The Power of Sunlight:
Investigations in Photosynthesis and Cellular Respiration

Student's Guide

Have you ever thought about how a tiny seed becomes a corn plant or even a large oak tree that can weigh over 28,000 pounds? What processes do plants rely on to grow? In this module, you will work through a variety of activities to learn more about the processes of photosynthesis and cellular respiration to help answer these questions.

After completing some introductory activities to learn about asking a research question and conducting scientific investigations, you will join a research team to investigate photosynthesis and cellular respiration. You and your teammates will decide on a research question and then carry out experiments to help answer the question. You will also create a team blog where you'll post your ideas and share your data with a plant biologist and share what you learned about photosynthesis and respiration with your classmates. Here is what's in store:

- **Get reacquainted with plants:** You will develop ideas about plants, plant growth, photosynthesis, and cellular respiration by analyzing data from experiments that have been carried out by other scientists.

- **Laboratory investigations:** You will work in small teams to brainstorm research questions and develop a plan for your own experiments. Your research questions and investigations may take advantage of the experimental method that you learned in the introductory activities or you may use other methods that you learn about in a reference manual. As you plan and conduct your investigations, you will share your ideas with and get feedback from a scientist mentor.

- **Think like a scientist:** Once you finish your lab investigations, your team will develop a storyboard that will be used to present its findings. As you look at data from all of the teams, the class will work together to make sense of it all—to explain how different environmental and plant characteristics might affect a plant's ability to carry out photosynthesis and respiration.

GET REACQUAINTED WITH PLANTS

From a Tiny Seed to a Large Tree

Purpose: These activities will help you to
1. express what you currently think about plant growth and
2. consider how the results from two experiments challenge your thinking about how plants can increase in mass.

Completion of these activities will help prepare you for the guided and independent research activities that will follow.

Time Required: Approximately 45 minutes

Procedures

Part 1: The von Helmont Experiment

Have you ever planted a seed in your garden or in a flower pot? Maybe you ended up with a colorful flower or with vegetables that you could eat for dinner. Have you ever seen a giant redwood tree? These 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?

1. Write the following focus question for this lesson in your science notebook: "Where does the mass of a plant come from?"

2. Take a moment to reflect on what you already know about how a huge tree can grow from a tiny seed. Answer the following questions in your science notebook. Don't worry if you are unsure of your answers. You will have an opportunity to revise them later based on what you learn in this module.

   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?

3. In this activity, you are going to look at data from an experiment that was done a long time ago. Read the following paragraph that summarizes the experiment.

   > Jan Baptist von Helmont was a Belgian scientist who lived from 1580 to 1644. He wanted to find out where the mass of a tree comes from. At that time, many people thought that the mass of a tree might come from

the soil. Von Helmont designed an experiment to test that idea. He planted a young willow tree in a pot containing 90 kilograms (kg; about 200 pounds) of dried soil. The willow tree weighed 2.2 kg (about 5 pounds) when it was first planted. For the next five years, he watered the tree with either rainwater or distilled water as needed.

4. It is important to think about what an experiment can and cannot tell you. Before you learn more about von Helmont's experiment and his results, write down your initial thoughts. Answer the following questions in your science notebook.

   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 thinking.

   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.

5. Your teacher will show you a brief video about von Helmont's experiment and his results.

   As a reminder of what you saw in the video, the following are the data from von Helmont's experiment.

Mass	**At the start of the experiment**	**5 years later**
Mass of tree	2.2 kg (about 5 pounds)	77 kg (about 169 pounds)*
Mass of dried soil	90 kg (about 200 pounds)	89.4 kg (about 200 pounds less 2 ounces)

*He did not weigh the leaves that fell off the tree each year.

6. Using what you have learned from the results of von Helmont's experiment, write your answers to the following questions in your science notebook.

   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?"

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? If you revise your answer, use a different colored pen or pencil to make revisions so you can see how your thinking has changed.

Part 2: The Radish Experiment

Von Helmont's experiment gave you some useful information about plant growth and mass. However, you still need more information to answer the focus question for this lesson.

8. Your teacher will show you diagrams of some of the most common molecules that make up trees and plants. What observations can you make about the atoms that are important for making up the mass of trees and plants? Record your ideas in your science notebook.

9. Your teacher will show you a brief video that describes the setup of the radish seed experiment. The following is a recap of what you learned in the video.

   The scientist put exactly 1.0 gram (g) of radish seeds in each dish. Each dish received a different treatment:

   - Dish 1 was placed in the LIGHT and was watered.
   - Dish 2 was placed in the DARK and was watered.
   - Dish 3 was placed in the LIGHT but was NOT watered.

   The dishes were kept in these conditions for two weeks. After that time, this is what the scientists saw:

Dish 1

Dish 2

Dish 3

Dish 1: Almost all seeds germinated (sprouted); short seedlings; green leaves
Dish 2: Almost all seeds germinated; longer seedlings; pale green leaves
Dish 3: None of the seeds germinated

Next, the scientist put each dish into a drying oven to remove all the water from the dishes and the seeds or seedlings.

10. It is important to understand why an experiment was carried out the way it was. In your science notebook, write your answer to the following question.

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

11. Making predictions and recording the reasoning you used to make those predictions is an important part of developing an understanding of science. In your science notebook, write down a prediction about how you expect the mass to change (increase, decrease, or stay the same) for each of the 3 experimental treatments following the 2-week growth period. Be sure to include your reasoning for each prediction.

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})			
Change in mass ($M = M_{final} – M_{initial}$)			

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. Be ready to share your ideas in a class discussion.

14. Consider the dish with seedlings that INCREASED in mass. Read and discuss the following statements with a partner. Decide if each statement is reasonable or not reasonable and record it your science notebook. For each statement, also 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

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

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

15. Consider the dish with seedlings that DECREASED in mass. Read and discuss the following statements with a partner. 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

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

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

16. Consider the dish with seeds that STAYED ABOUT THE SAME in mass. Read and discuss the following statements with a partner. 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

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

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

Part 3: Communicating with Your Mentor

17. If you have not already done so, introduce yourself and your team members to your scientist mentor using the blog. You can ask some get-acquainted questions, such as these:
   - What is your research about?
   - Why do you like working with plants?
   - What do you do for fun?

Or, come up with your own questions! Later, you will discuss your investigations with your scientist mentor, but this is a chance for you to get to know each other a little.

LABORATORY INVESTIGATIONS

Getting Ready to Do an Investigation

In the **guided investigations in this module**, you will explore photosynthesis and cellular respiration in plants. You will also consider how these investigations were designed to answer specific questions. This knowledge will help prepare you to do your independent investigations later in this module.

When planning and carrying out your own investigation you will need to keep in mind the following elements. These elements do not necessarily occur step by step, and you may go back and revise your procedure, your plan for recording data, or even your question as your investigation progresses.

Asking a Question

Scientists wonder about the world around them. They then decide upon a question that they want to answer through their investigations. Usually, scientists have some prior knowledge about the topic that guides their questions. They may also read information that will help provide some background on the topic.

One thing that is important when asking a question is that it is testable. Can you design an experiment that will provide evidence to answer the question? In the guided investigations that you will do, you will focus on questions that have already been identified. Later, for your independent investigations, you and your team members will decide on your own question about photosynthesis or cellular respiration to investigate.

Planning and Preparing for the Investigation

When you follow an experimental procedure, it is important that

- you understand the science behind it,
- you have tried it out and can convince yourself and others that it works, and
- you are comfortable with handling the materials and procedures.

Why do scientists test methods? Isn't this a waste of time? Scientists often use trials to get a technique "up and running" before they launch an experiment. Materials are often expensive and plant samples might be rare, collected only at a certain time of year or from a distant place. A scientist may also have slightly different equipment than what was originally used to develop a method. This is a bit like trying out a new recipe before making it for guests. Recipes aren't foolproof. If one comes out too salty or overcooked the first time, you can make changes to the recipe on the second trial. When it is time to cook for your guests, you will have a recipe that looks and tastes good.

Making Predictions and Testing the Question

- As you think about your predictions, consider these questions:
  - What do I expect to happen and why?
  - What do I think is happening biologically that makes my predictions credible?
- See Student Roadmap through an Investigation's *Research Question* to learn more about research predictions and how to develop one as a team.

Making a Plan for Collecting and Recording Data

Think about your data:

- What equipment and supplies will you need to collect data (A ruler? A pH probe?)
- What will you record?
- How often will you record data?
- Where will you record data?
- What format will you use? (Do you need a table? Will you record data on a diagram?)
- What materials do you need to record it?
- Who will record it?

Carrying Out the Investigation

- Follow your procedure.
- Collect the data as you planned.
- Sometimes, things don't go as planned or mistakes are made. If something changed with your procedure or if you observe something that you didn't expect, you should make notes about those things in your notebook or computer file.
- If time permits, you may want to redo your investigation.

Making Sense of the Investigation

See the **Student Roadmap through an Investigation**'s *Making Sense of Findings* for a guide to help develop explanations about what you observed or measured.

- Write out a **well-reasoned, convincing argument** to explain to someone how you can tell if the method was working and what the overall results mean. Include your data and what you think you understand about plants, photosynthesis, and respiration. You should include a claim and support your **claim** with **evidence** from your investigation and scientific **reasoning**.
- Be prepared to discuss your ideas with the whole class in a Storyboard Discussion. Your teacher will help guide this process.

Investigating Photosynthesis Using a Leaf Disk Floatation Method

Purpose: This guided investigation is intended to help you

1. learn what plants need for photosynthesis and
2. enhance your understanding of how scientific investigations are designed.

This guided investigation will take you through a process similar to what you will use when carrying out your independent research project later.

Time Required: Approximately 3 45-minute class periods

Materials

The following materials are available. If you need other supplies for your experiment, check with your teacher.

- Plastic straw
- 3 clear, wide-mouth plastic cups
- Baby spinach leaves
- 0.2% baking soda solution (sodium bicarbonate)
- Liquid dish or hand soap (diluted)
- Distilled water (room temperature)
- Single-hole paper punch (or plastic straw, No. 3 cork borer, or scissors)
- Index card (3 × 5 inch) or a small piece of paper
- Small paint brush
- 3 10-mL or larger disposable syringes, without needles
- Permanent marker
- Light source (40 W or more; this could be a light bank with adjustable shelves or height used by the whole class)
- Ruler
- Hand lens
- Stopwatch, timer, watch, or clock with a second counter

Procedures

1. Your teacher will lead a discussion that relates the previous lesson to your need for learning more about photosynthesis.

2. During this lesson, you will investigate inputs and outputs associated with photosynthesis. In your science notebook, write a few statements that summarize what you currently know about photosynthesis. Even if you are not sure of something, go ahead and write it down. You can come back and revise your statements later.

   You will be working with small pieces (disks) of spinach cut from large leaves. Using small leaf disks allows you to carry out the investigation more easily than if you used the entire leaf. For the purpose of investigating photosynthesis, the leaf disk functions like an intact leaf.

3. Your teacher will conduct a brief demonstration that provides some basic information about leaf structure and describes how you will be manipulating the leaf disks during your investigation.

   To further your understanding of leaf structure, read Reference 1: Plant Structure and Photosynthesis. *Think about how this information relates to the model used for the demonstration.*

4. This investigation is designed to address the research question, "How does carbon dioxide affect photosynthesis?" Write down this question in your science notebook.

5. First, read through the procedure steps before starting the investigation. Ask questions if you are uncertain about what to do.

6. Gather together the materials needed to set up the investigation. (See the materials list presented earlier.)

7. Prepare solution for three different treatment conditions:
   7a. Label the three cups as follows:
       breath
       baking soda
       water
   7b. Add distilled water to each cup to a level about 2 cm deep.
   7c. Work first with the cup labeled **"breath."** Using a straw inserted *into* the water (not just above the water), blow for 60–90 seconds.
   7d. To the cup labeled **"baking soda,"** add 0.2 percent baking soda (sodium bicarbonate) solution. Stir to dissolve.
   7e. To the cup labeled **"water,"** do not add anything.
   7f. Add 1–2 drops of diluted liquid soap to all 3 cups and stir until thoroughly mixed. Do not stir vigorously and make suds!
   7g. Set the cups to the side while you continue with the setup.

8. The information in the shaded box below helps you understand the different treatment conditions. Use this information to answer the following questions in your science notebook.

   8a. What are you adding to the water when you blow into it?
   8b. What are you doing when you add baking soda to the water?
   8c. How is blowing into the water similar to adding baking soda to the water?

What Happens to Carbon Dioxide in Water?

Let's think about carbon dioxide. You probably know that carbon dioxide is a gas in the air around us. But, did you know that carbon dioxide can exist in other forms? Have you ever seen dry ice? Dry ice is carbon dioxide in a solid form. Did you know that carbon dioxide can also be in an aqueous form in water? Carbon dioxide actually dissolves in water. Most oxygen molecules do not dissolve in water, but instead they cluster together to form bubbles. In fact, at the growing temperatures for most plants, about 40 times more carbon dioxide than oxygen dissolves in water.

How can we add carbon dioxide to water? What happened when you blew air into the water? When you blew through the straw, you were exhaling carbon dioxide into the water. Most of this carbon dioxide dissolves in the water—so you won't see bubbles or anything to know it is there. Even so, the carbon dioxide is changing from a gas to an aqueous form.

$$CO_2\ (gas) \longrightarrow CO_2\ (aqueous)$$

You also added baking soda to a different cup of water. Baking soda, whose chemical name is sodium bicarbonate, has the chemical formula of $NaHCO_3$. In water, the atoms in sodium bicarbonate come apart as seen below:

$$NaHCO_3 \xrightarrow{\text{in water}} CO_2 + H_2O + Na^+$$

9. Make your leaf disks.
   - 9a. Select enough leaves to make about 36–40 leaf disks.
     - This method works best with healthy plant material. Choose the darker green leaves.
     - Make enough leaf disks so that you have at least 10 disks per treatment condition. (Starting with a few extra disks is helpful in case a few get damaged.)
   - 9b. Use a paper hole punch to punch out your leaf disks.
     - Avoid the heavy leaf veins.
     - Put the disks onto the card. This will make it easier to pour all the disks into the syringe in Step 10.
     - Use a small brush to help move the leaf disks around without damaging them.

10. Remove the gases inside the leaf disks and infiltrate them with the 3 solutions prepared in Step 7.
   - 10a. First, remove the plunger from a syringe.
   - 10b. Pour about 12 leaf disks into the barrel of the syringe.
   - 10c. Tap the syringe on the table or in your hand so that the leaf disks move toward the narrow end where a needle would normally go. A small brush may help you move the disks down farther into the syringe barrel.
   - 10d. CAREFULLY push the plunger back into the syringe.
     - Avoid damaging the leaf disks.
     - Push the plunger nearly all the way into the barrel—about 1/10th of the way from the tip. You want to leave enough space so you don't damage the disks.
   - 10e. Place the syringe tip into the breath + soap solution (from the **breath** cup) and pull up some of the solution until the syringe is about 1/3 full.

10f. Holding the tip of the syringe upwards, tap the side of the syringe to get the leaf disks down into the liquid as much as possible.
10g. Hold the tip of the syringe upwards. Push out any air from the syringe that you can but be careful of the leaf disks.
10h. Continue holding the syringe with the tip upward. Cover the tip of the syringe with your finger. Slowly pull back on the plunger a bit (to about the 2 or 3 cc mark on the syringe) with your finger still blocking the open tip. You will feel a vacuum pulling on your fingertip.
- You may notice your leaf disks darkening in color and/or sinking as they become infiltrated with the solution.

10i. Hold the vacuum for about 10 seconds. Then, gently release the plunger while continuing to hold your finger over the tip of the syringe. You should see at least some of the leaf disks sink.

Careful! Keep the syringe pointing upward throughout Steps 10f–i.

10j. Take your finger off the tip of the syringe. If there is air space at the top of your syringe, push the syringe plunger to get rid of the air.
10k. Pull a vacuum 3 more times or until all of the leaf disks sink in the solution.
- If you have done this 5 times and some leaf disks are still floating, add more soap to the solution and try again.

10l. Once all leaf disks have sunk, they are ready for testing.
10m. Pour the infiltrated leaf disks into the cup with breath + soap solution **(breath** cup). To transfer the leaf disks from the syringe to the cup, hold the syringe sideways over the cup. Gently pull the plunger out of the syringe. When the plunger comes out, the disks should flow with the liquid in the syringe into the cup.
- If some of the leaf disks get stuck. Pour a small amount of the liquid back into the syringe and then pour out the liquid and leaf disks again.

Troubleshooting problems with infiltration
Several common problems can be easily solved:
- Air bubbles may get trapped on the surface of leaf disks. Try tapping the syringe or cup to dislodge any bubbles if leaf disks float unexpectedly.
- Cut edges of leaf disks can be sticky, causing them to adhere to a syringe or cup. Tap to release them.
- Start the infiltration process with extra leaf disks. If one of the leaf disks won't sink during infiltration, you can discard it and use the ones that did sink in the syringe.

11. Repeat the infiltration process (Steps 10a–m) using the other 2 solutions [the water + soap solution **(water** cup) and the baking soda + soap solution **(baking soda** cup)].

    Hint: One team member can infiltrate disks for the **breath** cup at the same time other team members infiltrate disks for the **baking soda** or the **water** cup.

12. Adjust the volume of solution in each cup by eye so that they have the same amount of liquid in them. About 2 cm deep is sufficient.

13. Count the number of leaf disks in each cup. Try to use the same number of leaf disks in each cup. All leaf disks should be at the bottom of the cups after infiltration. You can remove any floating disks if you have at least 10 disks that are at the bottom of the cup.

14. In your science notebook, record your predictions about what will happen with the leaf disks in each cup when you put them in the light. Also include your reasons for your predictions.

15. Prepare a data table in your science notebook similar to the one on the next page. Remember that you may need to collect data for 20–25 minutes.

Time (minutes)	**Breath cup**		**Baking soda cup**		**Water cup**	
	Number floating	Number NOT floating	Number floating	Number NOT floating	Number floating	Number NOT floating
0						
1						
2						
3						
4						
5						
6						

16. Place your 3 cups in the appropriate spots for testing.
    - You will want to put them close to a light source. Do NOT turn the light on yet.
    - The 3 cups should be an equal distance from the light (2–5 cm between the light and the liquid).
    - Measure the distance between the light and the top of the liquid in your cups (or the side of your cups, depending on whether your light is over the cups or to the side of your cups).
    - Record the distance between the light and the liquids in the cups in your notebook.

17. Record the number of leaf disks that are floating or not floating in each cup in your data table. This is time zero.

18. The treatment begins when you turn the light on. Start a timer or stopwatch when you begin the treatment to keep accurate data.

19. At one-minute intervals after you begin treatment, count the number of leaf disks that are floating in each cup and record these numbers in the data sheet you prepared beforehand. You can also use a hand lens to look at the leaf disks during the investigation. After about 25 minutes, you can stop collecting data.

20. Now that you have completed your investigation and collected your data, what can the data tell you? Use the following questions as a guide. Write your answers in your science notebook. The reading, *Reference 2: Photosynthesis*, may help you link your experimental results to photosynthesis.

20a. 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.

20b. Write a one sentence answer to your research question.

20c. How did your results compare with your predictions?

20d. What did you learn from the demonstration that helped you understand the leaf disk activity?

20e. Were the results of your experiment similar to those of other teams? If not, can you think of reasons to account for the differences?

20f. Did you notice anything during your experiment that seemed unusual or problematic? Please describe and explain why it was a problem.

20g. 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?*

20h. Refer back to the ideas about photosynthesis that you wrote for Step 2 in your science notebook. Do your experimental data provide information that either supports or contradicts some of your initial ideas about photosynthesis? Please explain.

21. Be ready to participate in a class discussion led by your teacher.

Reference 1

Plant Structure and Photosynthesis

Leaf Structure

At some point in your life, you have probably noticed that plant leaves take on many different shapes and sizes. You may even have identified different species of trees based on the shape of their leaves. One common feature of most leaves is that they are thin and flat. This basic shape helps optimize leaves for capturing sunlight for photosynthesis.

Even though leaves are thin, they have a fairly complex structure inside (figure R1.1). Covering both the upper and the lower surfaces of the leaf is a transparent layer of cells called the epidermis. Epidermal cells secrete a waxy substance that forms a waterproof coating called the cuticle. This waxy cuticle helps prevent the leaf from losing too much water and drying out. Some plants that live in very dry areas have a thicker cuticle to help prevent water loss. Plants that live in wetter areas do not need a thick cuticle because they are less susceptible to drying out.

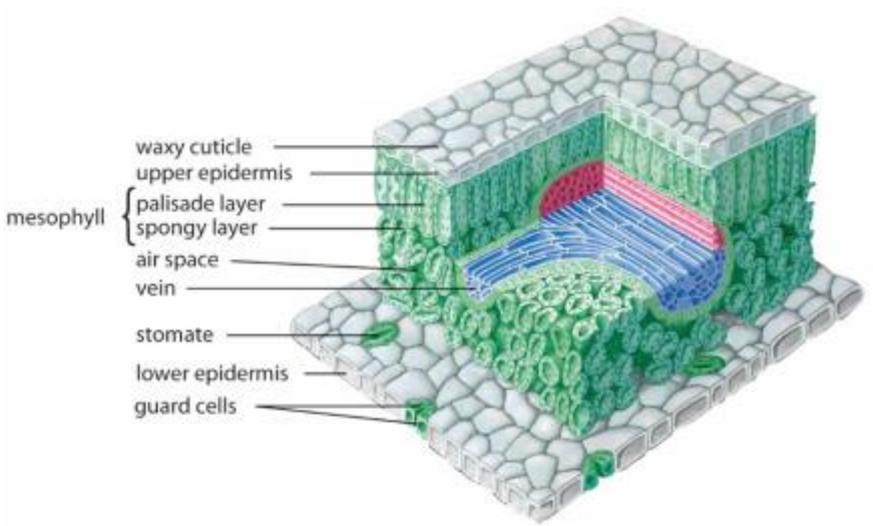

Figure R1.1: This diagram of a section of a leaf shows its internal structures. Although colors are used to highlight the different types of cells and tissues, note that cells that conduct photosynthesis are naturally colored green because they contain chloroplasts.

Photosynthesis occurs in the mesophyll cells that contain numerous chloroplasts. There are two types of mesophyll cells. In the upper palisade layer, the mesophyll cells are elongated and packed together tightly. This space-saving arrangement exposes the maximum number of cells to light in the minimum amount of space. In the lower spongy layer, the mesophyll cells are rounder and packed loosely with many empty air spaces between them. These spaces allow gases to move around freely and diffuse into all the mesophyll cells.

Substances enter and leave the leaf by two different routes: veins and stomates. Veins, which are continuations of the vascular tissues of the stem and root, supply the leaf cells with water and nutrients. Gases move into and out of a leaf by diffusion through millions of stomates, which are slit-like openings in the leaf surface. The stomates open into the spongy mesophyll's air spaces and allow the carbon dioxide used in photosynthesis and the oxygen used in cellular respiration to reach all the cells of the leaf (figure R1.2).

Figure R1.2: Scanning electron micrograph of the surface of a leaf. The stomates, surrounded by guard cells, allow gases to enter the leaf.

Guard Cells Regulate Water Loss

Although water molecules are present in the air as water vapor, they are never as abundant in the air as they are in the leaf. Thus, the plant loses water as it diffuses into the air through the stomates. This water loss is called transpiration.

When plant cells have adequate supplies of water, the water exerts a pressure known as turgor pressure against the cell walls. Turgor pressure supports the stems and leaves. If more water is lost from a plant by transpiration than is replaced through the roots, the cells lose turgor pressure. As a result, the stems and leaves are no longer held upright and the plant wilts. If the water is not replaced, the cells and then the plant will die.

How can a plant conserve water and still allow the needed carbon dioxide to enter? Each stomate is surrounded by a pair of specialized cells called guard cells (figure R1.3). When water is abundant, the guard cells fill with water. This causes the guard cells to bend outward and the stomates open allowing carbon dioxide to diffuse into the leaf. When a plant loses more water than it can replace, the turgor pressure of the guard cells decreases. The guard cells no longer bend outward and, as a result, the stomates close. In this manner, the plant is able to reduce the loss of water under dry conditions. During these times, however, little photosynthesis takes place because there is little carbon dioxide available to be converted into sugars.

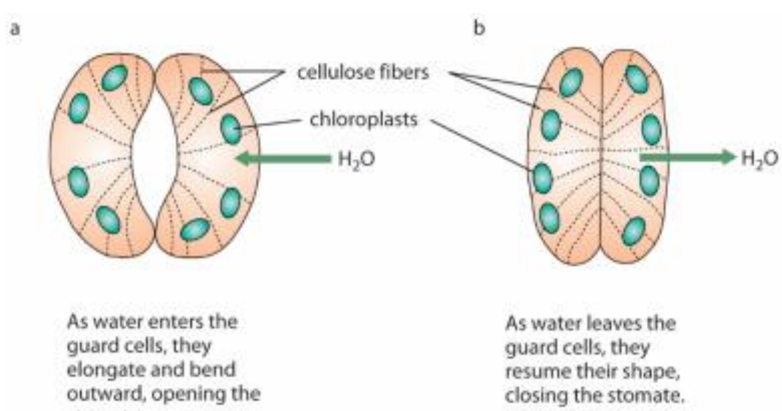

Figure R1.3: Guard cells control the opening of stomates. Because they are attached to each other at both ends and encircled by rigid cellulose fibers, the guard cells elongate and bend outward when they take up water.

Not All Leaves Photosynthesize and Photosynthesis May Take Place in Other Parts of the Plant

Although the major function of most leaves is photosynthesis, some leaves photosynthesize very little, if at all. These leaves have other functions that are adapted to the environmental conditions in which the plants live. For example, the spines on spurge and on cacti are modified leaves that are hard, sharp, and nonphotosynthetic (figure R1.4). Their function is help protect the plant against predators that want to eat them. Plants with smaller leaves (and, therefore, less surface area) lose less water than do plants with larger leaves because water loss occurs mostly from leaves.

Figure R1.4: Members of the spurge family have spines that actually are modified leaves. Photosynthesis takes place in the stems of plants like spurge and cacti to minimize the amount of water lost from the plant through the leaves.

In addition to leaves, photosynthesis takes place in green stems of plants. You are probably familiar with green asparagus in your grocery store. Have you ever seen white asparagus? White asparagus is the same plant as green asparagus. The difference results from the way the asparagus is grown. To grow white asparagus, farmers cover the asparagus shoots with dirt or plastic that blocks the light from getting to the plants, thereby preventing photosynthesis from occurring. Cacti are another example of plants where photosynthesis occurs in stems. In the dry habitats in which cacti are found, spines reduce water loss and help protect the cactus from herbivores. Photosynthesis takes place in the stems of the cacti rather than the spines (leaves).

Other plants in dry habitats have modified leaves that function to store water in addition to carrying out their role in photosynthesis. These plants, known as succulents, have tissues filled with so much water that water can be squeezed from them. After a rainstorm, the roots of succulents quickly absorb more water than the plant can use immediately. The water is stored in the leaves of succulents (and in the stems of cacti) until the plant needs it. A waxy cuticle so thick it can be scraped off with a fingernail helps the leaves hold water.

Reference 2

Photosynthesis

Living things that carry out photosynthesis play an incredibly important role in supporting life on Earth. Photosynthesis is the key biochemical process responsible for capturing energy from the Sun and channeling it into other living systems. This process also releases oxygen as one product. Plants and other photosynthetic organisms, such as algae, microbes, and some protists, use photosynthetic products to fuel the cellular processes they need to live and grow. Humans and other animals cannot do this. We depend on photosynthetic organisms as our energy sources, either directly as food or indirectly as food for the animals we eat.

How Does Photosynthesis Work?

Photosynthesis transforms the carbon from carbon dioxide (CO_2) in the air into carbohydrates. This process, called carbon fixation, is a chemical reaction that requires energy. The energy comes from the Sun in the form of sunlight. Water, which is needed for the reaction to proceed, is transformed into oxygen gas (O_2) as a product of photosynthesis. The overall process (figure R2.1) can be visualized in terms of inputs, energy and organisms, and outputs:

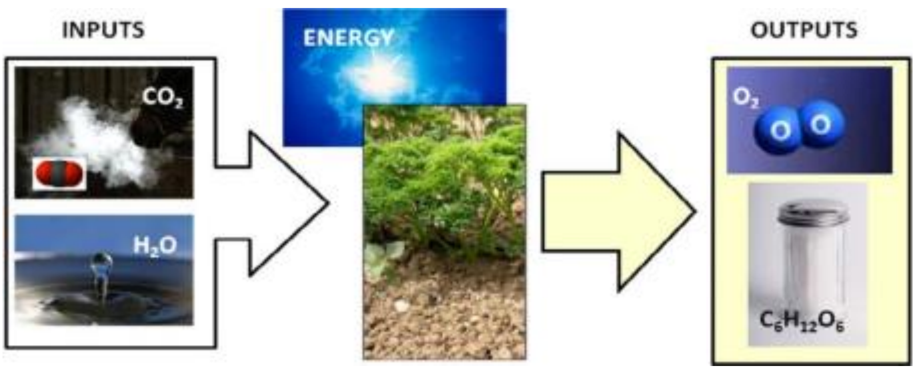

Figure R2.1: Pictorial representation of the photosynthesis process.

Photosynthesis can also be summarized in a simple biochemical equation:

$6\ CO_2$	+	**$6\ H_2O$**	+	**light**	$\longrightarrow$	**$C_6H_{12}O_6$**	+	**$6\ O_2$**
carbon dioxide		water		energy		carbohydrate		oxygen

The carbohydrates produced by photosynthesis can be used in cellular processes or stored for later use. Glucose is the chemical energy source for cellular respiration and also provides chemical structures for the synthesis of new proteins, carbohydrates, and fats needed to make cells, leaves, roots, flowers, seeds, or spores. If more sugar is produced than the plant can use, glucose molecules are linked together to form starch and stored either temporarily or for the long-term, such as during the winter.

Photosynthesis Takes Place in Chloroplasts

Photosynthesis is a series of reactions in which plants use the Sun's energy to synthesize complex, energy-rich molecules from smaller, simpler molecules. In eukaryotic cells all of these reactions take place in the structures known as chloroplasts (figure R2.2). Even when they are removed from a cell in a laboratory, chloroplasts can carry on the entire process of photosynthesis by themselves.

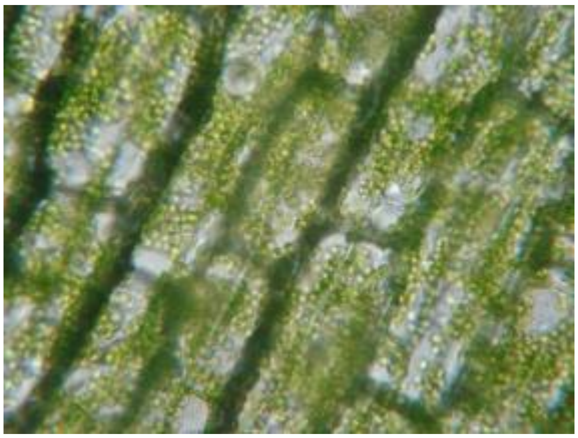

Figure R2.2: Inside each plant cell are many green oval bodies. These bodies, called chloroplasts, are the organelles that capture light for photosynthesis.

Electron micrographs, such as the one in figure R2.3, reveal the internal structure of chloroplasts. They show a highly organized array of internal membranes called thylakoids. Thylakoids may form stacks of flattened disk-shaped structures called grana. Chlorophyll, other pigments, and enzymes are embedded in the thylakoids. Surrounding the thylakoids is the stroma, a colorless substance that contains other enzymes as well as DNA, RNA, and ribosomes.

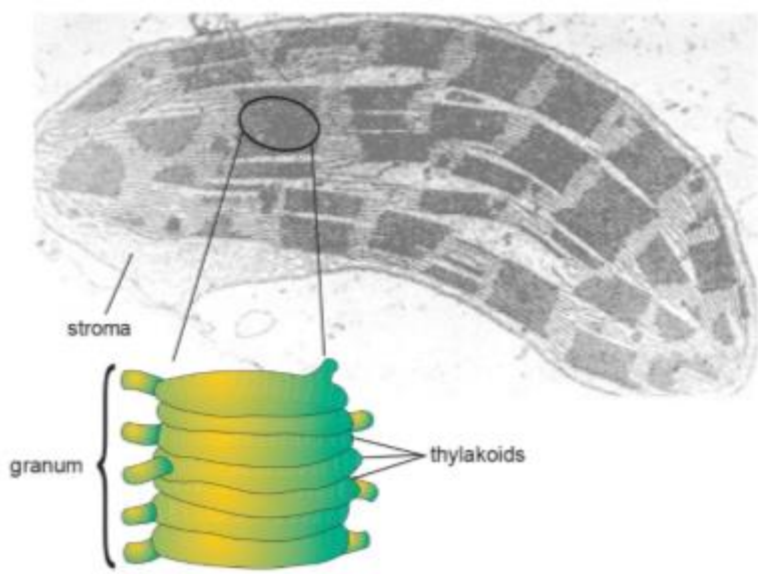

Figure R2.3: This electron micrograph shows a chloroplast in a leaf of corn that has been magnified 24,000 times. The darker areas are stacks of thylakoids called grana. The drawing shows the structure of a granum enlarged still more.

Investigating Light and Dark

Purpose: The purposes of these guided investigations include
1. learning more about photosynthesis and cellular respiration in plants,
2. practicing planning and conducting an investigation, and
3. communicating your experimental design and results to your scientist mentor.

Time Required: 2 class sessions (45 minutes or more)

Materials
The following materials are available. If you need other supplies for your experiment, check with your teacher.

Part 1

Baby spinach leaves
2 clear, wide-mouth plastic cups
Baking soda (sodium bicarbonate) solution (0.2%)
Liquid dish or hand soap (diluted)
Distilled water (room temperature)
Single-hole paper punch (or plastic straw, No. 3 cork borer, or scissors)
1 10-mL or larger disposable syringe, without needles
3 index cards (3 × 5 inch) or small pieces of paper
Small paint brush
Aluminum foil
Empty cardboard box large enough to cover your leaf-disk cup
Permanent marker
Light source (40 W or more)
Ruler
Stopwatch, timer, watch, or clock with a second counter

Part 2

4 large test tubes
Phenol red solution
2 pieces of Elodea (approximately 6-8 cm in length)
2 test tube racks (or beakers to hold the test tubes)
1 straw
Plastic cup
1 piece of plastic wrap
Safety goggles (1 pair per student)

Procedures

1. Participate in a class discussion led by your teacher. The discussion will review aspects of your previous experiment using the leaf disk floatation method and will lead to further questions that can be investigated.

2. In your science notebook, write down the following research question.

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

   The investigations you will do next will help you answer this question.

Part 1

3. Read through the entire procedure for Part 1 before you start designing your investigation.

4. For this investigation, you will modify the leaf disk floatation method to answer this new research question. You will investigate what happens when some leaf disks are placed in the light while others are placed in the dark.

5. Working with your teammates, start developing your experimental design. Keep in mind the following questions as you plan your experiment.
   - How many leaf disks will you use?
   - In what type of solution will you place the leaf disks?
   - How will you keep some leaf disks in the dark?
   - What data will you collect?
   - How frequently will you collect data?
   - What will your data table look like?

   When describing your experimental design, you do not need to write out all the details of each experimental step if they are written somewhere else. For example, you do not need to describe all the steps for preparing your leaf disks. You can simply state that you will use the same basic procedure for preparing leaf disks that you used in the previous investigation. You only need to write things that are new or different in your procedure. Be sure you include your predictions about your investigation's outcomes.

Hint! The time it takes for a leaf disk to respond to the dark condition may not be the same as the time it takes to respond to light.

6. After designing your experiment, ask your teacher to check it before you start conducting your investigation. Make sure you record all your data in your science notebook.

   Important! When you finish collecting data from your investigation, DO NOT discard your materials. KEEP your cups and leaf disks as they are at the end of your data collection. Make sure you keep them in either the light or the dark conditions they have been in. You will use them for the next part of your investigation.

7. As is often the case in science, the results of one experiment can suggest more questions. Write the following research questions in your science notebook. Continuing the investigation will help answer these questions.
   "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. For this phase of the investigation, you and your teammates will design your own experiment. Your starting point will be the leaf disks that you used in the earlier part of the investigation (after Step 6). In your science notebook organize your experimental design by first writing down your predictions about the two research questions from Step 7. Next, answer the following questions about your investigation:
   - What conditions, plants, or other variables will you be manipulating in your experiment?
   - What aspects (variables) of the experiment will be kept the same during the investigation?
   - What data will you collect? What will you measure?
   - How will you present your data to others (charts, graphs, photos, etc.)?
   - How do your predictions reflect your ideas about how photosynthesis and cellular respiration work?
   - Describe how your experiment tells you something about plants in the world around us (not just in a laboratory).

9. After you finish designing your investigations, exchange plans with another team for review. Consider the following questions when reviewing an experiment design:
   - Does this design seem likely to answer the research questions (from Step 7)?
   - Does the design provide enough detail so that I could do the experiment by following the description?
   - Can we provide any feedback that would make the design better?

10. After you get feedback on your design from the other team, work with your team members to make decisions about revising your plan.

11. Before you start your experiment, make sure you have a plan for how you will record your data. If you need to create a data table, make sure you do that before you start the experiment. Also decide who will be responsible for different tasks during the experiment.

12. Begin your experiment. Make sure to take notes in your science notebook if you notice things that are unexpected or different from what you planned.

13. After completing your experiment and cleaning up, summarize and analyze the results. In your science notebook, you should already have written down the research questions and your predicted experimental outcomes. Use complete sentences to describe what the data tell you in terms of answering the research questions. Indicate whether the data support or refute your predictions.

13a. What conditions or variables did you manipulate in your experiment? What were your controls?

13b. Describe evidence from your experiment that helps answer your research questions.

What evidence from your experiment helps you answer your research question?	**Relevant Science Ideas** (You may have information from the reference readings or even prior activities that relate to your experimental findings)

13c. Write a sentence or two answering your research questions.

13d. Were the results of your experiment similar to those of other teams? If not, can you think of reasons to account for the differences?

13e. Did you notice anything during your experiment that seemed unusual or unexpected? Please describe and explain why it might be a problem.

13f. If you did this experiment again, would you change anything in the procedure? Why or why not?

14. Part of analyzing the data is relating it to information that is already known. Read *Reference 3: Cellular Respiration* and *Reference 4: More about Photosynthesis* (or refer back to other references) to help you.

Part 2

15. In this experiment, you will use an indicator called phenol red. Read the following information box, "*Phenol Red Is an Indicator*" to learn about this indicator.

Phenol Red Is an Indicator
An **indicator** is a substance that shows a visible change when conditions in a solution change. Many indicators change color when a solution changes. Phenol red is an indicator dye that changes color when the pH of the solution changes. In other words, phenol red changes color depending on whether the solution becomes more acidic or more basic.

pH 7 (neutral)	phenol red is orange or light pink
pH 6.4 or below (acidic)	phenol red turns yellow
pH 8.2 or above (basic)	phenol red turns dark pink or red

These color changes give you a quick way to see how the pH of a solution changes just by looking.

16. Pour some phenol red solution into a clear plastic cup. Insert a straw and then cover the cup with plastic wrap (around the straw). Using a straw, blow into the phenol red solution. Blow gently at first so you don't blow solution out of the cup.

    Make sure you are wearing goggles!

    Do not ingest the phenol red solution.

17. Answer the following questions in your science notebook.
    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. Label 2 of the test tubes "light" and 2 of the test tubes "dark."

19. Add 1 piece of Elodea to one of the "light" tubes and to one of the "dark" tubes.

20. Add phenol red solution to all four tubes. Make sure the Elodea is completely covered. The level of phenol red solution should be about the same in all 4 tubes. Cover the top of each tube with a piece of plastic wrap.

21. Cover the "dark" tubes (one with and one without Elodea) under a box or wrap in aluminum foil so it is completely dark.

22. Place the "light" tubes under a lamp.

23. Draw a picture in your lab notebook of your experimental setup. Make sure you include details about what the phenol red solution looks like at the beginning of the experiment.

24. Use the information that you read about phenol red as well as what you know about photosynthesis to make predictions about what will happen in each of the four tubes in your experiment. Write your predictions in your notebook.

25. Look at all four test tubes after approximately 24 hours. Answer the following questions in your notebook.

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

    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.

Your teacher may instruct you to communicate about your experiments with your science mentor. It may be helpful to take photographs of your experimental setup to include with information about your research questions, predictions, and data analysis.

ResearchBlog Opportunity

Part 3

26. Think back to the experiments you analyzed at the beginning of this module—the von Helmont experiment with the willow tree and the radish seed experiment. Based on what you now know about photosynthesis and cellular respiration, how would you account for the changes in plant mass in those experiments? Write down any changes to your thinking in your science notebook.

Reference 3

Cellular Respiration

Cellular respiration is a critical biochemical process for life on Earth. All cells require a continuous supply of energy to maintain order, build organic molecules, grow, and carry on all their other activities. Plants and other organisms can recover the solar energy stored in the molecular bonds of glucose by breaking down the sugar. Energy can then be stored in the bonds of ATP, which is used for a variety of processes that a cell must carry out to live. Cellular respiration is the most efficient way that glucose can be broken down to generate energy for other cellular reactions. In a sense, cellular respiration can be thought of as a type of controlled burning. When something is burned, a great deal of energy is released. The process requires oxygen and releases carbon dioxide and water and produces ATP. Cellular respiration can be summarized as:

$C_6H_{12}O_6$	+	$6\ O_2$	$\longrightarrow$	$6\ CO_2$	+	$6\ H_2O$	+	32 ATP & heat
carbohydrate		oxygen		carbon dioxide		water		energy

During cellular respiration, the energy stored in a glucose molecule is released slowly as the molecule is broken down (figure R3.1). Cellular respiration occurs in three phases. In the first steps, known as **glycolysis**, glucose is split into two 3-carbon molecules. This releases energy, some of which is transferred to ATP. Glycolysis takes place in the cell cytoplasm. The second stage is called the **Krebs cycle**. During the Krebs cycle, each of the 3-carbon molecules is disassembled in a series of reactions to form six carbon dioxide molecules. Hydrogen atoms are also released. Special molecules carry the hydrogen atoms to the third stage, the electron transport system. This system stores the relatively large amount of energy present in a glucose molecule in several smaller and more useful packets of ATP. Each hydrogen atom is separated into an electron and a proton. The electrons are eventually taken up by oxygen molecules to form water. The Krebs cycle and the **electron transport system** operate in the mitochondria (figure R3.2).

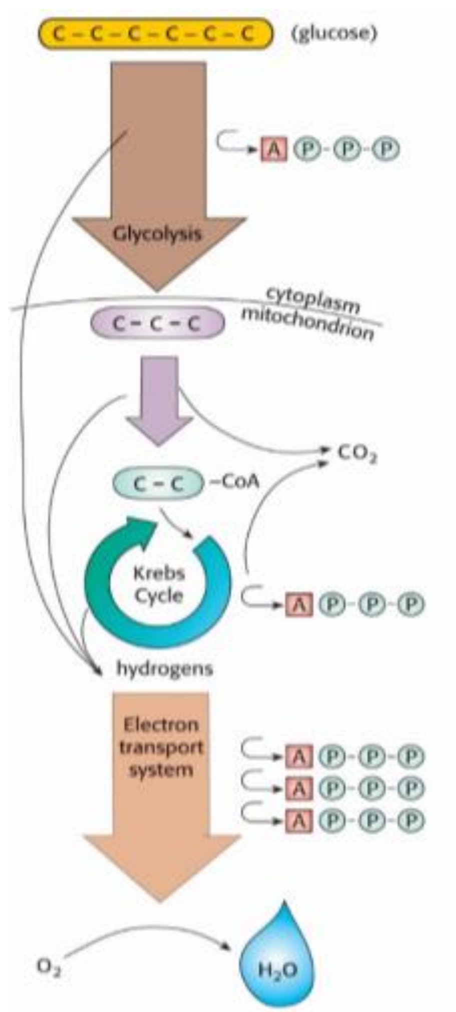

Figure R3.1: Cellular respiration occurs in three stages. Glycolysis occurs in the cytoplasm; the Krebs cycle and the electron transport system take place in mitochondria.

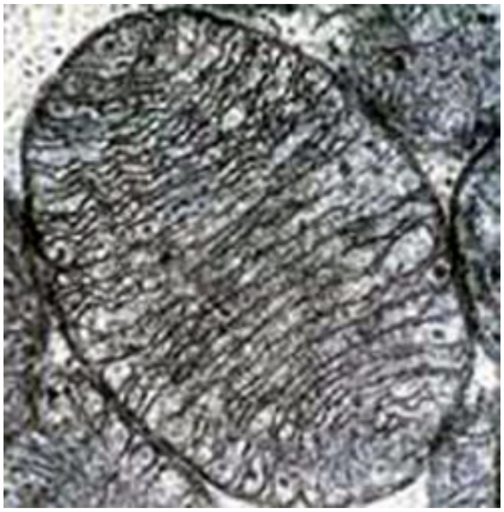

Figure R3.2: Mitochondria carry out two of the three phases of cellular respiration. The fingerlike projections, or cristae, are folds in the inner membrane which separates the intermembrane space and the large matrix.

Where Does the Mass of a Plant Come From?

When you started this unit you were asked to think about how a tiny seed can become one of the tallest trees on Earth—a giant sequoia. So where *does* all this mass come from—and what does photosynthesis have to do with it?

Remember that carbohydrates, including glucose, are outputs of photosynthesis. Glucose is a sugar made up of carbon, hydrogen, and oxygen. These carbon, hydrogen, and oxygen atoms then recombine to form glucose which is then used to make more new compounds that the plants need, including proteins, fats, and other carbohydrates that the plants use to survive and grow. This means that the mass in plants comes mostly from photosynthesis. It's amazing but true: Almost all of the mass in the giant sequoia comes from carbon dioxide in the atmosphere as the process of photosynthesis fixes one carbon dioxide molecule after another!

For example, glucose molecules, that were produced during photosynthesis from carbon dioxide and water, link together to form the polymer cellulose. Cellulose is a chain of several hundred to many thousands of linked glucose molecules. You might know that cellulose is the substance that forms the cell walls surrounding plant cells. Cellulose is the most abundant organic polymer on Earth. Approximately 50 percent of the matter in a tree is cellulose. Cellulose is also the substance that makes tree trunks and limbs strong.

Cellular Respiration and Mass

Virtually all cells, including plant cells, go through cellular respiration to break down food to provide the energy needed for normal functioning and growth. Similar to photosynthesis, the atoms in food molecules are rearranged during cellular respiration. Remember that one of the inputs to cellular respiration is carbohydrate, specifically glucose. Plants form glucose by photosynthesis and animals get glucose by breaking down the food they eat. During cellular respiration, glucose combines with oxygen to release energy and to form carbon dioxide and water. Most of the carbon dioxide in animals is released into the air when the animal breathes. This carbon dioxide can then be used by plants for photosynthesis. When plants respire, they also release carbon dioxide that can be used for photosynthesis, or the excess may be removed from the plant through the leaves.

Plants and animals can also store energy in molecules such as fat or starch. In animals, including humans, if you do not have enough glucose in your bloodstream (from the food you eat) to supply your cells with glucose, your body will break down these fats into glucose for your body to use for cellular respiration. In this way, the carbon that is in the body fat is transformed to carbon dioxide which you breathe out.

Unlike animals, green plants go through both photosynthesis and cellular respiration. Determining which process is occurring at a greater rate depends on the state of the plant. If the plant is growing and gaining mass, which would be occurring at a greater rate, photosynthesis or cellular respiration?

Reference 4

More about Photosynthesis

Photosynthesis Requires Light

Most life on Earth depends on the continual release of light energy from the Sun. Of the sunlight that reaches our planet, only about one percent is involved in photosynthesis. The rest is absorbed or reflected by clouds or dust in Earth's atmosphere or by Earth's surface. Visible light, which is only a small fraction of the energy coming from the Sun, consists of a spectrum of colors, each with a different wavelength and energy content (figure R4.1). When light strikes an object, it may be transmitted, absorbed, or reflected. In plant cells, several different pigments can absorb light energy. Each pigment is a chemical compound that absorbs only certain wavelengths of light and reflects or transmits all others. Green plants, for example, appear green because chlorophyll absorbs most wavelengths of visible light except green, which it reflects.

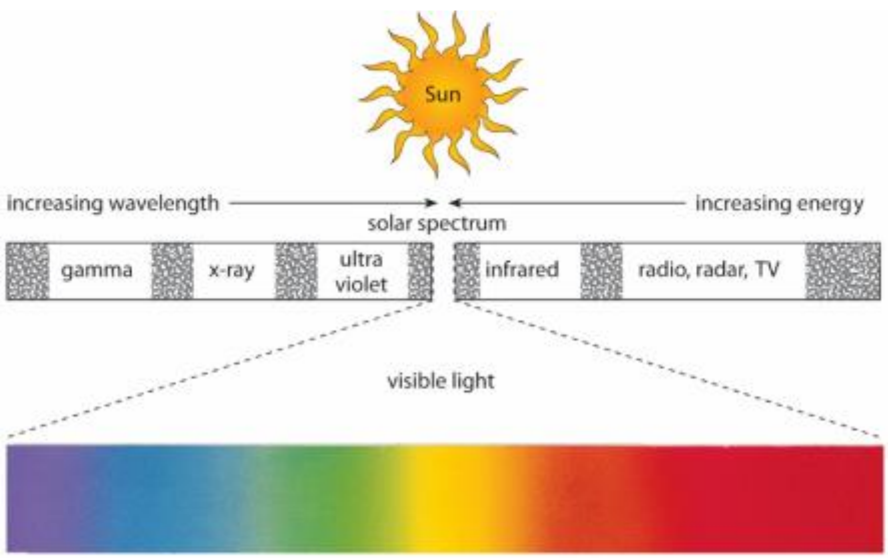

Figure R4.1: Radiations from the Sun form a continuous series. The range of radiations that organisms can detect with the eyes—visible light—is roughly the same range that plants use. Shorter wavelengths (blue light) are more energetic than longer wavelengths (red light). Leaves are green because chlorophyll absorbs red and blue wavelengths and only a little green. Chlorophyll mainly reflects green light.

Photosynthesis depends on the green pigment chlorophyll, which occurs in several forms. Chlorophyll *a* apparently is present in all photosynthetic plants; other forms may be present in different combinations. Figure R4.2 shows an absorption spectrum (a simple graph that displays the percentage of light absorbed by a pigment at each wavelength) for chlorophylls *a* and *b*. Note that the chlorophylls absorb much of the light in the violet/blue and orange/red wavelengths and very little or none in the green/yellow wavelengths. Plants can use only the energy from absorbed wavelengths. The action spectrum at the top of figure R4.2 shows this clearly. An action spectrum measures the rate of photosynthesis at certain wavelengths of light.

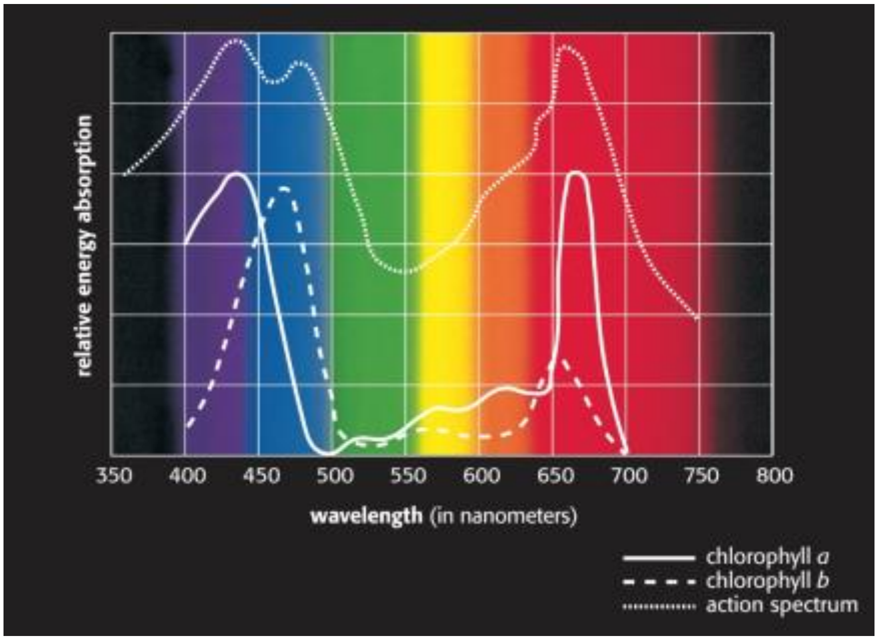

Figure R4.2: The upper curve shows the action spectrum for photosynthesis. The lower curves show absorption spectra for chlorophylls *a* and *b*. It is clear from comparing the action spectra that both chlorophylls are required to absorb the full range of wavelengths of light used in photosynthesis. Which wavelengths do these chlorophylls absorb most? least?

Photosynthesis Involves Many Interdependent Reactions

Three major events occur in photosynthesis: (1) absorption of light energy, (2) conversion of light energy into chemical energy, and (3) storage of chemical energy in carbohydrates (sugars). The reactions by which these events occur may be considered in two distinct but interdependent groups, shown in figure R4.3.

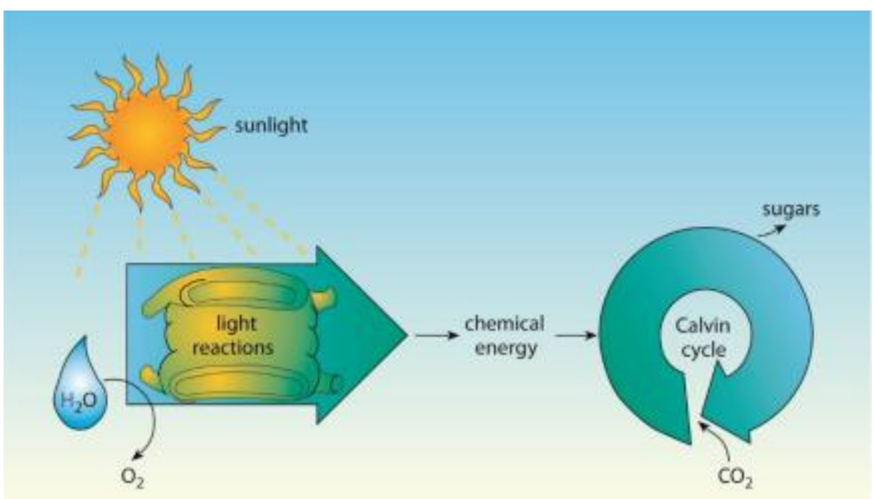

Figure R4.3: The reactions of photosynthesis occur in two groups: the light reactions and the Calvin cycle.

In the first group of reactions, the light reactions, light is absorbed and converted into chemical energy as short-lived, energy-rich molecules are formed. These molecules are then used to make 3-carbon sugars from carbon dioxide in the second group of reactions known as the Calvin cycle. In this cycle, chemical energy is stored in the carbohydrates, and new carbon is incorporated into the plant for future growth.

The light reactions of photosynthesis convert the energy in visible light into the chemical energy that powers sugar production. In these reactions, chlorophyll and other pigments in the thylakoid absorb light energy; water molecules are split into hydrogen and oxygen, releasing oxygen gas to the atmosphere; and light energy is stored as chemical energy.

The enzyme-catalyzed reactions of the Calvin cycle do not involve the absorption of light energy. They do, however, require the ATP and energy-rich molecules produced in the light reactions. The Calvin cycle is a series of reactions in which carbon dioxide is combined with the hydrogen split from water in the light reactions.

The Calvin cycle and the Krebs cycle are similar in involving many rearrangements of carbon chains. Both produce carbon skeletons for use in biosynthesis reactions. Carbon dioxide is used in the Calvin cycle and released in the Krebs cycle. Much ATP is used in the Calvin cycle, and a little is formed in the Krebs cycle.

Photosynthesis takes place in cellular organelles called chloroplasts. Inside chloroplasts, green-colored chlorophylls and other plant pigments capture light energy during a phase of photosynthesis called the light reactions. The captured light energy is used to transform water molecules into oxygen, which also releases electrons and hydrogen ions. These are bound to NADP+ to form NADPH, a temporary storage form of energy. In the second phase of photosynthesis, the Calvin cycle, captured light energy and hydrogen in NADPH is used to fix carbon dioxide, forming the sugar glucose and regenerating NADP+. The light energy that was captured from sunlight is thus partially stored in the chemical bonds of the sugar. By photosynthesis in green tissues, plants produce usable forms of energy and carbon that they need to live and grow.

What Makes Plants Green?
The colors we see are wavelengths of light reflected. Plants are green because their chlorophylls reflect green light. However, chlorophylls capture other wavelengths of light and use the energy for photosynthesis. Land plants have two major forms of chlorophyll, and distinct families of algae produce three other types. Chlorophylls *a* and *b*, found in land plants, absorb energy in the wavelengths shown below.

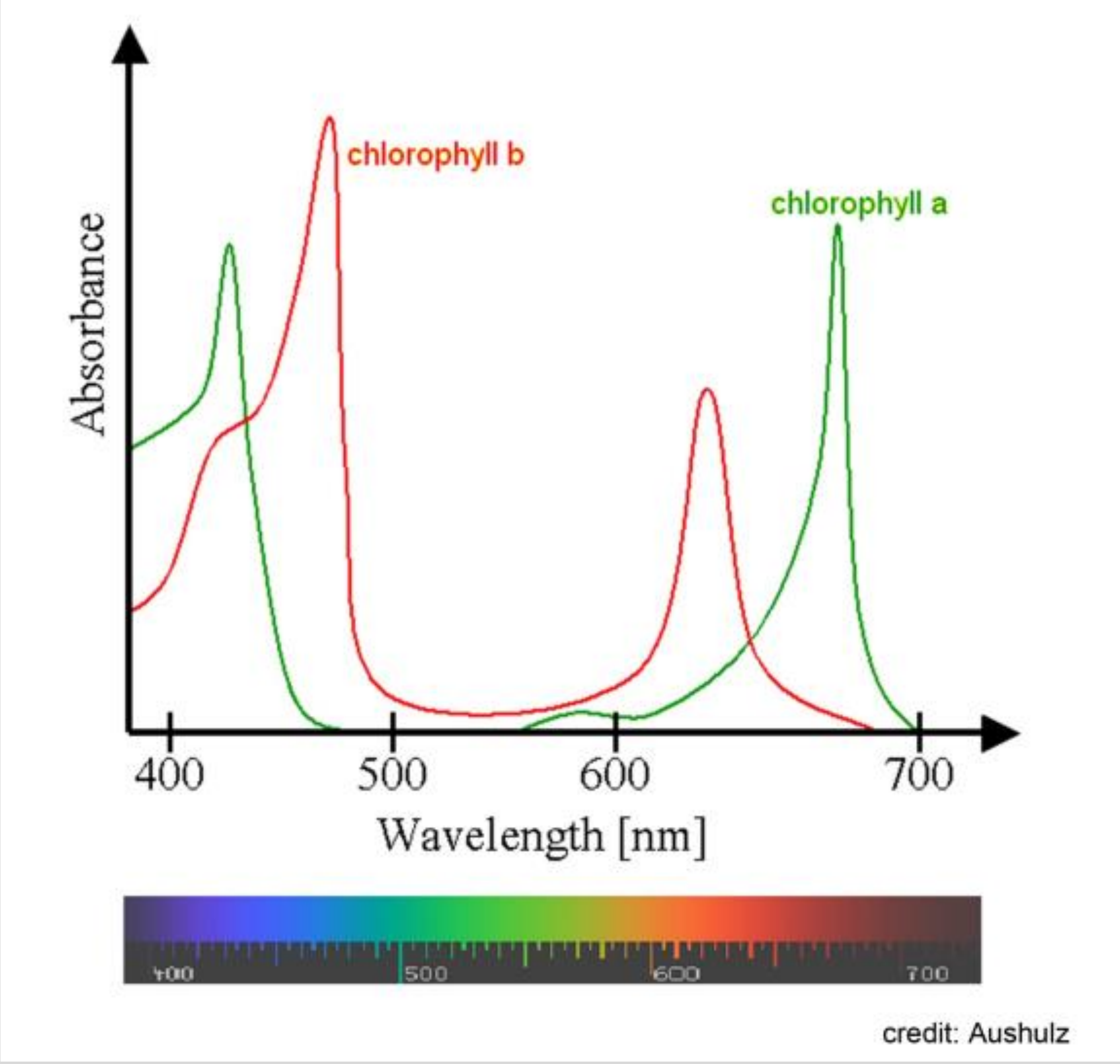

Figure R4.4: Chlorophylls *a* and *b* differ slightly in their absorption of visible light. For example, light with a wavelength of 460 nm is not significantly absorbed by chlorophyll *a* but will instead by absorbed by chlorophyll *b*. The two forms of chlorophyll in plants complement enable plants to meet their energy requirements by absorbing light from the blue and red parts of the spectrum.

planting science

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

Purpose: The purposes of this open-inquiry investigation include
1. building on your knowledge of photosynthesis and cellular respiration,
2. developing testable research questions,
3. gaining experience planning and conducting an investigation, and
4. communicating your experimental design and results to your scientist mentor.

Time Required: 6 class sessions (45 minutes or more).

Materials
To conduct your investigation, you will of course need materials and supplies. Your teacher will provide you with similar types of materials that you have used before. Depending on your investigation, however, you may need additional supplies. After brainstorming ideas with your teammates, and with advice from your scientist mentor, you will settle on a research question. You will need to check with your teacher to find out if the needed materials are available for your use.

Procedures

Through the previous activities you have learned not only about photosynthesis and cellular respiration but also about how to conduct scientific investigations. In this independent investigation, you will have an opportunity to study some aspect of your own choosing about how the environment affects a plant's ability to carry out photosynthesis and/or cellular respiration. At this point, you have examined how light influences these two processes. Now you have a chance to explore more broadly.

1. Read through all of the steps in this activity before you begin your investigation.

2. Review the Student Roadmap Through an Investigation resource (https://www.plantingscience.org/resourcelibrary/studentlibrary/studentroadmaps) on the PlantingScience website. This information should help guide you through the process of planning and carrying out your investigation.

3. Think about what interests you about the topic of photosynthesis and/or cellular respiration. Click on the *Explore Your Topic* link in the Student Roadmap and read through it for advice on how to get started and brainstorm ideas with your teammates.

4. For the purpose of this investigation, your research question must satisfy two main requirements:
   1) the question must be testable and
   2) the question must relate to photosynthesis and/or cellular respiration.

How do you know if a question is testable? Some characteristics of testable questions are listed below.

Testable questions
- ask about objects, organisms, and events that are part of the natural world;
- can be answered through collecting and analyzing measurable evidence;
- can be answered through investigations that involve experiments, observations, or surveys;
- do not relate to the supernatural or to nonmeasurable phenomena; and
- relate to scientific ideas and not preferences or morals.

5. Next, click on and read the information in the *Research Question* section of the Student Roadmap. This section has more to say about where good testable questions come from, deciding if the question is meaningful, and relating questions to predictions.

6. With your teammates, think of 2–3 research questions that you might like to investigate. For each of your ideas, respond to the following in your science notebooks.
   - What is the research question?
   - Why do you think this investigation will help you learn something new about photosynthesis and/or cellular respiration?
   - Write a brief outline of how you will do your investigation.
   - What data will you measure and record?
   - What supplies or equipment would be necessary for investigating this question?

It is a good idea to think of more than one research question. As you progress in planning your investigation, you may find that some research questions seem more interesting or more suitable for investigation in the classroom. It's best to get your ideas on paper now and revise them as you go along.

You may come up with a perfectly good research question that interests you but cannot be answered with the resources available to you in the classroom. This is an unfortunate limitation that even scientists must deal with. Be sure to ask your teacher and mentor about such practical concerns when they come up.

Your research question might be addressed using the leaf disk floatation method you have already used, or it might require you to use a new method. Another PlantingScience resource called the Power of Sunlight Toolkit (https://plantingscience.org/resourcelibrary/planttoolkit) is available for you to explore. Here you can learn about different methods used to conduct both field and laboratory investigations. It's a good idea to explore this toolkit and discuss with your teacher the available equipment and supplies before committing to a particular series of experiments.

7. After your team brainstorms 2–3 ideas for research questions and has completed the questions in Step 6, take a photo of your answers to the questions and upload it to your blog page for your mentor to review. Make sure the work you photograph include ideas from all team members.

Your scientist mentor can use the information you post to give you some feedback on your research questions. Your mentor may help you think about which questions are testable and which ones may need to be revised.

8. After getting feedback from your mentor, work with your teammates to select the one research question your team will investigate. Add information to your notes from Step 6 to reflect the feedback your team received from your mentor.

9. Now it is time to design an experiment to answer your research question. Click on the *Planning Your Study* link in the Student Roadmap. Here you will find guidance on matching your experimental method to your research question as well as developing research and data collection plans.

10. Work with your team to design your investigation for your chosen research question. The following steps should help you think through your experimental design in more detail.
    - 10a. What is your research question?
    - 10b. What conditions, plants, treatments, or other variables will you be changing in your experiment?
    - 10c. What conditions will you keep the same throughout your experiment?
    - 10d. Describe the steps you will follow to complete your experiment.
    - 10e. What will you measure? What data will you collect?
    - 10f. How will you present your data to others (charts, graphs, photos, and so forth)?
    - 10g. What do you predict will happen in this investigation? Why do you think this?
    - 10h. Describe how your experiment tells you something about plants in the world around us.

11. Make sure all team members agree on the experimental design. Take photographs of your notebook pages and upload those to your team's project page for your mentor to review.

12. After you have feedback from your mentor on the experimental design, begin your investigation. It may be helpful to try out any new techniques and perfect your procedure before starting your full investigation. Don't be afraid to ask questions of your mentor if you run into trouble. Your experiment may produce interesting results that can lead to a new research question.

13. During and after each experiment, record, photograph, illustrate, or graph your data as needed. Summarizing the data in the best way will help you see trends and patterns in your observations and help you make sense of them. This type of analysis can also open up more questions that might lead to new experiments.

14. After completing your data collection, it is time for you and your teammates to make sense of your results. Use the following questions to help you connect your data to environmental factors that influence photosynthesis and/or cellular respiration as addressed in your research question. This will also help summarize your entire investigation for sharing with your mentor. Record the following in your science notebook.

14a. Write out your research questions under the heading, “Research Question(s)”.

14b. Did you make any changes to your experimental design as you were doing your experiment? If so, describe your changes.

14c. In a table like the one below, describe evidence from your experiment that helps answer your research questions.

What evidence from your experiment helps you answer your research question?	**Explain your reasoning.**

14d. Write a sentence summarizing your claim (answer to the question).

14e. How do the data help you explain the biological processes of photosynthesis and cellular respiration?

Hint: *Make sure to link your experimental data and your reasoning to your answer to the research question.*

14f. Did you notice anything during your experiment that seemed unusual or problematic? Please describe and explain why it might be a problem. Do any of the data you collected not support your claim?

14g. If you did this experiment again, would you change anything in the procedure? Why or why not?

14h. Write any other notes or comments you wish to share with your mentor.

15. After your team has finished writing answers to the questions in Step 14, take a picture of your team’s answers and post to your project page for your mentor.

16. As a team, prepare to present your investigation and outcomes to your class. Make sure everyone on the team has a role in the presentation. Include any feedback or ideas from your mentor to help your presentation.

17. Present your findings to the class and participate in the discussions about different teams' investigations and how each contributes to understanding more about photosynthesis and cellular respiration.

18. If time permits, conduct another open inquiry investigation. This may be something from your original set of interesting research questions or a new idea that arose when you were conducting your investigation.

Information about the following experimental methods is available in the PlantingScience Power of Sunlight Toolkit:

- Measuring Cellular Respiration Using a Respirometer
- Measuring Photosynthesis and Respiration Using a Computer-Based Probe
- Monitoring pH to Assess Photosynthesis and Respiration of Aquatic Plants
- Identifying Starch in Plant Leaves Using an Iodine Staining Method
- Visualizing Plant Cells and Chloroplasts Using a Microscope
- Identifying Chlorophyll and Other Plant Pigments
- Visualizing and Counting Stomates Using the Epidermal Peel Method
- Quantifying Fresh and Dry Mass of Plants
- Preparation of Citrate-Phosphate Buffer for Maintaining pH

If you think that one or more of the above methods might help your team test a research question that interests you, ask your teacher which ones are available for you to use.