Teacher Notes for “Photosynthesis and Cellular Respiration – Understanding the Basics of Bioenergetics and Biosynthesis”

In this minds-on activity, students analyze the relationships between photosynthesis, cellular respiration, and the production and use of ATP. Students learn that sugar molecules produced by photosynthesis are used for cellular respiration and for the synthesis of other organic molecules. Thus, photosynthesis contributes to plant metabolism and growth. The optional final section challenges students to explain observed changes in biomass for plants growing in the light vs. dark.

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Learning Goals
In accord with the Next Generation Science Standards:
   • This activity helps students to prepare for Performance Expectations:
      o HS-LS1-5, "Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy."
      o HS-LS1-7, "Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy."
      o HS-LS2-5, "Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere…"
   • Students learn the following Disciplinary Core Ideas:
      o LS1.C: "The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen. The sugar molecules thus formed contain carbon, hydrogen, and oxygen; their hydrocarbon backbones are used to make amino acids and other carbon-based molecules… Cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken”, carbon dioxide and water are formed, and the energy released is used in the production of ATP from ADP and P. Then, the hydrolysis of ATP molecules provides the energy needed for many biological processes.
      o Students engage in recommended Scientific Practices, including constructing explanations, developing and using models, and interpreting data.
   • This activity can be used to illustrate the Crosscutting Concepts:
      o “Energy and matter: Flows, Cycles and Conservation” – “matter is conserved because atoms are conserved in physical and chemical processes… Energy may take different forms…”
      o “Cause and Effect: Mechanism and Prediction” – Students “suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems”.

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1 By Dr. Ingrid Waldron, Department of Biology, University of Pennsylvania, 2017. These Teacher Notes and the related Student Handout are available at http://serendip.brynmawr.edu/exchange/bioactivities/photocellrespir. I thank Brianna Chang for suggesting the use of puzzle pieces for this activity.
2 Quotations are from http://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf
**Supplies**

Each student or pair of students will need a piece of paper that they can tear or cut into 16 rectangles and label as directed on page 2 of the Student Handout. If you prefer, you can print copies of the last page of these Teacher Preparation Notes and have students cut the pieces and then write the names of the molecules in the pieces from the first column. If you have not used the introductory activities described below, you may prefer to change the pieces so your students can represent cellular respiration as:

\[ C_6H_{12}O_6 + 6 O_2 + \sim 29 \text{ ADP} + \sim 29 \text{ P} \rightarrow 6 \text{ CO}_2 + 6 \text{ H}_2\text{O} + \sim 29 \text{ ATP} + \sim 29 \text{ H}_2\text{O} \]

**Instructional Suggestions and Background Information**

**General**

Before your students begin this activity, they should have a basic understanding of photosynthesis and cellular respiration. For this purpose I recommend the analysis and discussion activities:

- How do biological organisms use energy?  
  [http://serendip.brynmawr.edu/exchange/bioactivities/energy](http://serendip.brynmawr.edu/exchange/bioactivities/energy)
- Using Models to Understand Photosynthesis  
  [http://serendip.brynmawr.edu/exchange/bioactivities/modelphoto](http://serendip.brynmawr.edu/exchange/bioactivities/modelphoto)

To maximize student participation and learning, I suggest that you have your students work in pairs (or individually or in small groups) to complete groups of related questions and then have a class discussion after each group of related questions. In each discussion, you can probe student thinking and help them to develop a sound understanding of the concepts and information covered before moving on to the next group of related questions.

To help students understand the big picture and consolidate their understanding of photosynthesis and cellular respiration, you can use a modified version of storyboarding with this activity, as follows:

- Before students begin the Student Handout, students work in pairs and use their background knowledge to respond to the Introductory Photosynthesis and Cellular Respiration Storyboard (shown on page 9 of these Teacher Notes). This will help to activate students’ memory of relevant concepts and information. I recommend that you review these initial storyboards to learn more about your students’ knowledge and any misconceptions they may have. This storyboard is intended for formative assessment only.
- As students increase their understanding of photosynthesis and cellular respiration during the activity, they can modify their Introductory Storyboards.
- After completing the activity presented in the Student Handout, students complete the Follow-up Storyboard (shown on page 10 of these Teacher Notes) without looking at their earlier storyboard or the Student Handout. After they complete the Follow-up Storyboards, students should have prompt feedback so they can improve the accuracy and completeness of their storyboards; you can accomplish this in a class discussion where students compare their storyboards. This type of active recall with feedback helps to consolidate student understanding and retention of the concepts learned during the activity.4

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3 This general approach is described in “Using Storyboarding to Model Gene Expression”, American Biology Teacher 77:452-457, 2015.

4 Evidence for the benefits of active recall with prompt feedback is described in [http://www.scientificamerican.com/article/researchers-find-that-frequent-tests-can-boost-learning/](http://www.scientificamerican.com/article/researchers-find-that-frequent-tests-can-boost-learning/).
A key for the Student Handout and the storyboards is available upon request to Ingrid Waldron (iwaldron@sas.upenn.edu). The following paragraphs provide additional instructional suggestions and background information.

For background information on photosynthesis and cellular respiration, please see the overview, “Cellular Respiration and Photosynthesis – Important Concepts, Common Misconceptions, and Learning Activities” (http://serendip.brynmawr.edu/exchange/bioactivities/cellrespiration) and the Student Handout and Teacher Preparation Notes for “How do biological organisms use energy?” (http://serendip.brynmawr.edu/exchange/bioactivities/energy) and “Using Models to Understand Photosynthesis (http://serendip.brynmawr.edu/exchange/bioactivities/modelphoto).

First Three Pages of Student Handout

The figure on the top of page 1 of the Student Handout shows glucose as the sugar produced by photosynthesis. Photosynthesis directly produces a three-carbon sugar glyceraldehyde-3-phosphate which is used to synthesize glucose and fructose. Some of the glucose and fructose are used to make sucrose which is transported to other parts of the plant.

As you know, hydrolysis refers to a chemical reaction in which a molecule is split into smaller molecules by reacting with water. Students may be less familiar with this term and may need help to recall this definition. This figure shows the hydrolysis of ATP. (There appears to be some disagreement about the details of where the atoms in the water molecule end up, but there is general agreement about what the products are.) For simplicity, the Student Handout represents $P_i + H^+$ as P.

The Student Handout does not mention that the hydrolysis of ATP usually occurs after the ATP has bound with a substrate molecule, e.g. a motor protein or one of the reactants in a synthesis reaction. In this way, the exergonic hydrolysis of ATP is coupled with the endergonic change in conformation of the motor protein or the synthesis reaction.

The flowchart in question 3 should help students understand why plants need three processes (photosynthesis, cellular respiration, and hydrolysis of ATP) to provide energy for the activities of life. To reinforce the importance of producing ATP, you may want to ask your students whether cells can directly use sunlight to provide the energy needed for biological processes (and then ask the same question for glucose). Although it is common to describe chemical energy as stored in glucose, it is more accurate to describe the potential energy as a property of the system of glucose and $O_2$ which interact to produce $CO_2$ and $H_2O$. Breaking bonds always requires energy input and energy is released only when new more stable bonds are formed. The same considerations apply to ATP. (An expanded explanation is provided in “Cellular Respiration and

After discussing question 6, you may want to have your students compare and contrast the diagram of photosynthesis and cellular respiration that they have developed in their answers to questions 4-6 with the diagram shown in the figure on page 1 of the Student Handout.

**Question 7** helps students to understand two important points:

- All organisms (including plants) need to make ATP which provides energy in the form needed to carry out many cellular processes (e.g. pumping substances into and out of cells and synthesis of organic molecules). Most organisms carry out cellular respiration to produce ATP.\(^5\)
- All organisms need a source of organic molecules for cellular respiration, but plants use photosynthesis to make organic molecules, whereas animals eat food to get organic molecules.

Page 3 of the Student Handout introduces the concept that the sugar molecules produced by photosynthesis are used not only for cellular respiration, but also for the synthesis of other organic molecules in plants. (Organic molecules are complex, carbon-containing molecules found in living organisms.) This figure provides some additional information about how glucose is used to synthesize a variety of organic molecules. Obviously, nitrogen and phosphorus from soil water will also be needed to synthesize amino acids, nucleotides, and phospholipids.

The figure on the top of page 3 in the Student Handout shows that glucose monomers are joined in different ways in cellulose and starch polymers. This difference in how the glucose monomers are linked results in different shapes for these polymers. Starch molecules have a spiral form. In contrast, cellulose molecules are straight and cross-linked by hydrogen bonds to form microfibrils that gives strength to plant cell walls.

\(^5\) If you want to reinforce this concept, you could use this question:

“Cells in plant leaves have both chloroplasts and mitochondria. If plant cells can carry out photosynthesis to produce sugars, why do plant cells need mitochondria?”

The important point that plants need to carry out cellular respiration contrasts with some diagrams of the carbon cycle in ecology which show photosynthesis occurring in plants and erroneously show cellular respiration occurring only in animals.

The present activity provides a useful preparation for understanding carbon cycles. To help your students learn about carbon cycles, I recommend "Food Webs, Energy Flow, Carbon Cycle, and Trophic Pyramids" [http://serendip.brynmawr.edu/exchange/bioactivities/foodweb](http://serendip.brynmawr.edu/exchange/bioactivities/foodweb). A sequence of activities for teaching about transformations of energy and matter at multiple levels from the molecular through carbon cycles and energy flows is available through Carbon TIME (http://carbontime.bscs.org/) and [http://ibis.colostate.edu/MSP/CTIME/TeachingUnitDashboard.php?TeachingUnitID=6#](http://ibis.colostate.edu/MSP/CTIME/TeachingUnitDashboard.php?TeachingUnitID=6#).
The figure below provides some additional information about starch synthesis. Notice that:

- Starch synthesis requires ATP; this is an example of how ATP provides energy for the processes of life.
- Starch synthesis requires enzymes.
- Glucose monomers are added one at a time to synthesize the starch molecule.

(These points are also relevant for the synthesis of other biological polymers.)

Starch synthesis is useful for storing glucose to be used for cellular respiration in future situations where photosynthesis cannot occur. For example, starch is stored:

- in seeds for use when seedlings first sprout
- in tubers for use in generating a plant after a cold or dry season
- in leaves during the day to provide glucose for cellular respiration during the night (see Optional Activity on page 10 of these Teacher Preparation Notes).

When you discuss question 12, you may want to point out the similarities between the dual functions of sugar molecules produced by photosynthesis and the dual functions of food molecules, as discussed in "Food, Energy and Body Weight" (http://serendip.brynmawr.edu/exchange/bioactivities/foodenergy).

**Plant Growth Puzzle**

The previous section (the first three pages of the Student Handout) provides the background for students to analyze the plant growth puzzle. In this optional section, students are introduced to the concept of biomass and then apply their understanding of photosynthesis and cellular respiration to predict and then interpret changes in biomass for plants growing in light vs. dark. You may prefer to substitute either of the following analysis and discussion activities, both of which utilize and reinforce the concepts learned in the first three pages of the Student Handout:

- "Where does a plant's mass come from?" (http://serendip.brynmawr.edu/exchange/bioactivities/plantmass)
  In this analysis and discussion activity students analyze evidence to evaluate four hypotheses about where a plant’s mass comes from. The evidence that students analyze is presented in a chemical equation, figures, a table, and prose. Students evaluate whether Helmont’s interpretation of his classic experiment was supported by his evidence. Thus, students engage in scientific practices as they learn that plants consist mainly of water

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6 This figure shows starch synthesis in amyloplasts. In chloroplasts, starch synthesis begins with a different first step (http://www.uky.edu/~dhild/biochem/10/lect10.html).

and organic molecules and most of the mass of organic molecules consists of carbon and oxygen atoms originally contained in carbon dioxide molecules from the air.

- An analysis of diurnal shifts between the synthesis and breakdown of starch in leaves (see Optional Activity on page 11 of these Teacher Preparation Notes)

Hydrolysis is the process responsible for the **breakdown of starch to glucose molecules** discussed on page 4 of the Student Handout. As shown in this figure, the hydrolysis of a polymer is the reverse of the dehydration synthesis of a polymer.

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**Dehydration Synthesis**

During dehydration synthesis, two monomers or a monomer & polymer are bonded together by removing water when forming the covalent bond between them.

**Hydrolysis**

During hydrolysis, a polymer is taken apart, making a smaller polymer and a monomer, or two monomers. Water must be placed back in the area where the covalent bond was broken.

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**Question 16** asks students to predict the change in biomass in each experimental condition and give a reason for each prediction. At this point, students may lack some of the information needed to make accurate predictions, but the goal is for each student or group of students to use what they know thus far to make a prediction that they can support with a reasonable, logical explanation. The next page of the Student Handout provides the opportunity to discuss the actual results and the reasons for these results.

**After** the students have completed question 16 you should inform your students of the results of the experiment.

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<tr>
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<th>Light, no water</th>
<th>Light, water</th>
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<tr>
<td>Biomass after 10 days</td>
<td>1.46 g</td>
<td>1.63 g</td>
<td>1.20 g</td>
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The lack of change in the biomass of the dry seeds reflects their dormant condition in which very little cellular respiration and no photosynthesis is occurring.
Question 18 asks students to explain the apparent discrepancy between the decreased biomass of the plants in the “water, no light” condition vs. the larger volume and total weight of these plants compared to the seeds. The key to resolving this apparent discrepancy is the observation that ~75-90% of the mass of actively growing plant tissues is water, and water is not part of the biomass. (Woody parts such as a tree trunk are ~45-60% water.) Much of the water in plant cells is in the central vacuole.

This figure may help your students visualize how plants get the water and carbon dioxide needed for photosynthesis.

The plants in the experiment described were grown in petri dishes with water, but no soil. This observation can be used to reinforce the important concept that most of a plant’s biomass comes from the air (CO₂) and relatively little from the minerals in the soil. See "Where does a plant's mass come from?" (http://serendip.brynmawr.edu/exchange/bioactivities/plantmass) for additional information. For growth to continue, some minerals would be required.
Additional Background and Activities

Sources for figures in Student Handout
- page 2 – modified from https://classconnection.s3.amazonaws.com/954/flashcards/1172954/jpg/biopic132880784092.jpg
Introductory Photosynthesis and Cellular Respiration Storyboard  Name __________________

1. Draw lines to connect each molecule that is the same in the upper and lower figures in the left-hand column.
2. For each figure on the left, write the name of the process in the rectangle.
3. Describe what is happening in each of the four figures shown. Use terms such as: cellular respiration, photosynthesis, hydrolysis of ATP, carbon dioxide, glucose, oxygen, water, provides energy for many biological processes.
4. Note any questions you have.

![Diagram of photosynthesis and cellular respiration processes]
1. Fill in the blanks to show an overview of photosynthesis.

2. Add to your diagram to show cellular respiration and how cellular respiration is related to photosynthesis.

3. Add to your diagram to show how ATP provides energy for the processes of life. Show how this reaction is related to cellular respiration.

4. Add a caption to describe how plants use the processes shown to provide energy in the form needed for many of the activities of life.

5. Sometimes the rate of photosynthesis exceeds the rate of cellular respiration, so some of the glucose molecules produced by photosynthesis are not used for cellular respiration. Add to your diagram to show what happens to the glucose molecules that are produced by photosynthesis and are not used for cellular respiration.
Optional Activity (possible substitute for Plant Growth Puzzle in Student Handout)

When photosynthesis produces more glucose than the plant needs, the excess glucose is stored in starch molecules. Starch molecules can be broken down to provide glucose when glucose is needed for cellular respiration.

14a. A plant needs to carry out cellular respiration throughout the day and night in order to produce the ATP which provides energy for the processes of life. In the reversible reaction below, write “night” to label the arrow which shows how the plant gets the glucose needed for cellular respiration at night.

\[ \text{multiple glucose molecules} \xrightarrow{\text{night}} \text{starch molecule} \]

14b. Do you think that leaves have more starch molecules at the end of daylight or at the end of the night? Explain your reasoning.

15a. In the dark, a plant produces more CO₂ than it takes in. Explain why.

15b. In the light, a growing plant takes in more CO₂ than it produces. Explain why. Where do the carbon atoms from the CO₂ go?

Teacher Notes for this Optional Activity

The figure below shows the diurnal fluctuation of starch levels in leaves of coleus. During daylight hours, photosynthesis produces glucose, and some of the glucose is used to produce starch. During the night, starch is broken down to provide the glucose needed for cellular respiration. Therefore, starch levels in leaves tend to be highest at the end of daylight and lowest at the end of the night.

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