Name

Chapter 10: Photosynthesis

This chapter is as challenging as the one you just finished on cellular respiration. However, conceptually it will be a little easier because the concepts learned in Chapter 9—namely, chemiosmosis and an electron transport system—will play a central role in photosynthesis.

1. As a review, define the terms *autotroph* and *heterotroph*. Keep in mind that plants have mitochondria and chloroplasts and do both cellular respiration and photosynthesis!

Autotroph: An organism that obtains organic food molecules without eating other organisms or substances derived from other organisms. Autotrophs use energy from the sun or from oxidation of inorganic substances to make organic molecules from inorganic ones.

Heterotroph: An organism that obtains organic food molecules by eating other organisms or substances derived from them.

Concept 10.1 Photosynthesis converts light energy to the chemical energy of food

2. Take a moment to place the chloroplast in the leaf by working through Figure 10.4. Draw a picture of the chloroplast and label the *stroma, thylakoid, thylakoid space, inner membrane*, and *outer membrane*.

See page 186 of your text for the labeled figure.

3. Use both chemical symbols and words to write out the formula for photosynthesis (use the one that indicates only the net consumption of water). Notice that the formula is the opposite of cellular respiration. You should know both formulas from memory.

 $6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \text{Light energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2$

4. Using ¹⁸O as the basis of your discussion, explain how we know that the oxygen released in photosynthesis comes from water.

Scientists confirmed van Niel's hypothesis that oxygen released from photosynthesis comes from water with the use of ¹⁸O, a heavy isotope, as a tracer to follow the fate of oxygen atoms during photosynthesis. The experiments showed that the O_2 from plants was labeled with ¹⁸O only if water was the source of the tracer. If the ¹⁸O was introduced to the plant in the form of CO₂, the label did not turn up in the released O_2 .

5. Photosynthesis is not a single process, but two processes, each with multiple steps.

a. Explain what occurs in the *light reactions* stage of photosynthesis. Be sure to use $NADP^+$ and *photophosphorylation* in your discussion.

The light reactions are the steps of photosynthesis that convert solar energy to chemical energy. Water is split, providing a source of electrons and protons (hydrogen ions, H^+) and giving off O_2 as a by-product. Light absorbed by chlorophyll drives a transfer of the electrons and hydrogen ions from water to an acceptor called NADP⁺ (nicotinamide adenine dinucleotide phosphate), where they are Copyright © 2011 Pearson Education, Inc. temporarily stored. The light reactions use solar power to reduce NADP⁺ to NADPH by adding a pair of electrons along with an H⁺. The light reactions also generate ATP, using chemiosmosis to power the addition of a phosphate group to ADP, a process called photophosphorylation.

b. Explain the *Calvin cycle*, utilizing the term *carbon fixation* in your discussion.

The cycle begins by incorporating CO_2 from the air into organic molecules already present in the chloroplast. This initial incorporation of carbon into organic compounds is known as carbon fixation. The Calvin cycle then reduces the fixed carbon to carbohydrate by the addition of electrons. The reducing power is provided by NADPH, which acquired its cargo of electrons in the light reactions. To convert CO_2 to carbohydrate, the Calvin cycle also requires chemical energy in the form of ATP, which is also generated by the light reactions.

6. The details of photosynthesis will be easier to organize if you can visualize the overall process. Label following figure. As you work on this, underline or highlight the items that are cycled between the light reactions and the Calvin cycle.

See page 188 of your text for the labeled figure.

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

This is a long and challenging concept. Take your time, work through the questions, and realize that this is the key concept for photosynthesis.

7. Some of the types of energy in the electromagnetic spectrum will be familiar, such as X-rays, microwaves, and radio waves. The most imporant part of the spectrum in photosynthesis is visible light. What are the colors of the *visible spectrum*?

Red, Orange, Yellow, Green, Blue, Indigo, Violet

8. Notice the colors and corresponding wavelengths. Explain the relationship between wavelength and energy.

Light is a form of energy known as electromagnetic energy, also called electromagnetic radiation. Electromagnetic energy travels in rhythmic waves analogous to those created by dropping a pebble into a pond. Electromagnetic waves, however, are disturbances of electric and magnetic fields rather than disturbances of a material medium such as water. The distance between the crests of electromagnetic wave sis called the wavelength.

9. Study Figure 10.9 carefully; then explain the correlation between an *absorption spectrum* and an *action spectrum*.

Absorption spectrum is the range of a pigment's ability to absorb various wavelengths of light; also a graph of such a range.

Action spectrum is a graph that profiles the relative effectiveness of different wavelengths of radiation in driving a particular process.

10. Describe how Englemann was able to form an action spectrum long before the invention of a spectrophotometer.

In 1883, Theodor W. Engelmann illuminated a filamentous alga with light that had been passed through a prism, exposing different segments of the alga to different wavelengths. He used aerobic bacteria, which concentrate near an oxygen source, to determine which segments of the alga were releasing the most O_2 and thus photosynthesizing most. Bacteria congregated in greatest numbers around the parts of the alga illuminated with violet-blue or red light.

- 11. A *photosystem* is composed of a protein complex called a reaction center complex surrounded by several light-harvesting complexes.
- 12. Within the photosystems, the critical conversion of solar energy to chemical energy occurs. This process is the essence of being a producer! Using Figure 10.13 as a guide, label the diagram and then explain the role of the components of the photosystem listed below.

See page 193 in your text for the labeled figure.

- a. Reaction center complex: This complex of proteins associated with a special pair of chlorophyll a molecules and a primary electron acceptor. Located centrally in a photosystem, this complex triggers the light reactions of photosynthesis. Excited by light energy, the pair of chlorophylls donates an electron to the primary electron acceptor, which passes an electron to an electron transport chain.
- b. Light-harvesting complex: This complex of proteins associated with pigment molecules (including chlorophyll a, chlorophyll b, and carotenoids) that captures light energy and transfers it to reaction-center pigments in a photosystem.
- c. Primary electron acceptor: In the thylakoid membrane of a chloroplast or in the membrane of some prokaryotes, the primary electron acceptor is a specialized molecule that shares the reaction center complex with a pair of chlorophyll a molecules and that accepts an electron from them.
- 13. *Photosystem I (PS I)* has at its reaction center a special pair of chlorophyll *a* molecules called P680. What is the explanation for this name?

Perhaps you caught that the reaction center molecules for photosystem I are a special pair of chlorophyll molecules called P700. So, the question has a mistake—but the response should be either to note this error, and explain what is meant by P700, or note the error and explain that P680 molecules form the reaction center for photosystem II. These reaction center molecules (either P680 or P700) are named for the wavelengths of light that are most effectively absorbed by each (680 nm or 700 nm)

14. What is the name of the chlorophyll *a* at the reaction center of PS I called?

P700

15. *Linear electron flow* is, fortunately, easier to understand than it looks. It is an electron transport chain, somewhat like the one we worked through in cellular respiration. While reading the section "Linear Electron Flow" and studying Figure 10.14 in your text, label this diagram number by number as you read.

See page 194 in your text for the labeled figure.

- 16. The following set of questions deals with linear electron flow:
 - a. What is the source of energy that excites the electron in photosystem II? light
 - b. What compound is the source of electrons for linear electron flow? water
 - c. What is the source of O_2 in the atmosphere? splitting of water
 - d. As electrons fall from photosystem II to photosystem I, the cytochrome complex uses the energy to pump hydrogen ions. This builds a proton gradient that is used in chemiosmosis to produce what molecule? ATP
 - e. In photosystem I, NADP⁺ reductase catalyzes the transfer of the excited electron and H⁺ to NADP⁺ to form NADPH.

*Notice that two high-energy compounds have been produced by the light reactions: ATP and NADPH. Both of these compounds will be used in the Calvin cycle.

- 17. *Cyclic electron flow* can be visualized in Figure 10.16. Cyclic electron flow is thought to be similar to the first forms of photosynthesis to evolve. In cyclic electron flow no water is split, there is no production of NADPH and there is no release of oxygen.
- 18. The last idea in this challenging concept is how chemiosmosis works in photosynthesis. Describe four ways that chemiosmosis is *similar* in photosynthesis and cellular respiration.
 - 1. In photosynthesis and cellular respiration, an electron transport chain assembled in a membrane pumps protons across the membrane as electrons are passed through a series of carriers that are progressively more electronegative.
 - 2. In photosynthesis and cellular respiration, ATP synthase complex couples the diffusion of hydrogen ions down their gradient to the phosphorylation of ADP.
 - 3. The inner membrane of the mitochondrion pumps protons from the mitochondrial matrix out to the intermembrane space, which then serves as a reservoir of hydrogen ions. The thylakoid membrane of the chloroplast pumps protons from the stroma into the thylakoid space (interior of the thylakoid), which functions as the H⁺ reservoir.

- 4. In the mitochondrion, protons diffuse down their concentration gradient from the inter- membrane space through ATP synthase to the matrix, driving ATP synthesis. In the chloroplast, ATP is synthesized as the hydrogen ions diffuse from the thylakoid space back to the stroma through ATP synthase complexes, whose catalytic knobs are on the stroma side of the membrane.
- 19. Use two key differences to explain how chemiosmosis is *different* in photosynthesis and cellular respiration.

There are noteworthy differences between oxidative phosphorylation in mitochondria and photophosphorylation in chloroplasts. In mitochondria, the high-energy electrons dropped down the transport chain are extracted from organic molecules (which are thus oxidized), whereas in chloroplasts, the source of electrons is water. Chloroplasts do not need molecules from food to make ATP; their photosystems capture light energy and use it to drive the electrons from water to the top of the transport chain. In other words, mitochondria use chemiosmosis to transfer chemical energy from food molecules to ATP, whereas chloroplasts transform light energy into chemical energy in ATP.

20. Label all the locations in this diagram. Then, follow the steps in linear electron flow to label the components of the light reactions in chemiosmosis that are seen in this figure.

See page 197 of your text for the labeled figure.

21. List the three places in the light reactions where a proton-motive force is generated by increasing the concentration of H⁺ in the stroma.

Water is split by photosystem II on the side of the membrane facing the thylakoid space
As plastoquinone (Pq), a mobile carrier, transfers electrons to the cytochrome complex, four protons are translocated across the membrane into the thylakoid space
A hydrogen ion is removed from the stroma when it is taken up by NADP⁺.

22. To summarize, note that the light reactions store chemical energy in ATP and NADPH, which shuttle the energy to the carbohydrate-producing Calvin cycle.

Concept 10.3 The Calvin cycle uses ATP and NADPH to convert CO₂ to sugar

The Calvin cycle is a metabolic pathway in which each step is governed by an enzyme, much like the citric acid cycle in cellular respiration. However, keep in mind that the Calvin cycle uses energy (in the form of ATP and NADPH) and is therefore anabolic. In contrast, cellular respiration is catabolic and releases energy that is used to generate ATP and NADH.

- 23. The carbohydrate produced directly from the Calvin cycle is not glucose, but the three-carbon compound glyceraldehyde 3-phosphate (G3P). Each turn of the Calvin cycle fixes one molecule of CO₂; therefore, it will take 3 turns of the Calvin cycle to net one G3P.
- 24. Explain the important events that occur in the *carbon fixation* stage of the Calvin cycle.

The Calvin cycle incorporates each CO_2 molecule, one at a time, by attaching it to a five- carbon sugar named ribulose bisphosphate. The enzyme that catalyzes this first step is RuBP carboxylase, or rubisco. The product of the reaction is a six-carbon intermediate so unstable that it immediately splits in half, forming two molecules of 3-phosphoglycerate

- 25. The enzyme responsible for carbon fixation in the Calvin cycle, and possibly the most abundant protein on Earth, is rubisco.
- 26. In phase two, the *reduction stage*, what molecule will donate electrons, and so is the source of the reducing power?

NADPH

- 27. In this *reduction stage*, the low-energy acid 1, 3-bisphosphoglycerate is reduced by electrons from NADPH to form the three-carbon sugar G3P.
- 28. Examine Figure 10.19 in your text while we tally carbons. This figure is designed to show the production of one net G3P. That means the Calvin cycle must be turned three times. Each turn will require a starting molecule of *ribulose bisphosphate (RuBP)*, a five-carbon compound. This means we start with 15 carbons distributed in three RuBPs. After fixing three molecules of CO₂ using the enzyme rubisco, the Calvin cycle forms six G3Ps with a total of 18 carbons. At this point the net gain of carbons is 3, or one net G3P molecule.
- 29. Three turns of the Calvin cycle nets one G3P because the other five must be recycled to RuBP. Explain how the *regeneration of RuBP* is accomplished.

In a complex series of reactions, the carbon skeletons of five molecules of G3P are rearranged by the last steps of the Calvin cycle into three molecules of RuBP. To accomplish this, the cycle spends three more molecules of ATP. The RuBP is now prepared to receive CO_2 again, and the cycle continues.

30. The net production of one G3P requires 9 molecules of ATP and 6 molecules of NADPH.

Concept 10.4 Alternative mechanisms of carbon fixation have evolved in hot, arid climates

31. Explain what is meant by a C_3 plant.

A plant that uses the Calvin cycle for the initial steps that incorporate CO_2 into organic material, forming a three-carbon compound as the first stable intermediate.

32. What happens when a plant undergoes *photorespiration*?

During photorespiration, which is a metabolic process, the plant consumes oxygen and ATP, releases carbon dioxide, and decreases photosynthetic output. Photorespiration generally occurs on hot, dry, bright days, when stomata close and the O_2/CO_2 ratio in the leaf increases, favoring the binding of O_2 rather than CO_2 by rubisco.

33. Explain how photorespiration can be a problem in agriculture.

Rice, wheat, and soybeans are C_3 plants that are important in agriculture. When their stomata partially close on hot, dry days, C_3 plants produce less sugar because the declining level of CO_2 in the leaf starves the Calvin cycle, limiting growth.

34. Explain what is meant by a C_4 plant.

A plant in which the Calvin cycle is preceded by reactions that incorporate CO_2 into a four-carbon compound, the end product of which supplies CO_2 for the Calvin cycle.

35. Explain the role of *PEP carboxylase* in C_4 plants, including key differences between it and *rubisco*.

This enzyme adds CO_2 to phosphoenolpyruvate (PEP), forming the four-carbon product oxaloacetate. PEP carboxylase has a much higher affinity for CO_2 than does rubisco and no affinity for O_2 . Therefore, PEP carboxylase can fix carbon efficiently when rubisco cannot—that is, when it is hot and dry and stomata are partially closed, causing CO_2 concentration in the leaf to fall and O_2 concentration to rise.

36. Conceptually, it is important to know that the C_4 pathway does not replace the Calvin cycle but works as a CO_2 pump that prefaces the Calvin cycle. Explain how changes in leaf architecture help isolate rubisco in regions of the leaf that are high in CO_2 but low in O_2 .

In effect, the mesophyll cells of a C_4 plant pump CO_2 into the bundle sheath, keeping the CO_2 concentration in the bundle-sheath cells high enough for rubisco to bind carbon dioxide rather than oxygen.

37. Using Figure 10.19 in your text as a guide, explain the three key events in the C_4 pathway.

In mesophyll cells, the enzyme PEP carboxylase adds carbon dioxide to PEP.
A four-carbon compound conveys the atoms of the CO₂ into a bundle-sheath cell via plasmodesmata.
In bundle-sheath cells, CO₂ is released and enters the Calvin cycle.

38. Compare and contrast C₄ plants with CAM plants. In your explanation, give two key similarities and two key differences.

Both C₄ and CAM plants thrive in hot, dry conditions. Both have evolved methods to reduce water loss and to "fix" carbon dioxide in an intermediate compound before it enters the Calvin cycle.

 C_4 plants have Kranz anatomy, with thick-walled bundle-sheath cells. CO_2 is added to PEP to make a four-carbon intermediate so that CO_2 will not be lost through photorespiration.

CAM plants prevent water loss by closing their stomata during the day, but in order to have CO_2 available, it is fixed in crassulacean acid when the stomata are open at night.

In C₄ plants, the initial steps of carbon fixation are separated structurally from the Calvin cycle.

In CAM plants, the two steps occur at different times (temporal separation of steps.)

39. Explain this statement: "Only the green cells of a plant are the autotroph while the rest of the plant is a heterotroph."

Technically, green cells are the only autotrophic parts of the plant. The rest of the plant depends on organic molecules exported from leaves via veins. In most plants, carbohydrate is transported out of the leaves in the form of sucrose, a disaccharide.

40. Now that you have worked through the entire chapter, study Figure 10.22. Go back to the figure used in question 6. On the left side of that figure, list additional information for the light reactions; on the right side, summarize additional information for the Calvin cycle reactions. Finally, label this entire figure without looking back in your book! If you can do this, you understand the "big picture."

See page 203 in your text for the labeled figure.

Test Your Understanding Answers

Now you should be ready to test your knowledge. Place your answers here:

1. d 2. b 3. c 4. d 5. c 6. b 7. d