The Power of Sunlight:
Investigations in Photosynthesis and Cellular Respiration

Teacher's Guide

Overview

Premise: Many students are familiar with the terms "photosynthesis" and "respiration." Beyond reciting the biochemical reactions, what do students really understand about them? Research has shown that even Harvard graduates are not connecting these processes to plant growth, even though they know the basic facts needed to build the conceptual understanding. It is important that students understand that photosynthesis is the key biochemical process responsible for capturing energy from the Sun and using it to generate biomass, and that cellular respiration uses photosynthetic products to fuel the chemical reactions needed for growth. From this understanding, one can appreciate that photosynthetic organisms occupy the vital roles of producers in ecosystems thereby supporting all life on Earth.

How the *Power of Sunlight* Module Works: This module consists of two thought investigations, two guided laboratory investigations embedded in classroom and online discussions, and an independent investigation. The investigations build upon one another and move from guided to open-ended inquiry. Unlike many classroom investigations, these investigations are not designed to confirm what was taught in lecture. Rather, they are designed to produce results that students do not expect. By "rocking students' boats," the investigations aim to illustrate the importance of unexpected results and to demonstrate they can lead to new models, hypotheses, and experiments. Beyond the lab investigations, three other types of activities are essential to fully benefit from this module:

- **Classroom discussion:** authentic classroom dialogue before, during, or following lab activities
- **ResearchBlogs:** regular online contact between students and scientist mentors and peers
- **Storyboard discussion:** an extended post-lab discussion in which students share and reconcile data within and across teams

We have found that a teacher's commitment to dialogue and a focus on student ideas and reasoning emphasizing the process of science is an important aspect of building an open culture for science learning. Explanations using everyday vocabulary are valued over use of scientific vocabulary in the absence of explanations. A more detailed description of teaching and learning strategies used in the module can be found in the PlantingScience *Teacher's Handbook*.

Grade levels: High school—biology, AP biology, environmental science, AP environmental science, horticulture, botany, and other life science electives.

Class time: Students should be able to complete the thought investigations, the two guided inquiries, and the open investigation over a two- to three-week period. During that time period, there will likely be time that can be used for other aspects of your curriculum. For example, when students are waiting to hear back from their mentors, you can fill that class time with other lessons from your standard curriculum.

Computer access: Optimally, every other class session outside of the open-inquiry period and daily while designing the open inquiry; minimally, at least three times over the course of the full investigation period. Team blogs require logins.

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Planner

Suggested Schedule of Activities: The core of the *Power of Sunlight* module consists of two thought investigations in which students analyze experimental data, two guided inquiries related to photosynthesis and cellular respiration, and an open inquiry in which student teams ask their own research questions and carry out an experiment to answer them. This module also may include a follow-up independent inquiry based on results and new questions that arise from the open inquiry. For example, students may investigate photosynthesis and cellular respiration in aquatic plants but may want to do another investigation to learn about photosynthesis and cellular respiration in seeds before and during germination.

Suggested Assessment Schema: This module is designed so that students can be assessed continuously for changes in understanding. Classroom discussions, teacher interactions with teams during lab investigations, science notebook entries, and blogging online can all serve as embedded formative assessment tools. The post-lab class Storyboard Discussions, a final individual reflection, and the post-experience survey serve as summative assessment tools. If desired, summative assessment in an exam format could involve written responses to questions such as the following:

- What are the relationships between photosynthesis, cellular respiration, and changes in mass in a plant?
- Compare and contrast the biological roles of photosynthesis and cellular respiration in a plant.
- What are the inputs and outputs of photosynthesis and cellular respiration? How are they similar or different?
- What are the main pathways of cellular respiration, and in what sequence do they occur?

Additional Resources: The *Photosynthesis and Respiration Resources* document contains a bibliography of online videos, websites, articles, and books. References are organized by biological process and media type. They may relate directly to the biological process itself, to classroom tools and techniques for teaching about the process, or to education research relating to effective teaching and student misconceptions about the process.

You can expect to complete the *Power of Sunlight* module over the course of 2–3 weeks of class time. During this time, you will intersperse the *Power of Sunlight* activities with your normal classroom curriculum. For example, you may want to allow 2–3 days between when students contact their mentors and when you would begin the next activity in the *Power of Sunlight*. This would enable students to get the benefit of working with their mentor before beginning the next step in the module. If time permits, consider extending the module so that students can either repeat their independent investigations or extend their experience by conducting additional investigations.

Please let your scientist mentor(s) know

- which lessons you will be implementing;
- your expected start and end dates for interacting with students online;
- how frequently your students meet;
- the tentative dates for when students will be communicating with mentors;
- a brief summary of what students should know about photosynthesis, cellular respiration, and scientific inquiry;
- any special experiences or challenges that the students may have with respect to completing these activities;
- a brief description of the laboratory equipment and supplies available to your students; and
- how often students will have computer access.

Students should work in teams of 3 to 4, and individual team members are encouraged to post online. In the *Student's Guide*, the image at right indicates opportunities for Research Blogging. Teams may blog from school or from home.

planting science

GET REACQUAINTED WITH PLANTS

From a Tiny Seed to a Large Tree

Overview
These thought investigations set up discrepant events that will challenge students' thinking about plant growth and the processes that contribute to mass changes in plants. Students will watch videos and analyze data from two scientific experiments. Students will be challenged to compare their current thinking with the findings from these experiments. Students likely will not be able to answer all the questions about the science ideas from these two experiments. They will, however, refer back to these experiments and revise their explanations as they work through the two guided investigations that follow. This activity is likely to reveal one or more common misconceptions related to plants and photosynthesis.

Time Required: Approximately 1 45-minute class period

Learning Goals
- Elicit students' prior knowledge about photosynthesis and cellular respiration
- Reveal misconceptions about plant growth, photosynthesis, and cellar respiration
- Use data analysis to stimulate discussion and challenge student thinking

Common Misconceptions and Student Biases
- Plants and trees get their mass from the soil.
- Plants get their food from the soil.
- Photosynthesis takes place during daylight while cellular respiration takes place during the night.

Getting Ready

Student's Guide **Section and Resources Used in Lesson**

From a Tiny Seed to a Large Tree from the *Power of Sunlight Student's Guide*	1 copy per student
Master 1: Giant Redwood Trees	1 to project (optional)
Master 2: Common Molecules in Trees and Plants	1 to project
Master 3: Recording Predictions for the Radish Experiment	1 to project
Master 4: Results of the Radish Experiment	1 to project
Master 5: Results of the Pea Growth Experiment	1 to project (optional)

Materials and Supplies

Document camera or computer with projector	1 setup per class
Science notebook	1 per student
Radish seeds (approximately 3 g)	1 setup per class

3 petri dishes with lids (approximately 9 cm diameter; or other clear containers with lids)	1 setup per class
Filter paper or paper towel (cut to fit petri dishes)	1 setup per class
Lamp (preferably with CF or LED bulb)	1 setup per class
Lidded box lined with foil	1 setup per class
Index cards (3 distinct colors) (or other system for polling student ideas)	1 set per student
Computer and projector to show videos to class	1 setup per class
Log or piece of firewood	(If you cannot get a log, you can project the photos on *Master 1* that show a large tree.)
Scissors	1 pair per class
Materials for Pea Seed Experiment (optional)	See procedure for Optional Supplemental Investigation under *Preparations.*

Preparations

- Review the student and teacher procedures for the lesson.
- Prepare photocopies as indicated in the table above.
- Gather needed materials.
- (optional) Approximately 4–5 days before starting this lesson, set up the radish seed demonstration:
    a) Label the petri dishes as follows:
        1. With Light; With Water
        2. No Light; With Water
        3. With Light; No Water
    b) Cut pieces of filter paper or paper towel and place into the bottom of each petri dish.
    c) Weigh out 3 batches of 1 gram of radish seeds.
    d) Add 1 gram of radish seeds to each dish. Spread the seeds evenly over the bottom of the dish.
    e) Add water to Dish 1 and Dish 2.
    f) Place Dish 1 and Dish 3 under a light source that can be kept on for the course of the investigation.
    g) Place Dish 2 in a foil-lined box to keep it in the dark.
    h) Check Dish 1 and Dish 2 every couple of days and add water if needed.

Note to Teachers: Although it may seem reasonable to have students conduct the radish activity themselves as a hands-on investigation, we recommend setting up and growing the seeds as an optional demonstration so students can better visualize what the seeds and seedlings look like. However, use the data provided on *Master 4: Results of the Radish Experiment* for analysis. Pictures of the seeds and seedlings are included in the student procedural pages. The rationale for this approach are twofold:

1) The changes in mass can be small and difficult to measure accurately without a high quality balance.
2) The main purpose of these two thought investigations is to engage students with discrepant events that challenge their thinking. Students will come back to these experiments during the course of the module to build and refine their explanations. Having students do the activity themselves may distract from this main focus and shift their thinking more to experimental design. (Students will be engaging in experimental design during the remaining lessons in the module.)

Optional Supplemental Investigation
The radish seed experiment is convenient because the seedlings do not take up much space and the seeds grow rapidly. A more striking visual difference can be seen by using pea plants and the following procedure. *Even if you use the pea plants as a demonstration, you should still use the radish experiment with the class because it includes the needed mass measurements.* If desired, students can start the pea experiment after finishing this lesson and let it continue as they move forward with other lessons in the module.

a) Label 3 8-oz cups as follows:
    1. With Light; With Water
    2. No Light; With Water
    3. With Light; No Water
b) Fill each cup with vermiculite to a level about 3 cm from the top
c) Weigh out 3 batches of 1 gram of pea seeds.
d) Plant 1 batch of pea seeds in each cup.
e) Add water to Cup 1 and Cup 2.
f) Place Cup 1 and Cup 3 under a light source that can be kept on for the course of the investigation.
g) Place Cup 3 in a foil-lined box to keep it dark.
h) Check Cup 1 and Cup 2 every couple of days and add water if needed.
i) After approximately 6 days you should see clear differences among the 3 cups.
j) Take photos of the seeds/seedlings in each cup.


Cup 1


Cup 2


Cup 3

Procedure

Note to Teachers: The procedures that follow provide a framework for using this lesson in the classroom. However, you should feel free to modify it based on your students' prior experiences, knowledge, and abilities. The step numbers listed in these procedural steps match those in the student pages.

Part 1: The von Helmont Experiment

1. **Hold up the log or piece of firewood and remind students that this log is part of a larger tree that grew from a small seed. Write the focus question for the lesson, "Where does the mass of a plant come from?" on the board or chart paper.**

   Holding up a log or piece of firewood can help make the question real for students. If you do not have access to a log, you can project pictures of a giant redwood tree and the small seed that it grew from (on *Master 1: Giant Redwood Trees*). Giant redwoods are the largest trees in the world. Many Sierra redwoods are between 250 and 300 feet tall, but they can grow up to 325 feet tall. The diameter of these trees can be over 30 feet near the ground and they can weigh over 4,000 tons. Can you believe that each tree started from a seed so small that it would take over 100,000 seeds to weigh 1 pound?

2. **Ask students to answer in their science notebooks the following questions:**
   - **2a. Where do you think the mass of a tree comes from?**
   - **2b. Why do you think this? Have you seen or experienced something that makes you think this?**

   Allow approximately 5 minutes for students to write their answers.

   Explain to the class that it is OK if they do not know the correct answers. Encourage students to write down their best ideas and explain that they will have opportunities to revise their answers later.

   The purpose of these questions is to elicit students' current ideas about plant growth. Student responses will vary. Many students may say that the mass must come from the soil because that is the only option that seems to make sense. At this point, accept all correct responses.

3. **In this step, students read a short paragraph describing an experiment carried out during the seventeenth century by a Belgian scientist named von Helmont. The experiment was designed to test the idea that plants get their mass from the soil.**

   Depending on your situation, you can choose to have students read the paragraph independently or ask for a volunteer to read the paragraph aloud while others follow along.

4. **Before learning the results of the experiment, students are asked to answer questions that will reflect their current thinking.**

    4a. **If trees *do* get their mass from the soil, would the soil weigh more, less, or the same at the end of the five-year experiment? Record your prediction and explain your answer.**

    4b. **If trees *do not* get their mass from the soil, would the soil weigh more, less, or the same at the end of the five-year experiment? Record your prediction and explain your answer.**

    These questions are designed to help students think through the experiment and what it can tell them before seeing the results.

5. **Show the video that summarizes von Helmont's experiment.**

    Students aren't expected to remember everything in the video. The experimental results are included in the student pages.

6. **Allow time for students to answer the following questions in their science notebooks.**

    "Based on the results of von Helmont's experiment, does the mass of plants come from the soil around them? Why or why not?"

    Sample answers to the questions that students answer about the von Helmont experiment can be found on the answer key that follows the masters for this lesson (page 13).

7. **Have students look back to the answer they wrote to the question in Step 2a. Encourage them to revise and add to their answer.**

    By using a different colored pen or pencil to make their revisions, students can easily compare their previous ideas to what they think now informed by the data from the von Helmont experiment.

Part 2: The Radish Experiment

8. **Confirm for students that, based on von Helmont's experiment, the vast majority of a tree must not come from the soil. Remind students of the focus question for the lesson: Where does the mass of a plant come from? Explain that the focus question remains, but at this point, it may be helpful to think about what the mass of a tree actually consists of.**

    Project *Master 2: Common Molecules in Trees and Plants*. Explain that these are some of the most common molecules that make up trees and other plants. Point out

the different atoms that are represented by different colors. Ask students to make observations about the types of atoms that they see most frequently.

The main thing that students should notice is that the most common atoms in each of the different molecules are carbon, hydrogen, and oxygen. Students will see that there are a small number of other atoms, but carbon, hydrogen, and oxygen are predominant. Students should see that carbon is a major component in the molecules that make up a plant. Since water consists of hydrogen and oxygen, the plant must get its carbon elsewhere. As we learned from the von Helmont experiment, the carbon could not have come from the soil, so this leaves open the question about the carbon source.

If your students have had chemistry previously, they will likely see this pattern more readily. If your students have not had chemistry previously, these diagrams may be less familiar to them. Explain that they should just focus on looking at the type of atoms that are most frequent in these diagrams.

9. **Explain that you will continue your investigation of plant growth and mass by analyzing data from a second experiment. Show the video of the radish seed experiment to the class.**

The video helps students understand how the experiment was conducted. As before, students are not expected to remember everything from the video. The student pages include a summary of experimental design.

10. **Allow time for students to answer the question, "Why did the scientist dry the seeds and seedlings before measuring their mass?" in their science notebooks.**

Drying the seeds and seedlings is important so that scientists can compare the dry masses from each dish. Plants are continually taking in and releasing water. If the drying step was omitted, the amount of water would vary among the dishes, making accurate comparisons impossible.

11. **At this point, students are asked to make predictions about what will happen to the mass in each dish following 2 weeks of growth. They also should write down in their science notebooks the reason why they think the mass will increase, decrease, or stay the same.**

To give you an overall impression of what the students are thinking, conduct a quick poll. For each of the 3 dishes, ask students to use a colored index card to indicate how they think the mass will change after 2 weeks.

- Green card = the mass will increase
- Red card = the mass will decrease
- Yellow card = the mass will stay the same

Project *Master 3: Recording Predictions for the Radish Experiment* and record the results of the student poll. Note, if you are not able to write the results of the poll into the table on *Master 3*, then you can reproduce the table on a piece of chart paper or the whiteboard and record the student responses there.

12. **Project *Master 4: Results of the Radish Experiment*. Instruct students to record the data in their science notebooks and calculate the change in mass for the seeds/seedlings in each dish.**

13. **Allow time for students to think about how to explain the changes in mass that occur in each of the dishes. Encourage them to discuss their ideas with a partner before writing their ideas in their notebooks. After students have a chance to think about how they might explain the results, hold a class discussion to capture the ideas that students have.**

    Students may or may not have ideas to explain how the mass changes in the different dishes. It is likely that students may propose photosynthesis to explain the results in Dish 1, even if they are not sure how it might work to cause an increase in mass. Students are less likely to have ideas about what is happening to explain the results of Dish 2 and Dish 3. At this point, accept reasonable answers but do NOT reveal whether students' ideas are correct or incorrect. Students will have the opportunity to revisit these data at later points during the module.

    It may be helpful to write student responses about each dish on a piece of chart paper that you can save and refer back to in later lessons. In this way, when students have more information, they can revisit their previous ideas and see how their thinking has changed.

14. **In this step, students should work with a partner to discuss each of the 3 statements about Dish 1. They should decide whether each statement is reasonable or unreasonable based on what they have learned from the radish experiment. They also can indicate that they are not sure. They should write 1–2 sentences explaining each decision.**

    Sample responses to the questions about the radish seed experiment are included in the answer key at the end of this lesson. This key is included here for your information as the teacher. Do NOT go over the answers to the questions at this time. Students will learn more information in later lessons that they can use to refine their answers.

15. **As before, students should work with a partner to discuss each of the 3 statements. They should decide whether each statement is reasonable or unreasonable based on what they have learned from the radish experiment. They also can indicate that they are not sure. They should write 1–2 sentences explaining each decision.**

16. **As before, students should work with a partner to discuss each of the 3 statements. They should decide whether each statement is reasonable or unreasonable based on what they have learned from the radish experiment. They also can indicate that they are not sure. They should write 1–2 sentences explaining each decision.**

Part 3: Communicating with Your Mentor

17. Allow time for students to communicate with their scientist mentor online. If not already acquainted with the mentor, students should introduce themselves and their teammates and ask some general questions. If they have already sent their mentor a message, ask them to check to see if they have heard back from their mentors.

Additional Resources

You may wish to review the following websites for additional information related to this lesson. These sites are intended primarily for your use as a teacher.

- *Photosynthesis: Blinded by the Light* (produced by the Smithsonian Science Education Center), https://www.youtube.com/watch?v=PL9CRhRsy5A.

  This video presents common ideas about photosynthesis and discusses why they are misconceptions. Although this would not be appropriate to present to students at this point, it might be a helpful resource for you as the teacher to remind you of common misconceptions.

- *Lessons from Thin Air* (part of the *Minds of Our Own* series produced by the Harvard-Smithsonian Center for Astrophysics), https://www.learner.org/resources/series26.html#.

  This video includes brief interviews asking college graduates where plants (trees) get their mass (video time code 4:24–5:20). The answers from the college graduates reflect how common misconceptions are about this phenomenon. It might be interesting for students to see that this question is one that stumps many people—even those who you might expect would know the answer. (The video overall is focused on the challenges of teaching so students truly understand complex science ideas and would not be appropriate for students.)

Master 1

Giant Redwood Trees

The seed of a giant redwood tree

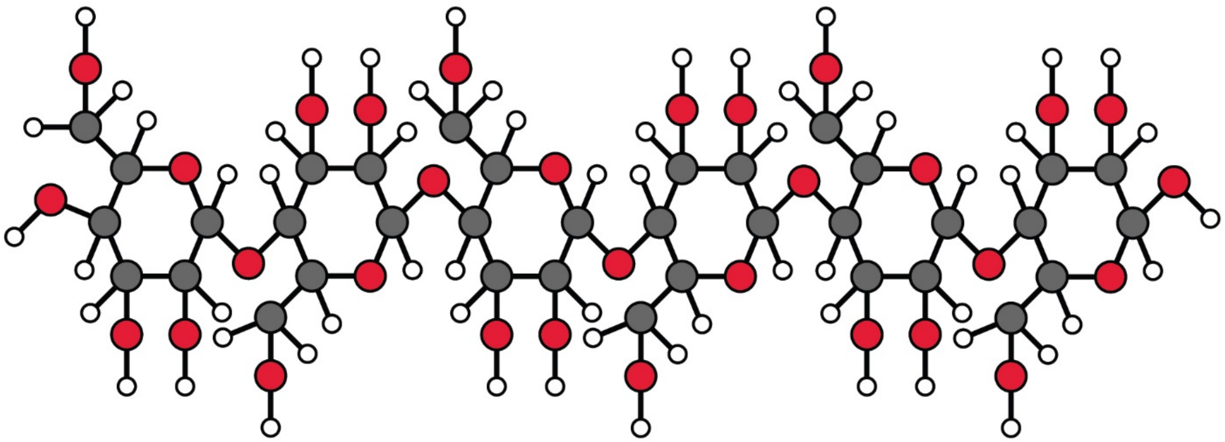
Linda & Dr. Dick Buscher

A giant redwood tree

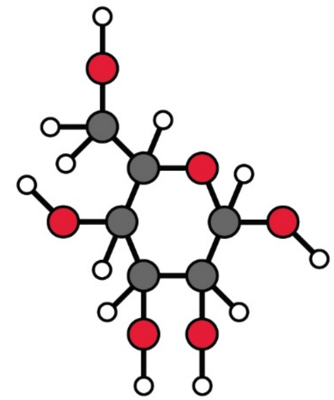
Master 2

Common Molecules in Trees and Plants

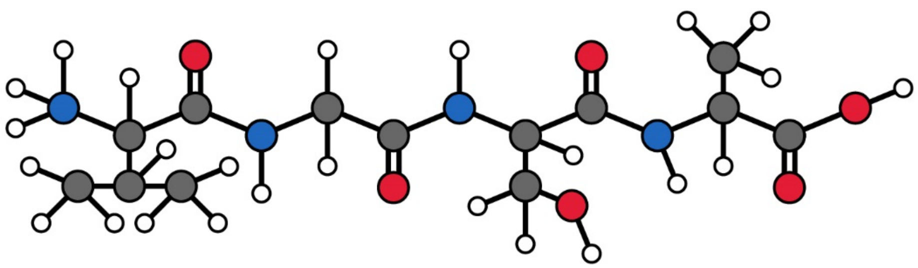
Cellulose



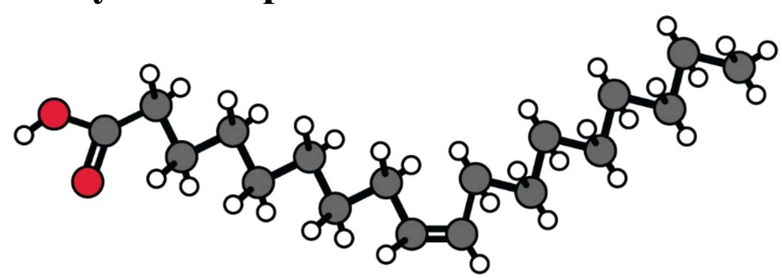
Glucose



Protein



Fatty Acid/Lipid



Key:

- Carbon
- Hydrogen
- Oxygen
- Nitrogen

Master 3

Recording Predictions for the Radish Experiment

Treatments	Dish 1	Dish 2	Dish 3
	Radish seeds: 1.0 g Light: Yes Water: Yes	Radish seeds: 1.0 g Light: No Water: Yes	Radish seeds: 1.0 g Light: Yes Water: No
Predictions about how the mass will change (change in mass = mass of seeds/seedlings after being dried – initial mass)	**Increase**	**Increase**	**Increase**
	Decrease	**Decrease**	**Decrease**
	Stay the same	**Stay the same**	**Stay the same**

Master 4

Results of the Radish Experiment

Treatments	Dish 1	Dish 2	Dish 3
	Radish seeds: 1.0 g (at beginning of experiment) Light: Yes Water: Yes	Radish seeds: 1.0 g (at beginning of experiment) Light: No Water: Yes	Radish seeds: 1.0 g (at beginning of experiment) Light: Yes Water: No
Initial mass of seeds ($M_{initial}$)	1.00 g	1.00 g	1.00 g
Mass of seeds or seedlings after being dried (M_{final})	1.20 g	0.77 g	0.98 g
Change in mass ($M = M_{final} – M_{initial}$)			

Master 5

Results of the Pea Growth Experiment

Cup 1

Cup 2

Cup 3

Cup 1: Almost all seeds germinated (sprouted); seedlings; green leaves

Cup 2: Almost all seeds germinated; longer seedlings; pale yellow leaves

Cup 3: None of the seeds germinated

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Answer Key to Questions about Thought Experiments (von Helmont and Radish Seeds)

Part 1: The von Helmont Experiment

2a. Where do you think the mass of a tree comes from?

Student answers will vary, but a common idea is that trees (and other plants) grow in mass because they take it from nutrients in the soil. As students learn more about photosynthesis, they will learn that almost all of the mass comes from carbon dioxide taken in from the air and used to make glucose during the dark reactions of photosynthesis.

2b. Why do you think this? Have you seen or experienced something that makes you think this?

Students may struggle with the idea that the mass of a tree comes mostly from a gas in the air. Some students may forget that gases have mass. The idea that trees get their mass from soil also may stem from seeing boxes of plant "food" or fertilizer. Although plant food or fertilizer may provide nutrients that plants need, they do not provide a source of energy. The use of the word "food" can be problematic when discussing plants and photosynthesis.

Since plants are largely made of carbon-containing molecules, H_2O cannot be the source of this mass. Some students may argue that plants also contain other elements besides C, H, and O. For example, phosphorus and nitrogen are used to make DNA, and sulfur and nitrogen are used to make proteins. These elements are taken in by the plant from the soil.

4a. If trees *do* get their mass from the soil, would the soil weigh more, less, or the same at the end of the five-year experiment? Record your prediction and explain your answer.

If the trees do get their mass from the soil, you would expect the soil to weigh less at the end of the experiment because the mass moved from the soil into the tree. (And you might expect to see a big hole where the soil used to be.)

4b. If trees *do not* get their mass from the soil, would the soil weigh more, less, or the same at the end of the five-year experiment? Record your prediction and explain your answer.

If the trees do not get their mass from the soil, you would expect the soil to weigh the same amount at the end of the experiment.

6. Based on the results of von Helmont's experiment, does the mass of plants come from the soil around them? Why or why not?

Based on von Helmont's experiment, the mass of plants does not come from the soil. The mass of the soil changed very little during the course of the experiment. This suggests that almost all of the dry mass of the tree or plant comes from something other than soil.

7. Look back to your answer to the question in Step 2a. Do the results from von Helmont's experiment support your answer or suggest that you should revise your answer?

Answers will vary depending on how students answered the question in Step 2a.

Part 2: The Radish Experiment

These answers are provided for your convenience, but it may be beneficial to wait until after the second guided inquiry to have students revisit their answers and think about this experiment again. At that time, they should have additional information that will cause them to think differently about the results of this experiment.

10. Why did the scientist dry the seeds and seedlings before measuring their mass?

The seeds and seedlings in the 3 dishes will contain different amounts of water. To compare the amount of plant matter among the 3 dishes, it is important to remove the water from the plants.

12. Draw a table similar to the one below in your science notebook. Your teacher will display data about the mass of the seeds or seedlings after they were dried. Record these data in your table. Calculate the change in mass of the seeds or seedlings for each treatment.

Results of the Radish Experiment

Treatments	Dish 1	Dish 2	Dish 3
	Radish seeds: 1.0 g (at beginning of experiment) Light: Yes Water: Yes	**Radish seeds: 1.0 g (at beginning of experiment) Light: No Water: Yes**	**Radish seeds: 1.0 g (at beginning of experiment) Light: Yes Water: No**
Initial mass of seeds ($M_{initial}$)	**1.00 g**	**1.00 g**	**1.00 g**
Mass of seeds or seedlings after being dried (M_{final})	**1.20 g**	**0.77 g**	**0.98 g**
Change in mass ($M = M_{final} - M_{initial}$)	0.20 g	-0.23 g	-0.02 g

13. Think about how you might explain the changes in mass for each of the different treatments. If you like, discuss your ideas with a partner. Record explanations for each dish in your science notebook. Don't worry if you are not sure that an explanation is correct. You will have a chance to revisit your explanations later.

	Dish 1	Dish 2	Dish 3
Treatments	**Radish seeds Light: Yes Water: Yes**	**Radish seeds Light: No Water: Yes**	**Radish seeds Light: Yes Water: No**
How might you explain the results from the experiment?	The seedlings increased in mass compared to the seeds. The ultimate explanation for this observation is that the plants took in CO_2 from the air which was used to make new organic molecules (biomass).	These seedlings lost mass compared to the seeds. In the absence of light, the plants only performed cellular respiration, not photosynthesis. In respiration, CO_2 is released, which caused the decrease in mass.	Most seeds need water to germinate. Because there was no water in this treatment, the plants did not perform photosynthesis or respiration at an appreciable rate. The very small mass decrease observed may represent measurement error.

14. Consider the dish with seedlings that INCREASED in mass. Decide if each statement is reasonable or not reasonable. For each statement, write down 1 or 2 sentences describing why you made your decision.

14a. The increase in mass was mostly due to the water the seedlings were given.
   i. reasonable
   ii. not reasonable
   iii. not sure

ii. The plants in this experiment were dried before their mass was taken, so the increase was not simply due to water taken in. Additionally, the seeds placed in water without light did not gain in mass. It is true that some of the mass from the plants in the light with access to water comes from atoms that were originally a part of water molecules, but most of the mass gain comes from incorporating CO_2 from the air.

14b. The increase in mass was mostly due to molecules in the air that the seedlings took in.
   i. reasonable
   ii. not reasonable
   iii. not sure

i. CO_2 in the air is incorporated into organic molecules during the dark reactions of photosynthesis.

14c. The increase in mass occurred because light itself has mass. The seedlings used the mass in light to become heavier.
   i. reasonable
   ii. not reasonable
   iii. not sure

ii. This is a confusion between matter and energy. Plants use CO_2 to gain mass. Light provides the energy to drive the process.

15. Consider the dish with seedlings that DECREASED in mass. Decide if each statement is reasonable or not reasonable. For each statement, write down 1 or 2 sentences describing why you made your decision.

15a. The decrease in mass was mostly due to losing water when the seedlings were dried.
  i. reasonable
  ii. not reasonable
  iii. not sure

ii. Water was removed from all of the seeds/seedlings and does not account for the mass change observed. The seedlings that decreased in mass were undergoing cellular respiration but not photosynthesis. The decrease in mass is largely attributed to CO_2 being released into the air.

15b. The decrease in mass was mostly due to the seedlings breaking down molecules stored in the seed into gas and releasing it into the air.
  i. reasonable
  ii. not reasonable
  iii. not sure

i. The seedlings that decreased in mass were undergoing cellular respiration but not photosynthesis. During cellular respiration, carbohydrates such as glucose are broken down and CO_2 is released into the air as a byproduct.

15c. The decrease in mass was mostly due to the lack of mass from light. Seedlings use the mass in light to become heavier.
  i. reasonable
  ii. not reasonable
  iii. not sure

ii. This is a confusion between matter and energy. Plants use CO_2 to gain mass. Light provides the energy to drive the process.

16. Consider the dish with seeds that STAYED ABOUT THE SAME in mass. Decide if each statement is reasonable or not reasonable. For each statement, write down 1 or 2 sentences describing why you made your decision.

16a. The lack of change in mass was due to the absence of water because water is needed for the seeds to germinate and begin growing.
  i. reasonable
  ii. not reasonable
  iii. not sure

i. Radish seeds do require water to germinate. Since water was lacking, germination did not occur. Since neither process (photosynthesis or cellular respiration) were active, no mass changes would be expected to be observed.

16b. The lack of change in mass was due to an equal balance of the seeds taking in molecules from the air and losing molecules to the air.

i. reasonable
ii. not reasonable
iii. not sure

ii. Since water was lacking, germination did not occur. The seeds remained metabolically inactive. This means that it was the absence of cellular activity rather than a balance of cellular processes that is responsible for the lack of a change in mass.

16c. The lack of change in mass was due to the light damaging the seeds so they could not germinate.

i. reasonable
ii. not reasonable
iii. not sure

ii. Light is not a requirement for radish seeds to germinate. However, light does not damage the seeds or prevent them from germinating. The reason for the seeds not germinating was the lack of water.

Investigating Photosynthesis Using a Leaf Disk Floatation Method

Overview
In this lesson, students explore photosynthesis using a spinach leaf disk floatation method. Students investigate the research question, "How does carbon dioxide affect photosynthesis?" By comparing leaf disks submerged in water, bicarbonate solution, and water with carbon dioxide blown into it, students learn that carbon dioxide is an input necessary for photosynthesis. The teacher's role is to help students use evidence and sound reasoning to construct explanations, while also laying groundwork for recognizing the importance of experimental design.

Time Required: Approximately 3 45-minute class periods

- **Day 1:** Opening discussion, demonstration, and beginning of the guided inquiry to gain experience with the method [Students can complete Steps 1–4, 9, and 10 (practicing infiltration). See the Note to Teachers following Step 4.]
- **Day 2:** Complete the guided inquiry to collect and analyze data (Steps 5–19).
- **Day 3:** Class discussion and storyboard development (Steps 20–21).

Learning Goals

- Understand the use of leaf disks as a model for leaves
- Use the leaf disk flotation method as an indirect measure of photosynthesis
- Link the leaf disk method to a conceptual model for photosynthesis
- Discuss how an experimental design relates to a research question
- Identify and explain unexpected data

Common Misconceptions and Student Biases

- Plants produce oxygen for use by animals.
- Only green plants carry out photosynthesis.

Students may try to "adjust" data to meet expectations (i.e., their conceptual models for growth). If assessments stress explanations over "right answers," students may be more honest.

Getting Ready

***Student's Guide* Section and Resources Used in Lesson**

Investigating Photosynthesis Using a Leaf Disk Floatation Method from the *Power of Sunlight Student's Guide*	1 copy per student
Reference 1: Plant Structure and Photosynthesis	1 copy per student
Reference 2: Photosynthesis	1 copy per student
Master 6: Storyboard Discussion	1 for teacher
Master 7: Why Does Carbon Dioxide Dissolve in Water While Oxygen Does Not?	1 copy per student (optional)

Materials and Supplies

Piece of cardboard (approximately 20 inches square; size can vary)	1 for class demo
Balloons	Approximately 15 green and 7 white
Transparent tape or masking tape	1 roll for class demo
Science notebook	1 per student
Safety goggles	1 per student
Clear, wide-mouth plastic cups	3 per team*
Plastic straw	1 per team
Baby spinach leaves	2–4 leaves per team
Baking soda solution (0.2%)	See *Preparation*.
Liquid dish or hand soap (diluted)	50 mL per class
Dropper bottles (for dilute soap solution)	1 per team
Distilled water (room temperature)	Approximately 1 gallon per class
Single-hole paper punch (or plastic straw, No. 3 cork borer, or scissors)	1 per team
Small pieces of paper (approximately 2” square or index cards (3 × 5 inch)	3 per team
Small paint brush	1 per team
10-mL or larger disposable syringes, without needles	3 per team
Permanent marker	1 per team
Light source (40 W or more)	1 per team (this could be a light bank with adjustable shelves or height used by the whole class)
Ruler	1 per team
Hand lens	1 per team
Stopwatch, timer, watch, or clock with a second hand	1 per team
Projector to show videos to class	1 per class

*Students should work in teams of 3–4 for this investigation.

Preparations

Review the student and teacher procedures for the lesson and view the supplemental leaf disc floatation assay video: https://vimeo.com/293030333.

Prepare demonstration.

- Blow up balloons.
- Tape balloons to cardboard. Intersperse the white balloons among the green ones.

Prepare dilute soap solution.

- Add approximately 1 mL of dishwashing liquid soap in 50 mL of water. Do this ahead of time so the soap fully dissolves into the water without making suds.
- Divide the solution equally into small containers (preferably dropper bottles) so that each team has a bottle.

Prepare 0.2% baking soda solution.

- Dissolve 2 g baking soda into 1,000 mL of distilled water.
- The amount of baking soda solution that you will need depends on the number of teams and the type of cups that you provide for the investigation. The procedure asks students to pour solution into their cup to a depth of 2 cm. During testing, 2 cm depth was equivalent to approximately 60 mL of solution.
- Alternatively, students can add distilled water to their cup and add a pinch of baking soda.

Prepare spinach leaves.

- Spinach is the recommended plant material for the leaf disk floatation assay. Buy spinach from the grocery store (or a farmer's market) just before your classes begin the activity so they are fresh. Some teachers report getting better results if they place the spinach leaves under a bright light overnight or for a few hours before students begin the activity. You may also want to dampen the spinach leaves so they do not dry out.

Procedure

Note to Teachers: The procedure that follows provides a framework for using this lesson in the classroom. However, you should feel free to modify it based on your students' prior experiences, knowledge, and abilities. The step numbers listed in these procedural steps match those in the student pages.

1. **Open the lesson by conducting a class discussion. Ask students to recall what happened with the radish seeds, especially those that were grown in the presence of both light and water. What explanations did students provide during the previous thought activity to explain how these seedlings increased in mass?**

   Although students may have been unsure about the processes involved, some students are likely to have suggested that photosynthesis is involved in the increase in mass.

2. **Explain that they will be conducting an investigation to learn more about photosynthesis. Allow approximately 5 minutes for students to write a few sentences in their notebooks summarizing what they currently know—or think they know—about photosynthesis.**

   Encourage students to write down their ideas even if they are unsure whether they are correct. Inform students that they will be able to revise their statements later.

3. **Explain that you will be using small disks cut from spinach leaves for the investigation. Before starting, it is first necessary to understand a little about basic leaf structure. Instruct students to pay attention as you conduct a brief demonstration.**

   Conduct the demonstration as follows:

- Display to the class the cardboard that has the balloons attached to it.
- Explain that this is a model for a piece of a leaf.
- State that the green balloons represent cells that are inside of the leaf and that the white balloons represent spaces between the cells in the leaf filled with air.
- Ask students what would happen if you put the leaf under a vacuum. (*Students should respond that the vacuum would pull air out.*)
- Ask a volunteer to come up and demonstrate what would happen in the model if the air was pulled out of the "leaf." (*Student should pull the white balloons off of the board.*)
- Ask, "If the leaf is in water, what would happen after you released the vacuum?" (*If the leaf is in water, when the vacuum is released, water would flow into the leaf spaces where the air used to be.*)

This demonstration will help students visualize the spaces between cells inside the leaf and appreciate the importance of the infiltration process, whereby air is drawn out of leaf disks using a syringe and replaced with carbon dioxide in liquid form (dissolved baking soda) or water.

The reading, *Reference 1: Plant Structure and Photosynthesis*, provides some additional information about the structure of leaves to give students more background information.

4. Have students write the research question, "How does carbon dioxide affect photosynthesis?" in their science notebooks. Explain that the investigation they are about to carry out will help answer this question.

Note to Teachers: If time permits, it would be helpful if students have the opportunity to practice preparing and infiltrating leaf disks before conducting their actual investigation. To do this, skip to Steps 9 and 10. Students can use tap water for their practice. When ready to do the actual investigation, students will carry out Steps 5–8 and then continue with Steps 9–10 and the remainder of the investigation.

5–8. Students should work in teams of 3–4 for this investigation. During these steps, students prepare their 3 different experimental solutions.

These steps should be fairly straightforward for students. However, if your students do not have much experience following a procedure, you may want to go over the steps one by one to make sure they understand what they are supposed to do.

9. Students cut out their leaf disks.

Advise students to prepare extra leaf disks. (The procedure says to make 36–40 leaf disks. Students should use 10–12 disks for each of the 3 treatments conditions.) Having extra leaf disks will ensure that they have enough in case some disks get damaged or do not infiltrate as expected.

10. **In this step, students infiltrate 1 set of leaf disks with an experimental solution consisting of water that a student has exhaled into for 60 seconds. It will be helpful if you demonstrate the method while students watch and follow along with their procedure.**

The syringes pull air out of the intercellular spaces within the leaf disks. When the vacuum is released, the air that occupied those spaces is replaced with either water or bicarbonate solution. Because the air is replaced with liquid, the disks will lose buoyancy and sink to the bottom of a cup rather than float.

11–15. **In these steps, students complete the infiltration process for the other 2 experimental conditions and prepare for their experiment.**

16–19. **Allow approximately 45 minutes for students to conduct their investigation (including up to 25 minutes for data collection).**

As the experiment proceeds, students should see leaf disks in the breath cup and the baking soda cup begin to float. On average, the leaf disks will start to float within 10 minutes of beginning the investigation, and all the disks will probably float within about 20–25 minutes.

Troubleshooting

If leaf disks do not float, the problem is likely due either to a concentration of carbon dioxide (baking soda or breath) that is too low or to damaged or otherwise unhealthy leaf tissue. If leaf disks adhere to the bottom of a cup, they can be released by gentle tapping.

If leaf disks do not sink, air bubbles may be trapped on the surface of the leaf disks or infiltration may be incomplete. Small amounts of liquid soap may help reduce surface tension and enhance the infiltration process.

In this leaf disk floatation assay, the leaves that are in a solution containing carbon dioxide (the **breath** cup and the **baking soda** cup) will float because photosynthesis takes place and produces oxygen bubbles. The leaf disks in plain water do not have a source of carbon dioxide and cannot carry out photosynthesis, so the leaf disks remain submerged.

Students may observe bubbles forming around the edges of the leaf disks in the **breath** cup and the **baking soda** cup. Some students may surmise these bubbles to be oxygen, whereas other students may be confused as to their identity. Although students cannot be sure what gas the bubbles contain, they may use the photosynthesis reaction to guess that these are oxygen because according to the reaction, oxygen is an output of photosynthesis.

The issue of the bubbles' composition can be confusing. It is important to remember that carbon dioxide readily dissolves in water—so you do not see bubbles containing carbon dioxide. In fact, carbon dioxide is about 40 times more soluble in water than is oxygen. You see bubbles of oxygen because the oxygen is not very soluble in water. Because oxygen gas is less dense than water, the oxygen bubbles produced by photosynthesis cause the leaf disks to float.

If you feel that your students can benefit from *Master 7: Why Does Carbon Dioxide Dissolve in Water While Oxygen Does Not?*, give each student a copy of this reading. It will give students additional background on the chemistry of carbon dioxide and what happens when it dissolves in water. This reading may be most advantageous if students have previously had chemistry. If you feel that this reading is too advanced for your students, you can simply explain that carbon dioxide molecules are surrounded by water molecules, and the carbon dioxide molecules dissolve into the water. Oxygen molecules, on the other hand, cluster together away from the water molecules, forming bubbles. Carbon dioxide forms hydrogen bonds with water molecules whereas oxygen molecules do not.

20. Have teams work together to discuss and answer the questions in this step. Students should write their own answers in their science notebooks.

Reference 2, *Photosynthesis*, may provide additional information that will help students make sense of their experimental data. Encourage students to create diagrams to help them develop and supplement their explanations. Diagramming can be a good shorthand for students to get their working ideas on paper—scientists often use this approach, too! If students are not used to sketching out their thoughts in pictures, you can model this by drawing pictures as the class develops a working model.

21. Hold a class discussion about the results of the investigation and what they learned about photosynthesis. In addition to using the questions from Step 20, refer to the questions that students considered at the end of the thought investigation lesson.

If desired, you could model the development of a storyboard as a class. Refer to *Master 6: Storyboard Discussion* for information about creating storyboards.

Additional Resources

Additional videos, webpages, books, and articles to support teaching and learning about photosynthesis can be found in the PlantingScience *Photosynthesis and Respiration Resources* document.

Additional Investigation Ideas

Students may want to investigate other plants (including those with different colored leaves) to see if they respond in a similar way to the spinach leaves. Alternatively, they might want to investigate whether photosynthesis occurs in other parts of a plant.

If time permits, students could conduct these experiments, or you might encourage students to write their ideas in their notebook so they can refer back when they do their independent investigations later.

Master 6

Storyboard Discussion

What is the purpose of a storyboard?
Storyboarding consolidates "the evidence" so students can consider how their data fits into their models of photosynthesis and cellular respiration. By **sharing** their stories and allowing other students to **question** their conclusions in light of data, observations, experiments, or every day and school science experiences, students learn to **reconcile** evidence as scientists do. This process is sometimes referred to as **scientific thinking**.

Preparing storyboards
A storyboard consists of the following elements:

- Research question
- How students investigated the question
- How students know the experiment was technically successful (i.e., the method worked)
- Data summaries
- What the data mean
- A model of how respiration and photosynthesis work, including how the data fit the model
- Data from class or other teams' experiments that are or are not consistent with their explanations and model

During this guided inquiry, students may make team storyboards if there is time. Each team can present their "story" to the whole class, then answer questions from the class.

Alternatively, the teacher may diagram the processes described by students as their ideas about photosynthesis and cellular respiration emerge during discussion. As the teacher models how a storyboard is constructed, students can see how to make their own team storyboards after their open-inquiry experiment(s).

Integrating writing and discussion
Students should be encouraged to diagram on paper to develop and supplement their explanations. Diagramming can be a good shorthand for students to get their working ideas on paper—scientists often use this approach, too! If students are not used to sketching out their thoughts in pictures, teachers can model this by drawing pictures as the class develops a working model.

The questions that students answer in their science notebooks during this investigation are only a guide. If students think other information should be recorded or if a drawing or diagram would help, they should be encouraged to add these items.

If poster-sized whiteboards are available for each team, a large erasable working surface can be helpful as students work through their thinking as a team. Their final "story" can then be presented from the whiteboard.

Juicy questions
What is the role of carbon dioxide in photosynthesis?
Teams should be able to use their observations from the guided inquiry to help answer this question.
Why did the procedure ask you to do the leaf disks in distilled water and in water a carbon dioxide source?

<table>
<tr>
<td>The goals of the guided inquiry lab are threefold:
To familiarize students with the leaf disk floatation method
To build student understanding of the role that carbon dioxide plays in photosynthesis
To integrate students’ understanding of photosynthesis with the flotation method
This discussion will therefore center on class data to (a) build conceptual models for photosynthesis and how carbon dioxide is important for photosynthesis and (b) troubleshoot problems with the method, which students will be using again in the next guided inquiry and perhaps in their open-inquiry.</td>
<td>This may be a good time to remind students of the importance of controls when doing a scientific investigation.
What were the bubbles that formed on the edges of the leaves during the floatation assay?
Students may notice small bubbles around the edges of the disks before they start floating. Depending on what students know about photosynthesis, they may guess that these bubbles are oxygen gas—an output of photosynthesis. However, an interesting discussion may arise as to whether you can confirm these bubbles are oxygen just from the leaf disk assay. This assay does not test those bubbles, which might be a limitation of the investigation. As discussed earlier, students may have difficulty understanding that the oxygen formed during photosynthesis results in bubbles around the edges of the leaf disks (and presumably inside the leaf disks as well) but that carbon dioxide dissolves in water and does not form bubbles. This is due to the fact that carbon dioxide is approximately 40 times more soluble in water than is oxygen.

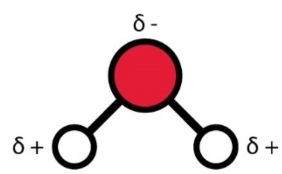
Key questions
What constitutes evidence?
How do the group’s data fit into its own model of photosynthesis?
In what ways is the method limited?
Can the method be improved?</td>
</tr>
<tr>
<td colspan="2">Product
At the end of the discussion, the class should arrive at a consensus model for the role of carbon dioxide in photosynthesis. The class may also speculate on the conditions promoting photosynthesis.</td>
</tr>
</table>

Master 7

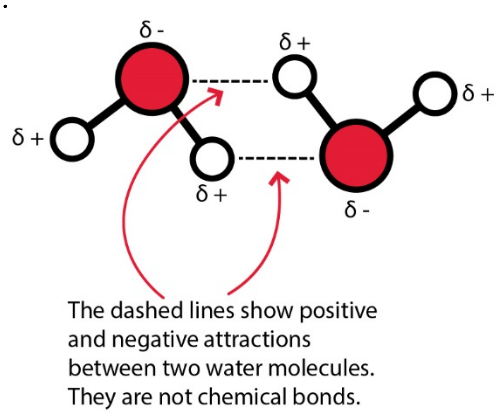
Why Does Carbon Dioxide Dissolve in Water While Oxygen Does Not?

Water

You may know that a water molecule has one atom of oxygen and two atoms of hydrogen. Oxygen and hydrogen share electrons, forming chemical bonds between the atoms. These electrons are not shared equally, however. The oxygen atom attracts the electrons more strongly than the hydrogen atoms do. The electrons spend more time near the oxygen atom than they do near the hydrogen atoms. As a result, the oxygen atom in each water molecule has a slight negative charge, while each hydrogen atom has a slight positive charge. When electrons in a chemical bond share electrons but don't share them equally, we describe the bond as a polar covalent bond. We draw the chemical structure like this:



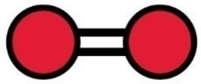
The red circle indicates the oxygen atom, the smaller white circles indicate hydrogen atoms, and δ stands for "partial." Each line represents two electrons that are shared between the atoms. The slight charges on the atoms within the water molecule are attracted to the slight charges on atoms within other water molecules:



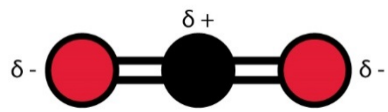
The dashed lines aren't chemical bonds and are *not* showing shared electrons. The dashed lines simply show the positive side of one water molecule being attracted to the negative side of another water molecule.

Oxygen

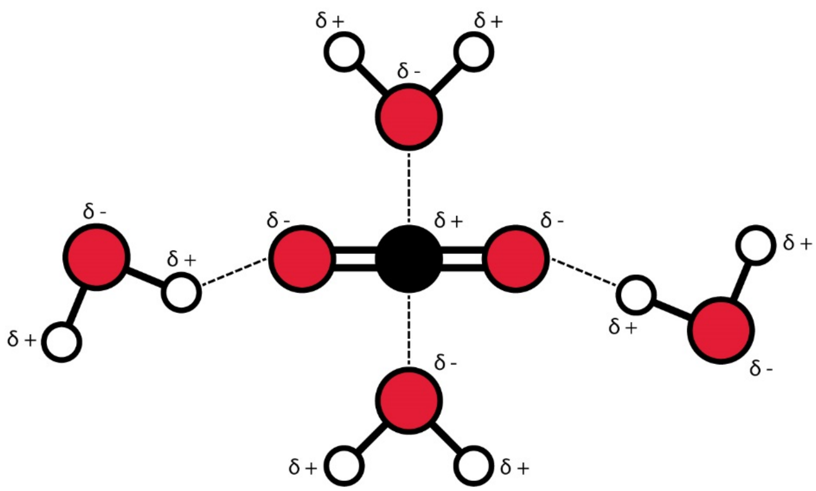
The two atoms in an oxygen molecule also form chemical bonds by sharing electrons. Because the two atoms in this gas are identical, these electrons are shared equally and so the molecule does not have slightly charged areas—the molecule is not polar. When electrons in a covalent bond are shared equally, we describe the bond as a nonpolar covalent bond. The chemical structure is shown as:



Carbon dioxide
In a carbon dioxide molecule, two pairs of electrons are shared between each oxygen atom and the carbon atom. The atoms are linked in chemical bonds. (The black circle below indicates the carbon atom.) As in water, the oxygen atoms attract the electrons the most. The electrons spend more time near the oxygen atoms than they do near the carbon atom. Thus, the oxygen atoms each have a slightly negative charge while the carbon atom has a slightly positive charge:

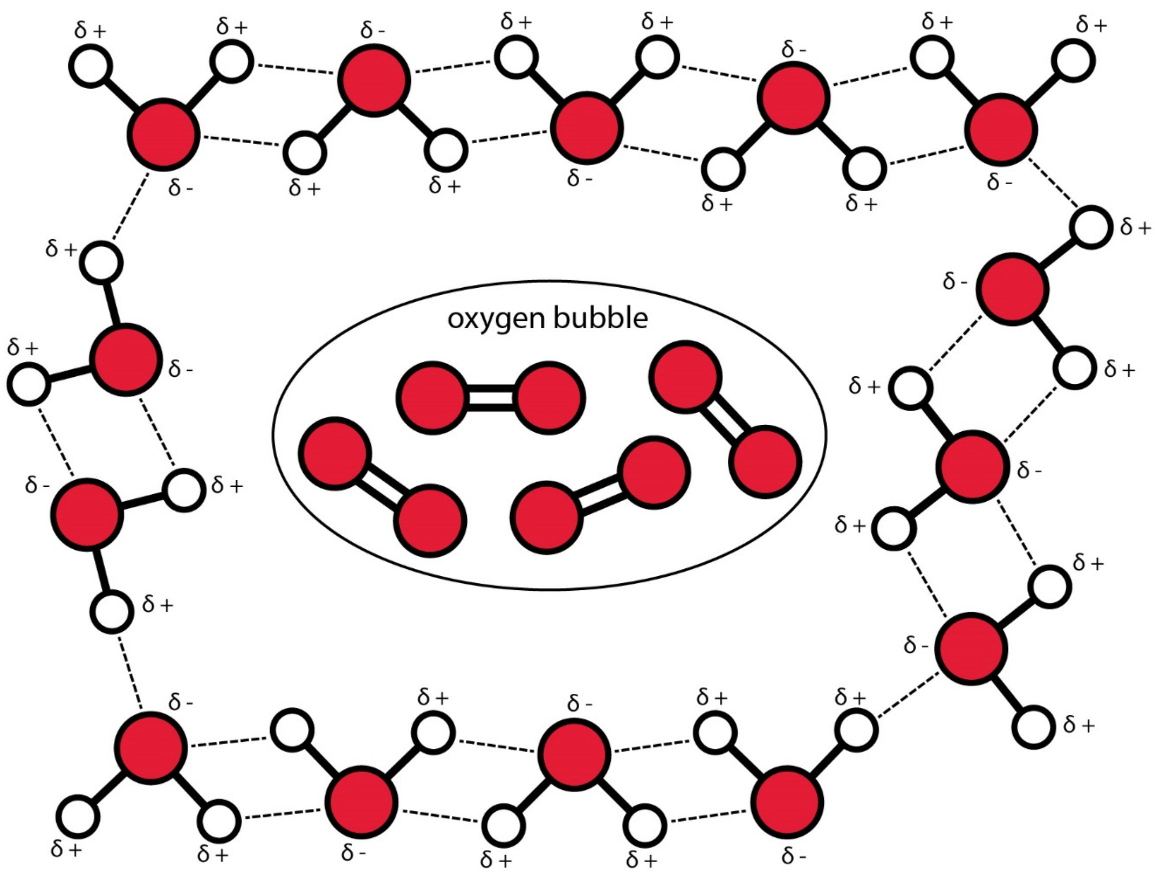


Carbon dioxide and oxygen in water
Because of the slight partial charges on atoms in a carbon dioxide molecule, a carbon dioxide molecule can be attracted to a water molecule:



When carbon dioxide is added to water, each carbon dioxide molecule is completely surrounded by water molecules. Carbon dioxide is still a gas, but the gas has dissolved in the liquid water. Carbon dioxide won't form bubbles in water unless there is a very high concentration of carbon dioxide (as is the case with soda drinks).

Unlike carbon dioxide, oxygen does not have partial charges on its atoms. Therefore, it won't be attracted to water molecules. But water molecules are attracted to other water molecules. The water molecules will tend to stick to each other. Because the water molecules tend to stick to each other, the oxygen molecules won't be surrounded by water molecules as much as carbon dioxide molecules are. Instead, the oxygen molecules will tend to cluster together away from the water molecules. In other words, oxygen doesn't dissolve as well as carbon dioxide does. Of course, oxygen does dissolve in water a little bit—if it didn't, all the fish would die. We won't go into the details of how a completely nonpolar covalent molecule can dissolve in water; the important point is that polar covalent molecules like carbon dioxide dissolve more easily than nonpolar covalent molecules like oxygen.



Answer Key for Student Questions

21a. Use the following chart to describe in your science notebook what you learned from your data.

What evidence from your leaf disk experiment helps you answer your research question? (You can continue on another piece of paper if you want more spaces.)	**Related science ideas** (You may have information from the reference readings or even prior activities that relate to evidence from your experiment.)
Example: Bubbles formed around the edges of the leaf disks in the water with baking soda and in the water that was breathed into.	*Example:* The bubbles caused the leaf disks to float because gas is less dense than water.
Bubbles were not seen in the leaf disks in distilled water.	Oxygen is an output of photosynthesis.
Leaf disks floated in the cups with carbon dioxide (either from baking soda or from breath).	Oxygen is an output of photosynthesis and the gas formed causes the leaf disks to float.
Bubbles do not form when baking soda is added to water but form as the experiment progresses.	Carbon dioxide is much more soluble in water as compared to oxygen.

21b. Write a one sentence answer to your research question.

How does carbon dioxide affect photosynthesis? Carbon dioxide is necessary for photosynthesis to occur.

21c. How did your results compare with your predictions?

Answers will vary depending on the students' predictions.

21d. What did you learn from the demonstration that helped you understand the leaf disk activity?

The hope is that the demonstration helped students realize that inside leaves are air spaces between the leaf cells. When these air spaces are removed under vacuum, surrounding liquid can rush in to fill those spaces. This concept is critical to understanding why the leaf disk method can be used to study photosynthesis.

21e. Were the results of your experiment similar to those of other teams? If not, can you think of reasons to account for the differences?

Answers will vary. If the leaf disk method is working, then most teams will see similar results, though variation in how fast the leaf disks sink will be expected. This variation may be due to the condition of the leaf tissue and/or how effectively the infiltration process was carried out.

21f. Did you notice anything during your experiment that seemed unusual or problematic? Please describe and explain why it was a problem.

Answers will vary. Even when the leaf disk method is carried out properly some students may report that air bubbles were trapped on the surface of leaf disks. Other problems commonly reported include "sticky" leaf disks that adhere to the syringe or cup or leaf disks that refuse to float or sink.

21g. How might you respond if someone asked, "How do you know that your experiment worked from a technical point of view?"

Hint: *Think about your procedure. How are controls important for answering this question?*

Assuming that the leaf disks in the sodium bicarbonate solution did float in response to the light, then the logical reason for this observation is that photosynthesis used carbon dioxide dissolved in the water to produce oxygen bubbles that caused the leaf disks to float. The other two experimental treatments serve as controls that support this claim. The **breath** cup contained water that someone breathed into for 60 seconds. Since we breathe out carbon dioxide, the fact that the leaf disks in this cup floated suggests that carbon dioxide from breath was used to support photosynthesis. The water cup lacked carbon dioxide and therefore would not support photosynthesis. Without the oxygen produced from photosynthesis, the leaf disks in water could not become more buoyant and rise to the surface.

21h. Refer back to the ideas about photosynthesis that you wrote in your science notebook for Step 2. Do your experimental data provide information that either supports or contradicts some of your initial ideas about photosynthesis? Please explain.

Answers will vary depending on the initial ideas expressed by the students.

Guided Inquiry: Investigating Light and Dark

Overview
In this lesson, students conduct two investigations to learn about the effects of light and dark on plants. Students also will be challenged to make decisions about the experimental design that they use for the investigation. After completing their investigations, students revisit the thought experiments from the beginning of the module to see how their ideas have changed and how their new knowledge can help them make sense of the unexpected results of the radish experiment.

Time Required: Approximately 2 or 3 45-minute class periods

- **Day 1:** Opening discussion, experiment planning, review experimental design (Students can complete Steps 1–4.)
- **Day 2:** Complete guided inquiries to collect and analyze data (Part 1, Steps 5–7 and Part 2, Steps 8–13).
- **Day 3:** Class discussion of experimental results and review of radish experiment; storyboard development (Part 2, Step 14 and Part 3)

Learning Goals
During this guided investigation, students will

- use an indicator solution to learn about the effects of light and dark conditions on plants,
- extend their use of the leaf disk floatation method to learn how light and dark conditions affect photosynthesis,
- use the leaf disk floatation method to learn about the process of cellular respiration in leaves,
- link the leaf disk floatation method to a conceptual model for photosynthesis and cellular respiration,
- modify the experimental design for the method to answer a new research question, and
- identify and explain unexpected data.

Common Misconceptions and Student Biases

- Plants photosynthesize and animals use cellular respiration. (Photosynthesis occurs in plants and cellular respiration occurs in animals.)
- Students may try to "adjust" data to meet expectations (i.e., their conceptual models for growth). If assessments weight explanations over "right answers," students may be more honest.

Getting Ready

***Student's Guide* Section and Resources Used in Lesson**

Using the Leaf Disk Floatation Method to Answer New Questions from the *Power of Sunlight Student's Guide*	1 copy per student
Reference 3: Cellular Respiration	1 copy per student
Reference 4: More about Photosynthesis	1 copy per student

planting science

Materials and Supplies

Science notebook	1 per student
Part 1: Another Investigation with Leaf Disks	
Clear, wide-mouth plastic cups	2 per team*
Baby spinach leaves	2–4 leaves per team
0.2% baking soda solution (sodium bicarbonate in water)	See *Preparation*
Liquid dish or hand soap (diluted)	1 small container per team (see *Preparation*)
Distilled water (room temperature)	Approximately 2 L
Single-hole paper punch (or plastic straw, No. 3 cork borer, or scissors)	1 per team
Small pieces of paper (approximately 2” square or 3 × 5” index cards)	2 per team
Small paint brush	1 per team
10-mL or larger disposable syringes, without needles	2 per team
Permanent marker	1 per team
Light source (40 W or more)	1 per team (this could be a light bank with adjustable shelves or height used by the whole class)
Ruler	1 per team
Hand lens	1 per team (optional)
Stopwatch, timer, watch, or clock with a second hand	1 per team
Cardboard boxes or foil to cover cups	1 per team
Index cards (green, red, yellow, and blue) or other system for polling student ideas	1 set per student
Sticky notes	2–5 per team (optional)
Part 2: The Elodea Investigation	
Clear plastic cup	1 per team (see *Preparation*)
Drinking straw	1 per team (see *Preparation*)
Plastic wrap	4 small pieces
Safety goggles	1 pair per student
Large test tubes (or clear plastic cups)	4 per team (see *Preparation*)
Dilute phenol red solution	(see *Preparation*)
Elodea	Each team will need 2 pieces approximately 6-8 cm in length depending on the size of the test tubes
Test tube racks (or beakers to hold the test tubes)	2 per team

Lamps	1 per team
Aluminum foil or cardboard boxes to cover tubes in the “dark” condition	1 per team
Part 3: Revisiting the Radish Seed Experiment	
Index cards (green, red, yellow, and blue) or other system for polling student ideas	1 set per student
Sticky notes	2–5 per team (optional)

*Students should work in teams of 3–4 for this investigation.

Preparations
Review the student and teacher procedures for the lesson.

Part 1: Another Investigation with Leaf Disks

- Prepare dilute soap solution.
  - Add approximately 1 mL of dishwashing liquid soap to 50 mL of water. Do this ahead of time so the soap fully dissolves into the water without making suds.
  - Divide the solution equally into small containers (preferably dropper bottles) so that each team has a bottle.
- Prepare baking soda solution.
  - Dissolve 2 g baking soda into 1,000 mL of distilled water.
  - The amount of baking soda solution that you will need depends on the number of teams and the type of cups that you provide for the investigation. The procedure asks students to pour solution into their cup to a depth of 2 cm. During testing, 2 cm depth was equivalent to approximately 60 mL of solution.
  - Alternatively, students can add distilled water to their cup and add a pinch of baking soda.
- Prepare spinach leaves.
  - Buy spinach from the grocery store (or a farmer’s market) just before your classes begin the activity so they are fresh. Some teachers have recommended placing the spinach leaves under a bright light overnight or for a few hours before students begin the activity. You may also want to slightly dampen the spinach leaves so they do not dry out.

Part 2: The Elodea Investigation

- If appropriate for your students, you can do Step 2 as a demonstration instead of having them do it within their teams.
- The Elodea experiment can be done using clear plastic cups if appropriate test tubes are not available. If using cups, students should place the Elodea in the appropriate cups and then add phenol red solution until the plant is covered (not to the top of the cup).
- Prepare phenol red solution
  - Add 2 mL of 0.04% phenol red stock solution into 400 mL water.

- This should give you a light pink solution. If you blow carbon dioxide into a sample of this dilute solution, it should turn yellow in 15-30 seconds. (Bromthymol blue should also work for this investigation if you are more familiar with that indicator.)
- Poke a small hole into each straw so that students cannot mistakenly suck up and ingest the phenol red solution. The hole should be above the liquid level in the cup.

CAUTION: Students must be careful not to suck up and ingest the phenol red solution.

Students should wear safety goggles or glasses when working with the phenol red solution.

Adjusting Procedure When Time Is Limited

If you have a block schedule, it is likely that students will be able to complete the Part 1 investigation during one class period. If you have shorter class periods (e.g., 45-minute periods), it may be difficult for students to complete this investigation during a class period. An alternate strategy is to have students complete the first part of the investigation (investigating effects of light and dark on leaf disk floatation) during one class period. To complete the next part of the investigation (moving cups from light to dark and dark to light), you could prepare leaf disks in advance [both in light (floating) and in dark (not floating)] that students could use as the starting point for their investigation (starting with Step 8).

Procedure

Note to Teachers: The procedural steps listed in this section align with the procedural steps in the *Student's Guide* for this investigation.

1. **Begin the activity by holding a class discussion. Use questions such as the following to guide the discussion:**
    - **What did you learn about photosynthesis during the previous leaf disk investigation?**
      Students should mention that carbon dioxide is a required input. They also may talk about oxygen being an output of photosynthesis (with the caveat that they could not prove that the bubbles were oxygen, but their experiment and information about photosynthesis from the *Reference 2: Photosynthesis* reading leads them to think that the bubbles are oxygen). They may also suggest that light is required since they did their investigation using a lamp, but they did not fully investigate this.

    - **What was your evidence that photosynthesis was occurring?**
      Leaves in the **breath** cup and the **baking soda** cup floated during the assay.

    - **Do you think that there are other things besides carbon dioxide that are needed for photosynthesis?**

If students do not mention it, you might foreshadow the rest of the investigation by discussing whether they could tell from their last investigation if light is necessary for photosynthesis.

2. **Students should write their research question in their science notebooks. This question will serve as a focus for the investigations in this activity.**

   What effect(s) do light and dark have on plants?

Part 1: Another Investigation with Leaf Disks

3. **In Part 1, students will use the same leaf disk floatation method that they used previously. In this step, students should read through the protocol for Part 1 in preparation for making design decisions about the investigation protocol.**

   At this point, it may be beneficial for students to concentrate on Steps 5–6 of the procedure. Reading the rest of the procedure will let them know what to expect in the full investigation, but for now it may help them focus if they concentrate on these two steps.

4. **Ask volunteers to share ideas about how they could use the leaf disk floatation method to investigate the research question.**

   A straightforward way to use the leaf disk method to investigate the effects of light and dark conditions on leaf disks is to repeat the previous experiment but put 1 cup in the light and 1 cup in the dark. Both cups should contain baking soda solution—since students now know that carbon dioxide is required for photosynthesis.

5–6 **Briefly explain that team members should work together to plan and conduct their investigations.**

The student procedure includes some questions that students should think about as they design their experiment. They may also think of other issues that should be included in their design. Make sure that students record these answers and observations in their science notebooks.

Depending on your students' experience designing experiments, you may want to discuss some of these design considerations as a class before students continue with conducting the investigation. Alternately, you could ask teams to get their design approved by you before continuing.

Important! At the end of the first part of the investigation, make sure students leave their leaf disks set up in their cups (in both light and dark) for use in the next part of the investigation (assuming that students will have time to complete the "dark phase" of the investigation during the class period). If they cannot finish the full investigation during the class period, they will discard their leaf disks. See *Adjusting Procedure When Time Is Limited* for some ideas about how to complete the investigation in shorter class periods.

7. **The part of the investigation conducted in Step 6 can set up thinking about two new questions that students should write in their notebooks:**

"What happens if you put leaf disks that have been in the light in the dark?"
"What happens if you put leaf disks that have been in the dark in the light?"

8-10. **Students should work with their teams to decide how to approach this next part of the investigation. They will then have another team look at their design and give feedback. Teams can modify their design based on feedback.**

The basic idea for the investigation is that teams will take the cup that has been in the light (with leaf disks now floating) and place it in darkness (wrapped in foil or covered with a box). The cup that was in the dark (leaf disks still at bottom of the cup) will then be placed in the light.

11-13, **Students prepare for, conduct, and analyze their experiments in these steps.**

Students may not anticipate that this part of the experiment could take longer than the initial "floating in the light" part of the experiment. In general, when the leaf disks are moved from light to dark, it may take longer for leaf disks to sink and it is likely that only some of the disks will sink. If students terminate the investigation early, they may never see any of the leaf disks sink when placed in the dark. Use questions to probe their ideas about what to expect and why the time may be different.

When the leaf disks that had been in the dark are moved to the light, they will start to float over time. This shows that the leaf disks are still viable—they start photosynthesizing when placed in the light. When the leaf disks that had been in the light previously (and are floating) are placed into the dark, they will sink over time. These leaf disks (now in the dark) can no longer carry out photosynthesis. Instead, they will be using the oxygen (that caused the leaves to float) for cellular respiration. As the oxygen is depleted, they will sink again to the bottom of the cup. This process will be slower than the time needed to start floating, and it is likely that students will need to continue this experiment longer than before. Students may decide, upon seeing slower changes, that they do not need to collect data as frequently as before.

14. **Remind students that the reading, *Reference 4: More about Photosynthesis* (and other readings) may be helpful for answering some of the questions.**

Part 2: The Elodea Investigation

Note to Teachers: Some members of a student team can set up the Elodea investigation (Part 2) at the same time other team members begin the leaf disk investigation (Part 1, Steps 11 and 12).

15. **Students read information about an indicator that they will use in this part of the activity. If you choose, you could ask volunteers to read this aloud to the class.**

16. In this step, students use a straw to blow into a cup containing phenol red solution. This will serve as a way for students to see that blowing carbon dioxide into the solution will cause a color change from pink to yellow, which will be important for the experiment using Elodea that they will do next. It should only take about 30 seconds of blowing to turn the solution yellow.

CAUTION: Students should take appropriate safety precautions, including wearing safety goggles.

17. Students should answer the following questions in their science notebooks.

17a. What are you adding to the phenol red solution when you blow into it?

17b. Complete the following sentence: When _______________ is added to a pink phenol red solution, the color of the solution turns ____________. Adding ______________ to the solution makes the pH _____________.

Choose from: increase decrease yellow red/dark pink carbon dioxide oxygen

18–22 In these steps, students set up their investigation using Elodea and phenol red solution. Two tubes will be placed in the light and the others will be covered so they are in the dark. It is likely that students will need to leave their investigation overnight to see the results.

23–24 Students should make predictions and draw a picture of their experimental setup.

25. After the investigation is complete, students should record their results and draw a new picture representing their new observations of their experiment.

25a. Add to the drawing in your notebook to illustrate how the experiment looks at the end.

25b. How do your results compare with your predictions?

25c. Do you think photosynthesis is occurring in any of the tubes? Which one(s)? Explain your reasoning.

25d. Based on your results, do you have evidence of something other than photosynthesis happening in any of the tubes? Please explain your thinking.

Part 3: Revisiting the Radish Seed Investigation

26. Wrap up this part of the investigation by holding a class discussion to summarize what students learned about photosynthesis from these investigations.

If time permits, students could post on their blog and describe their experiment and results for their mentor to read and respond to.

27. To conclude, hold a class discussion that revisits the radish seed experiment. Ask students if they can use what they have learned about photosynthesis and cellular respiration to explain what happened in each of the 3 dishes. To give you an overall impression of what the students are thinking, conduct a quick poll. For each of the 3 dishes, ask students to use a colored index card to indicate which process or processes best explain the changes in mass.

- **Green card = photosynthesis**
- **Red card = cellular respiration**
- **Yellow card = both photosynthesis and cellular respiration**
- **Blue card = neither photosynthesis nor cellular respiration**

Dish 1: Photosynthesis occurred because seeds had water, carbon dioxide (from the air), and light. The plants increased in mass as carbon dioxide was used to produce carbohydrates during photosynthesis. You can also remind students of the molecules that they looked at earlier (*Master 2: Common Molecules in Trees and Plants* from the From a Tiny Seed to a Large Tree activity). The carbohydrates (glucose) produced during photosynthesis are used to make important carbon-based molecules. These molecules, including lignin, form the mass of the tree (or other plant).

Dish 2: Photosynthesis could not occur in this dish because the seedlings were not exposed to light—a necessary input for photosynthesis. When plants need energy, they have to metabolize their stored sugars through cellular respiration, just as animals do. Plants need energy to maintain homeostasis, to perform normal functions, and to grow. The seedlings in this dish were able to carry out cellular respiration. They used the stored "food" contained in the seed for germination and initial growth. As cellular respiration continued, the plants lost mass by releasing carbon dioxide.

Dish 3: These seeds were placed in the light but were not given any water. The mass of these seeds did not change appreciably during the experiment. Without water, the seeds remained dormant. Cellular respiration is occurring at a very low level in these dormant seeds. (Some dormant seeds remain viable for several years.) The small decrease in mass in this dish can be attributed to use of a small amount of stored energy for cellular respiration, the loss of a small amount of water, or possibly to measurement error (balances commonly used in classrooms often are not accurate when measuring differences this small). Students could not completely rule out any of these explanations for why the seeds lost mass in these conditions. This could lead to an interesting class discussion because many students assume that experimental error almost always explains small differences without considering other options.

Students can also revisit their answers to the questions in Steps 14–16 in the From a Tiny Seed to a Large Tree activity. Ask them to use a different colored pen or pencil to revise their answers and to explain their reasoning.

If you are creating a class storyboard, add new information from this investigation to the storyboard.

Additional Resources
Additional videos, web pages, books, and articles to support teaching and learning about photosynthesis can be found in the *Photosynthesis and Respiration Resources* document.

Additional Investigation Ideas
These investigations may suggest other ideas for investigation. Encourage students to write their ideas in their notebooks. When they do their independent investigations, they may want to consider one of the ideas sparked by this investigation.

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Answer Key for Student Questions

Part 2: The Elodea Investigation

17a. What are you adding to the phenol red solution when you blow into it?

They are adding carbon dioxide to the cup of phenol red solution.

17b. Complete the following sentence: When _carbon dioxide_ is added to a pink phenol red solution, the color of the solution turns __yellow__. Adding_carbon dioxide_ to the solution makes the pH __decrease__.

Choose from:	increase	decrease	yellow	red/dark pink
	carbon dioxide	oxygen		

25a. Add to the drawing in your notebook to illustrate how the experiment looks at this time.

The controls (tubes without Elodea) should remain unchanged (pink). The tube with Elodea that has been placed in the dark should be yellow or much lighter pink/orange. The tube with Elodea that was in the light should be very similar to the control. (The tube with Elodea in the light may look slightly darker pink than the control. However, this is probably a very minimal change. Or, any slight color change could simply be due to comparing tubes with and without Elodea in them. There could possibly be a low level of photosynthesis occurring in the Elodea in this tube because of any carbon dioxide that diffused into the solution, but this would be minimal. Photosynthesis is mostly blocked in these tubes because the solution does not include a source of carbon dioxide for the plant.

25b. How do your results compare with your predictions?

Answers will vary depending on student predictions.

25c. Do you think photosynthesis is occurring in any of the tubes? Which one(s)? Explain your reasoning.

This is likely to be a somewhat challenging question for students. Students are likely to think that photosynthesis is occurring in the Elodea that has been in the light because they associate photosynthesis and light. However, students may not initially think about the fact that the phenol red solution does not contain any carbon dioxide source necessary for photosynthesis. If necessary, probe their understanding by asking them what happened in the cup containing distilled water (only) in their leaf disk experiment.

25d. Based on your results, do you have evidence of something other than photosynthesis happening in any of the tubes? Please explain your thinking.

Students should realize that the color change (pink to yellow) in the Elodea tube that was in the dark reflects something happening in the plant. Photosynthesis would not be happening because the necessary inputs (carbon dioxide and light) for photosynthesis are not available. The control tube placed in the dark informs them that the color change is not due to a breakdown or change in the indicator solution that occurs in the dark. Therefore, something else must be happening involving the plant (cellular respiration) to explain the color change. Cellular respiration produces carbon dioxide as an output which would cause the indicator to turn yellow.

Results of the Elodea Investigation: The tubes on the left remained in the light for 24 hours. The tubes on the right were placed in the dark for 24 hours.

If students think that the color changed because there is something wrong with the plant after being in the dark, you could ask them to think about how they might show that the plant is OK. Students could put the Elodea tube (with yellow phenol red solution) in the light. In the light, the Elodea would use the carbon dioxide in the solution for photosynthesis and, as photosynthesis consumes the carbon dioxide, the phenol red would turn pink again.

Open Inquiry: How Does a Plant's Environment Affect Photosynthesis and/or Cellular Respiration?

Overview
In this lesson, students generate ideas about photosynthesis and cellular respiration as they relate them to environmental conditions or biological variation. Students' ideas about these biological processes should build on or link to the guided inquiries they have completed earlier. Students will develop a specific research question, develop an experimental design, and draw conclusions from the data to refine their working model of photosynthesis and cellular respiration. Your role is to help students use sound reasoning and evidence to develop an experimental design that clearly addresses a research question. Students are challenged to construct explanations based on their experimental data while making connections to deeper concepts and scientific practices.

Time Required: Approximately 6 45-minute class periods
- **Day 1:** opening discussion, brainstorming
- **Day 2**: Finalize research question, ResearchBlogs
- **Day 3:** Design experiments, ResearchBlogs
- **Day 4:** Carry out experiments
- **Day 5:** Finish experiments, analyze data, ResearchBlogs
- **Day 6:** Storyboard discussion, ResearchBlogs

Optimally, you will schedule this lesson so that scientist mentors have time to respond to team blog posts before the students move on to their next step. The goal is for students to get feedback from mentors and be able to incorporate that feedback before moving on. Therefore, it is likely that the days for this investigation will not be consecutive class periods.

Learning Goals
During this activity, students will
- understand the connections among environment, photosynthesis, cellular respiration, and (optionally) plant productivity;
- develop a testable research question;
- select experimental approaches best suited to answer a research question;
- design and carry out an experiment;
- use sound reasoning to construct explanations from data; and
- generate models for how photosynthesis and cellular respiration work.

Getting Ready

***Student's Guide* Section Used in Lesson**

How Does a Plant's Environment Affect Photosynthesis and/or Cellular Respiration? from *Student's Guide*	1 copy per student

Materials and Supplies

Computer access to the *Student Roadmap through an Investigation* resource on the PlantingScience website	
Materials from leaf disk floatation investigations	The type and amount of materials will depend on student investigations and what you have available for use.
Additional species, ages, colors, and so forth of plant materials may be helpful (for biological variation experiments)	
Growth chambers or cooling/heating units (for temperature experiments)	
Thermometers (for temperature experiments)	
Color filters or colored lightbulbs (for testing the effect of light wavelength)	
Automatic lighting timers (for testing day length or temporary darkness)	
pH test strips and dilute acid/base (for pH experiments)	
Table salt (for testing osmotic effects)	

- Students will need to check with you regarding available materials and supplies before beginning their investigations. Depending on what is available, they may need to modify their investigation or experimental design.
- For teams using the leaf disk floatation method, similar technical considerations will apply here as in the guided inquiry.
- Method-specific technical notes are available in the *Power of Sunlight Toolkit* for teams that wish to use one of the alternative methods therein.
- If you happen to have other materials and supplies that can be applied to answering research question about photosynthesis and/or cellular respiration, then be sure to make students aware of this option.

Preparations

- Review the student and teacher procedures for the lesson.
- Gather a range of materials that students may use for their investigations.
- Students will post to their blog and receive feedback from their scientist mentors on their investigations at several points during this activity. Communicate with the mentors ahead of time to let them know when to expect blog posts and to find out how quickly they will be able to provide feedback. This information will help you schedule class time for completing the open-inquiry investigations.

Procedure

Note to Teachers: The procedure that follows provides a framework for using this lesson in the classroom. However, you should feel free to modify it based on your students' prior experiences, knowledge, and abilities. The step numbers listed in these procedural steps match those in the student pages.

1. **Ask students to share what they have learned about photosynthesis and cellular respiration from the previous lessons. If the class has been completing the storyboard, take time to review the progress. Introduce students to the idea that this time they will be developing their own research question and then planning and conducting their own investigation to answer the question.**

   Allow time for students to read through all the procedural steps in their student guide for this investigation.

2. **Introduce students to the *Student Roadmap Through an Investigation* resource (https://www.plantingscience.org/resourcelibrary/studentlibrary/studentroadmaps) on the PlantingScience website.**

   Students should refer to this resource at various times during their investigations for guidance.

3. **Students should begin thinking about what interests them about photosynthesis and/or cellular respiration. Instruct students to read through the information found at the *Explore Your Topic* link in the *Student Roadmap*.**

   Students can spend some time individually thinking about their interests. If, during previous investigations, they wrote ideas for future investigations, they can refer back to those now. After working individually, teams can start discussing their ideas together.

4–5. **During these steps, students read information about testable questions in their procedure and in the *Research Question* section of the *Student Roadmap*.**

   If helpful, hold a brief discussion about testable questions before students move on to the next step.

6. **Allow time for teams to work together to come up with 2–3 potential research questions to investigate. For each of their ideas, they should write answers to the questions listed in this step.**

   The questions should help students think more about their research questions and the possible investigations they would do. Because students will share this with their mentors, the questions also provide a framework for presenting ideas to the mentors.

   As teams are working on their research questions, they may have questions and need more information. The *Power of Sunlight Toolkit* (https://plantingscience.org/resourcelibrary/planttoolkit) may be a valuable resource that provides information about different techniques and methods for investigating photosynthesis and cellular respiration.

   One consideration related to potential research questions is relevance. Will this research question investigate something that has a real-world connection? For example, a common idea for student investigations is to see what happens to plant growth if they are watered with cola. Such a research question doesn't have a strong connection to real-world plant biology. Another problem with such investigations is that these beverages are complex mixtures of chemicals and vary depending on bottler, brand, and flavor. It would not be feasible in the classroom to identify which component of the beverage produced an effect. As the teacher, you can watch out for questions such as this, and the mentors will also provide feedback if students present a flawed research question.

7. **Teams should take pictures of their notebook pages with information about their brainstormed research questions and their responses to the Step 6 questions. Teams can upload these photos to their project page on the website for their mentor to view.**

   Each team should work together to reach a consensus about which information should be presented to the scientist mentor.

8. **After receiving feedback from their scientist mentor, each team should narrow their focus and decide on a single research question that they will investigate. Teams should add information and suggestions from their mentors to their notes from Step 6.**

   The feedback that teams get from their mentors can help identify potential problems or provide suggestions for how teams can strengthen their research questions.

9. **Allow time for students to read the *Planning Your Study* section in the *Student Roadmap*.**

   This information provides guidance on matching the experimental method to the research question as well as developing research and data collection plans.

10. **Allow time for teams to work on their experimental design for their chosen research question.**

    The questions listed in the procedure should help teams think through details about their experiment. Encourage students to check with you about materials or supplies that they may want to use. If certain supplies are not available, they may need to modify their design.

11. **After teams agree on their experimental design, they should post pictures of their notebook pages with details of their design for their mentors.**

    Allow time for mentors to review the experimental designs and provide feedback before moving forward with the investigations.

12. **Allow 2 class periods (45-minute periods—or perhaps 1 block schedule period) for students to conduct their investigations (after incorporating feedback from mentors).**

Be clear with students as to how much time they have to complete their investigations. Teams may need guidance about fitting their investigation into the available class time. For example, they may need to figure out whether they can complete their investigation in 1 day or whether they need to think about how they could do part on one day and the rest on the next day. If necessary, help students identify appropriate stopping points in their procedure.

Teams may need to spend some time testing parts of their procedure before beginning their real investigation. Encourage them to ask questions of their mentor if they run into problems.

13. **Allow time for teams to work on the analysis of their data.**

Encourage teams to think about the best ways to summarize their data. Sometimes, a photograph works well. In other cases, they may need a graph or diagram. Often, they may want to use multiple formats.

14–15. **Teams should work together to make sense of their results. The questions listed with Step 14 should help guide students' thinking and help them present their results to their mentors. When teams are ready, they can take pictures of their notebook pages and upload them for mentors to review and discuss.**

Optimally, you will allow time for mentors to view blog posts from students and give their feedback. Teams may want to discuss the feedback with the mentors before moving on with the rest of the investigation.

16. **Ask teams to create a presentation about their investigation and the results. Explain your preferences regarding presentation format and time.**

For example, do you want students to prepare posters or PowerPoint presentations?

17. **Have each team present its research question and experimental results with the class. As teams present, discuss how these results add to the storyboard that the class has been developing and how they are consistent (or inconsistent) with the results of other teams.**

Discussing how different investigations adds to students' knowledge of photosynthesis and cellular respiration helps students fit their experimental results into a larger conceptual understanding. Because different teams will investigate different aspects of cellular respiration and/or photosynthesis, this discussion can help students see how the results of their investigations relate to others. Do the results of their experiment make sense when thinking about other teams' experimental findings?

When conducting the discussion and adding to the storyboard, consider the following:

- How do these results relate to the previous investigations done in the module (thought investigations and guided investigations)?
- What is the quality of the evidence and reasoning for the explanation given?
- Are there weaknesses in reasoning that become apparent? (If this happens while presenting, assure students it is fine to reconsider their explanation.)
- How do the explanations developed by different teams reconcile with data from other teams' investigations?

18. If time permits, conduct another open-inquiry investigation. This may be something from the original set of interesting research questions or a new idea that arose during the investigation.

Often, one investigation will spark ideas for new investigations. If possible, allow time for students to experience the excitement of science by continuing with a new research question and continuing to interact with their mentors.

Additional Resources (optional)
Science Matters: Plant Genetics and the Environment
https://www.youtube.com/watch?v=fghFaDlgc-E
(30 minutes; University of California Television)

This video provides examples of social driving forces for understanding environmental impacts on plant productivity/growth and what some of these environmental factors are. Teachers are advised to preview the video and choose the best selection for the time available.

Background reading on photosynthesis and cellular respiration is available in the five reference readings in the *Power of Sunlight Student's Guide*. Additional videos, web pages, books, and articles to support teaching and learning about photosynthesis and cellular respiration can be found in the *Photosynthesis and Respiration Resources* document.