce oxygen. Choice (D) is incorrect because the light-dependent reactions send NADPH to the Calvin cycle and the Calvin cycle returns NADP^+ to the light-dependent reactions.
10. **(D)** NADP^+ is the final electron acceptor in the light-dependent reactions. NADP^+ becomes NADPH after accepting electrons. Choice

(A) is incorrect because oxygen is the final electron acceptor in cellular respiration, not photosynthesis. Water does not function as an electron acceptor, so choice (B) is incorrect. NAD^+ is not used in photosynthesis; it is used in cellular respiration. Thus, choice (C) is incorrect.

Short Free-Response

11. (a) Photosynthetic algae are autotrophs—they make their own food and are consumed by other organisms.
- (b) Kleptoplasty would give *Elysia crispata* a survival advantage because the chloroplasts that remained functional in the *Elysia crispata*'s cells would provide the sea slug with food.
- (c) Reducing the intensity of light in *Elysia crispata*'s habitat would have a negative impact on *Elysia crispata*'s survival.
- (d) Photosynthesis requires light energy, so reducing the light intensity would reduce the amount of photosynthesis the chloroplasts would perform and the amount of food from those chloroplasts that would be available to *Elysia crispata*. The sea slug might become more dependent on consuming other food sources.



- (c) Rubisco is an enzyme that is used in the light-independent reactions (the Calvin cycle) of photosynthesis, so the light-independent reactions would be most directly affected by an inhibitor of Rubisco.
- (d) The light-independent reactions of photosynthesis require ATP and NADPH that are produced by the light-dependent reactions of photosynthesis. If a plant was kept in the dark for a long period of time, the light-dependent reactions would stop and the ATP and NADPH that are required for the light-independent reactions would not be produced. Thus, the light-independent reactions would stop when their supply of ATP and NADPH was depleted.

Long Free-Response

13. (a) Chlorophyll *a* will absorb the most violet light because its peak absorbance is at approximately 425 nm, which is in the range for violet. Chlorophyll *b* will absorb the most blue light because its peak absorbance is at approximately 480 nm, which is in the range for blue. The carotenoids absorb the most green light because their peak absorbance is at approximately 510 nm, which is in the range for green.
- (b) An appropriate control would be a plant without the mutation that could produce chlorophyll *a*, chlorophyll *b*, and carotenoids. The independent variable would be the presence or absence of chlorophyll *a* and chlorophyll *b*. The dependent variable would be the rate of photosynthesis.
- (c) Rate of photosynthesis in the control plants = 400 microliters oxygen/30 minutes = 13.3 microliters oxygen/minute
- Rate of photosynthesis in the plants with the mutation = 100 microliters oxygen/30 minutes = 3.3 microliters oxygen/minute
- (d) The plants grown under light with a wavelength of 550 nm will perform the least amount of photosynthesis because carotenoids absorb the least amount of light energy at 550 nm. The absorbance is

greater at 450 nm and 500 nm than it is at 550 nm, so less photosynthesis will occur at 550 nm.