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ABSTRACT

Designed to address the major conceptual problems associated with respiration and photosynthesis, this module can be used with high school students or college nonscience majors including those in elementary education. It is one in a series developed by the project Overcoming Critical Barriers to Learning in Nonmajors' Science Courses. The materials offer guidance to teachers in diagnosing student deficiencies. in creating dissatisfaction with misconceptions, and in providing opportunities for application and practice. This module contains: (1) an introduction (discussing misconceptions related to photosynthesis and respiration and explaining how to use the module to overcome these barriers); (2) diagnostic test and commentary (designed to be used as a pretest and/or posttest); (3) materials for lecture or discussion with commentary (consisting of a series of copy-ready masters for use as overhead transparencies and student handouts); (4) laboratory activities and commentary (including lessons on molecular models of respiration and photosynthesis, food storage in coleus plants, and respiration and breathing rate); and (5) problem sets (addressing specific misconceptions on respiration and food for plants and animals). All instructional materials for the students are juxtaposed with instructor commentaries. (ML)

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Abstract

This module is one in a series developed by the project Overcoming Critical Barriers to Learning in Nonmajors' Science Courses. Each module is self-contained and addresses a specific topic in the physical and biological sciences: evolution by natural selection, light, heat and temperature, and ecology. The modules are appropriate for use with high school students or college nonscience majors including those in elementary education.

This module on respiration and photosynthesis is arranged with materials for the instructor on one page juxtaposed by those for the students. A short introductory essay describes the major conceptual problems found among students: thinking that respiration is breathing and that plants take in food. It then explains how activities in the unit are intended to help students overcome these problems.

A diagnostic test, which could be used as a pretest, posttest, or both, is designed to reveal important student misconceptions and provides notes for the instructor to interpret student responses. A set of student handouts and masters for overhead transparencies includes notes for the instructor about conceptual problems each is designed to address. Laboratory activities on molecular models of respiration and photosynthesis, photosynthesis and food storage in coleus plants, and energy requirements and breathing rates are followed by problem sets on respiration and food for plants and animals designed to address specific student misconceptions.

The first three parts can be used independently or in combination with the laboratory activities and problem sets after students have learned the relevant concepts. The materials help instructors accomplish three tasks essential to overcoming critical barriers to student learning: diagnosing student deficiencies, creating dissatisfaction with misconceptions, and providing opportunity for application and practice.

About the Author

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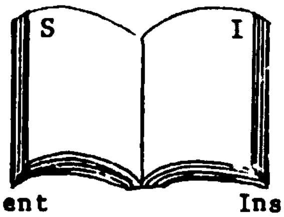


Student Pages

Instructor Pages

Pages with instructional materials to be used by students are on the left side

Pages with information for instructors are on the right side.

Preface

We hope that using this module helps you gain insight into your students' understanding, and misunderstanding, of respiration and photosynthesis. One of its main purposes is to provide opportunities for you to learn about your students' thinking. Because of what you discover about your students' thinking, you may have to move more slowly and cover less content than you would like. That may seem like a problem, but we don't think so. It is far better to have students learn to understand a little science than to have them misunderstand a lot.

I. Introduction

Memorizing or Making Sense?

"What does the term photosynthesis mean to you?"
"What does the term respiration mean to you?"

If these questions were posed to your students after they had taken your course in biology, what are the most basic, critical concepts that you would want them to remember? What are the most important ideas about respiration and photosynthesis that students must comprehend if they are going to be able to make sense of other biological concepts such as ecological relationships between organisms and physiological interactions within organisms? Is it sufficient that a student has correctly memorized the equations for photosynthesis and respiration? We believe not. Even a minimal understanding of these topics goes far beyond memorizing a pair of chemical formulas. We will begin by describing what we consider a minimal understanding of respiration and photosynthesis to be.

Importance of understanding respiration and photosynthesis. Because respiration and photosynthesis play such central roles in biologists' understanding of living systems, it is important that students develop an understanding of them that includes a sense of their role in larger biological systems and processes. For example, our digestive systems, circulatory systems, and respiratory systems all function in certain ways because of the needs of our body cells to engage in respiration.

Even more important, an understanding of respiration and photosynthesis is a prerequisite for any systematic understanding of ecology. The distinction between producers and consumers and discussions of food chains and food webs cannot be meaningful to students who do not understand photosynthesis and respiration. Photosynthesis and respiration are the essential processes in the most basic of all matter cycles: the carbon cycle. The reactants for one process are the products of the other, so that matter cycles endlessly through the two processes. Finally, respiration and photosynthesis play essential roles in the flow of energy throughout the ecosystem. It is through these processes that the energy in sunlight is captured and made available to support metabolic processes in all living organisms.

Conceptual goals of the module. This module is designed to help students abandon the learning strategy of simply memorizing "facts" about respiration and photosynthesis. Instead, the materials focus on helping students make sense of the key concepts or patterns of thought that unify biological understanding of photosynthesis and respiration. The ultimate goal of this module is to get students to think about the processes of photosynthesis and respiration in terms of the energy flow and changes in matter within organisms and within ecosystems.

The three concepts emphasized in this module and the reasons for their importance from the students' point of view are as follows:

1. Food. This word is rarely used with precision by either students or biologists. Biological usage, however, tends to be fairly consistent.

Biologists g :ally use the word *food* to refer to organic compounds that organisms can use for growth and metabolism. Other substances that organisms need, such as water, oxygen, and mineral salts, are not considered food. It is this distinction that makes the statement "plants make their own food" meaningful.

The biological distinction between usable organic substances (food) and inorganic substances (not food) is also critical to understanding the significance of photosynthesis and respiration. The glucose produced by photosynthesis is food even though the carbon dioxide and water from which glucose is made are not food. Glucose provides the essential organic raw material that plants and other organisms can use to produce the many other organic compounds that biologists also refer to as food. Food is broken down to release energy in respiration.

2. Energy. The significance of the distinction between organic and inorganic substances lies primarily in energy relationships. Photosynthesis captures energy from sunlight and converts it to chemical potential energy in organic compounds. This energy is later released for use by cells through respiration. These processes are significant in that they are the primary pathways for energy use in living systems.

Energy, however, is an abstract and difficult concept for most students. In order to appreciate the significance of energy in living systems, they must appreciate the critical role that it plays in all life functions, they must understand the many forms it can take and transformations it can undergo, and they must realize that since energy is conserved, its path can be traced through any interaction or system. This ability to follow the path that energy takes and the transformations that it undergoes is critical to a biological understanding of respiration and photosynthesis.

3. Matter. Biologists' conceptions of respiration and photosynthesis also depend on a chemical understanding of the nature of matter. The processes are described as chemical reactions, and the substances involved are characterized as chemical compounds. Most students in high school and college nonmajors' biology courses, however, have never taken a chemistry course, so they often find the formulas and reactions mysterious or only partially understandable.

We have chosen to emphasize these three concepts for several reasons. First, we believe these concepts are absolutely essential in order for students to make sense of photosynthesis and respiration. Secondly, these concepts are difficult for students to understand. Simply explaining the concepts to students is not enough, no matter how skillful those explanations are. Third, most textbooks and courses fail to treat these concepts adequately, forcing students to grapple with more advanced and difficult concepts before they have mastered these fundamental ideas.

If you believe that your students need only a quick review of these basic concepts before moving on to the development of more detailed understandings of photosynthesis and respiration, we urge you to read the next section about students' misconceptions, then give your students our diagnostic pretest. The pretest is designed to reveal whether your students share the misconceptions about respiration and photosynthesis that we found in our own students. We have developed this module because we believe that those misconceptions are far more common, and far more important, than most teachers realize.

Critical Barriers to Understanding Respiration and Photosynthesis

The students in our college nonmajors biology course have taken, and passed, an average of 1.5 years of previous high school and college biology courses. Thus they have already been exposed to instruction about respiration and photosynthesis, and their answers to the questions about respiration and photosynthesis posed at the beginning of this module give some indication of what they have learned and retained from their previous instruction and personal experiences. Typical student responses to those questions, which are included in our pretest, are the following:

What does respiration mean to you?

Exhaling CO_2 for humans, exhaling O_2 for plants.
Breathing.
Has lungs to breathe with.
Air in/air out.

These student answers and others on our pretests suggest that many students have memorized their way through biology without making sense of the most basic, critical concepts they are taught. The formula for photosynthesis may have been memorized to pass a test, but the students continue to believe that plants get their food by taking it in from the soil or the air and that respiration is simply the exchange of O_2 for CO_2 in the lungs. When asked to describe food for a bean plant, students often gave answers like these:

The chemicals it receives from the sunlight, soil, and fertilizer.
The nutrients in the soil that it's planted in.

What does photosynthesis mean to you?

All I remember is it has to do with green plants and light.
Plants take in CO_2 and change it to O_2.
I remember needing to know a formula for it in high school.
When the sun is directl[illegible] the pla[illegible]t--the plant will go through photosynthesis.
Keeps plants green.
Green plants turn sun and CO_2 into chlorophyll.

These students all indicated on other questions on our pretest that plants get all or some of their food by absorbing it through the roots from the soil. When asked what portion of plants' food is made by the plant, these students all answered "some" (the rest is absorbed through the roots or from the air) or "none."

Thus students' understanding of the processes of respiration and photosynthesis remains fundamentally disjointed, incoherent, and partially erroneous. The critical concept that plants can take in inorganic matter and change it into organic matter, which serves as food, has been missed.

Why do students memorize when they should be trying to understand? Why do they end instruction about respiration and photosynthesis holding such incomplete and inaccurate ideas about food-energy relationships? This module is based on one answer to the question. The answer arises from extensive research comparing inexperienced students with scientific experts as both deal with scientific problems. In general, this research shows that the students think and act in ways that make sense to them, but that are incompatible with scientific thought. For example, many students have trouble learning about photosynthesis because they assume that plants, like us, must somehow take in food from the environment.

The presence of these alternate ways of thinking makes the learning of science a far more complicated process than scientists normally imagine. Students cannot simply absorb or memorize scientific content. They must reassess and restructure their intuitive knowledge of the world. Furthermore, they must abandon misconceptions or habits of thought that have served them well all their lives in favor of new and unfamiliar ideas.

Old habits of thought can be amazingly resistant to change through instruction. They persist even after students have apparently learned the scientific alternatives. Many students become quite good at learning what is expected of them to pass science tests while continuing to use their old ideas in "real world" situations. We have adopted a phrase from David Hawkins and describe these enduring habits of thought that interfere with scientific thinking as "critical barriers" to the learning of science. Hawkins defines these as "irretrievably elementary stumbling blocks" that prevent students from fully understanding scientific concepts and principles. This module is the product of a research and development project in which we have tried to understand the critical barriers to student learning in a nonmajors' biology course, then design materials and activities that will help students overcome those barriers.

Beginning biology students usually have several important misconceptions or habits of thought that act as critical barriers to their understanding of respiration and photosynthesis. Some of these barriers that we have found are described below.

Misconceptions about respiration. As the student answers quoted earlier show, most students think of respiration as a synonym for breathing. Although this definition is reasonable and appropriate in some contexts, we believe that it constitutes a critical barrier to a full understanding of respiration in the biological sense. Students who think of respiration as breathing tend to focus primarily on the gas exchange between oxygen and carbon dioxide in the lungs of land animals. They show little awareness of the many other contexts in which cellular respiration occurs, and they cannot explain how we use oxygen or how exhaled carbon dioxide is produced. They are generally unaware that food plays any role in respiration. Finally, they show little appreciation of the function of respiration: to make energy available for cellular metabolism.

The table below summarizes some of the important contrasts between naive and biological conceptions of respiration. Note that the biological definition of respiration is a broad one, including both aerobic and anaerobic processes. Many texts distinguish respiration, which they define strictly as an aerobic process, from glycolysis and fermentation.

Table I
Students' Understanding of Respiration

Issue	Biological Conception	Naive Conception
The nature and function of respiration	Respiration is a process in which chemical energy in food is converted to a form usable by the cell (ATP).	Respiration is breathing.
Where respiration takes place	Aerobic or anaerobic respiration takes place in all living cells.	Respiration takes place in the lungs of land animals.
Respiration as a chemical conversion	Food + O_2 --> CO_2 + H_2O (aerobic respiration)	O_2 --> CO_2
Respiration as an energy conversion	Food energy --> ATP or energy for cells	No awareness

Misconceptions about photosynthesis. Most students enter our course with vague and confused notions about photosynthesis and the role it plays in plant growth and development. The misconceptions that seem to be the most important barriers to achieving a biological understanding of photosynthesis focus on two more common and apparently simple terms: food and light.

Biologists use the term food to describe a class of chemical compounds, all organic, that can be used by organisms as a source of energy. In contrast, our students tend to define food in a much broader and vaguer sense. Many students, for example, consider water, "plant food," or other materials that plants absorb from the soil to be food for plants. Other students define food simply as "energy." For students who are not clear about what biologists consider food, the statement "plants make their own food" can be virtually incomprehensible, and chemical formulas describing photosynthesis can be seen as isolated facts to be memorized.

Our students are also generally confused about the role that light plays in plant growth and development. Although most students begin our courses believing that plants need light to live and grow, very few can define the function of light for green plants. For example, although most students are aware that plants die when left in the dark, they tend to think of the cause of death as a kind of sickness caused by lack of light, rather than as starvation caused by the plants' inability to make food.

Table 2 summarizes some of the contrasts between biological conceptions and common naive conceptions of photosynthesis.

Table 2
Students' Understanding of Photosynthesis

Issue	Biological Conception	Naive Conception
Role of photosynthesis in plant growth and development	Plants use energy from sunlight to convert inorganic materials into food.	Plants need light to grow and survive, but food comes at least partially from outside of the plant.
Nature of food for plants	Food consists of high-energy organic compounds (e.g., $C_6H_{12}O_6$).	Food consists of a variety of materials taken in, used, or needed by organisms.
Source of food for plants	All food originates with compounds made during photosynthesis.	Food is at least partially taken in from outside the plant.
Reason plants need light	Light energy --> food energy (through photosynthesis)	Light is necessary. No reason given.
Chemical conversion in photosynthesis	$CO_2 + H_2O \rightarrow O_2$ + food ($C_6H_{12}O_6$)	Product of photosynthesis is not clearly identified with food.

Using This Module to Overcome Critical Barriers

For many students in a beginning biology course, the naive conceptions described above are deeply ingrained. We have found that for such students even the best explanations are not enough. Replacing easy and familiar naive conceptions with more abstract biological conceptions is a difficult process, requiring sustained effort on the part of the student, corrective feedback from teachers, and many opportunities for practice and application.

The materials in this module are ones that we have developed, field-tested, and found to be useful in helping students overcome the critical barriers described above. In addition to lecture materials providing clear explanations of respiration and photosynthesis (Section III), this module includes a diagnostic test that can be used as both a pretest and a posttest (Section II), laboratory activities (Section IV), and problem s s (Section V). These materials can be used either independently or in combination, and they do not need to be used in any particular order, although the laboratory activities and problem sets are designed to be done after students have read or heard explanations of the relevant concepts. The materials are useful because they help teachers do three things that are essential for helping students to overcome critical barriers:

1. Diagnose student difficulties. The diagnostic test, the laboratory activities, and the problem sets all contain questions designed to reveal how well students understand the biological conceptions of respiration and photosynthesis. The commentary for teachers describes specifically what each question is designed to reveal.

2. Create dissatisfaction with naive conceptions. Many students enter our course expecting to memorize facts and definitions when we would like them to think scientifically. The activities in this module provide students with many opportunities to see that their present ways of explaining and predicting scientific phenomena do not work very well and to understand how their ideas need to be changed.

3. Provide opportunities for practice and application. The scientific conceptions described above are important because they explain many different phenomena in a satisfying way. The activities in this module help students to see the power of these conceptions by applying them to a variety of phenomena. Since the basic purposes of scientific theories are to explain and to predict, we feel that the questions asking students for explanat'ons and predictions are especially important.

In short, the questions and activities in this module are designed as tools to help you, the instructor, help your students through the process of conceptual change. This module cannot substitute for your personal planning and judgment, but it can inform your plans and judgments better and thus help make them more effective.

II. Diagnostic Test and Commentary

This student test has been developed and tested over the course of several terms. It is designed to be given as a diagnostic pretest, and/or as a posttest. It should take about 15 minutes for most students to complete. As a pretest, it is designed to help you (a) assess your students' background in subjects critical to an understanding of respiration and photosynthesis and (b) become aware of the critical barriers to your students learning when they enter your class. As a posttest it gives you an opportunity to evaluate the success of your teaching.

On the following left-hand pages is the test as we have used it with our students. On the right-hand pages is a commentary explaining the purposes of each question and suggesting how student answers can be interpreted.

Your students' answers will probably be most revealing and useful if students do not take the test for a grade and if you ask them to try to describe how they think about the question even when they do not know the correct scientific answer. The students' incorrect answers to these questions are often more interesting and revealing than their correct ones.

Nutrition, Respiration, and Photosynthesis

1. How do you think a biologist would define the term "respiration"?

2. Humans engage in respiration.

   a. Which other living things engage in respiration? (circle all correct answers)

      snail bacteria rose plant cow mushroom

   b. Where in the human body does respiration take place? (circle all correct answers)

      muscles stomach lungs skin brain

3. How do you think that a biologist would define the term "photosynthesis"?

4. A bean plant needs energy to survive and grow. Where does the energy that a bean plant uses come from? (circle all correct answers & explain if necessary)

   air water sun soil worms & insects fertilizer

5. A human being also needs energy to grow and survive. Where do you think a person gets the energy he or she needs? (circle all correct answers & explain if necessary)

   air water sun exercise meat potatoes

6. Do plants need light? ________________ Why or why not?

7. How do you define "food" for a bean plant?

8. How do you define "food" for a person?

Commentary

1, 2a & 2b. This series of questions focuses on students' basic understanding of respiration. Answers to Question 1 should mention glucose or food as a chemical reactant and/or source of energy, rather than focusing exclusively on breathing or the exchange of oxygen for carbon dioxide. Question 13c (on next page) provides an independent check to see if students are aware that respiration can mean anything other than breathing.

Students operating with naive conceptions of respiration (i.e., respiration is breathing) tend to circle only animals in Question 2a, and circle only lungs and possibly skin (because they have heard that skin "breathes") in 2b.

3. This question focuses on student understanding of photosynthesis. Many students know that photosynthesis has something to do with light, energy, chlorophyll, or glucose. A few can also write a chemical formula. However, the key thing to look for in responses to this question is reference to the *function* of photosynthesis: providing food or energy for the plant.

4 & 5. These two questions indicate whether students can discriminate between substances that provide energy to organisms and substances that do not. It also will show if students consider the sources of energy to be fundamentally different for plants and animals.

In order to identify the correct answers (only the sun for plants, only meat and potatoes for humans), students must have a clear idea of both (a) what energy is and (b) how plants and animals obtain it from their environment. Many students have difficulties on both counts. Some identify low-energy inorganic compounds (water, fertilizer) as sources of energy for plants or animals. Other students incorrectly identify potential energy sources that cannot be used by those organisms (worms and insects for bean plants, sun for humans).

6. This question focuses on students' understanding of the function of light for a plant. Almost all students will answer that plants need light. However, answers to the second part of the question, such as "in order to survive" or "they'll die without it," illustrate these students are not thinking in terms of functional relationships. Even answers such as "for photosynthesis" indicate only that these students know that light is necessary for photosynthesis, not that they understand the function of light or even the function of photosynthesis itself. Ideal answers should include reference to light as an energy source for making food or for photosynthesizing.

7 & 8. These questions focus on students' understanding of the term food. Students often have vague conceptions of food, considering it something that an organism takes in. Such students will have difficulty with the concepts of respiration as the process by which energy is extracted from food and of photosynthesis as a food-producing process.

Students responding that "food *is* energy" often have confused notions about the distinction between matter and energy. These students often have difficulty seeing how matter and energy are both conserved in the processes of respiration and photosynthesis. We feel that the best answers should recognize that food can be defined in terms of its *function* for plants and animals: Food is organic matter that provides energy for metabolism and materials for growth.

In questions 9-11, circle the response you feel is most accurate. Use (?) only if you have no idea. If necessary, explain your answers in the space following the question.

9. What portion of their food do bean plants get by making it inside their bodies? ALL SOME NONE ?

10. What portion of their food do bean plants absorb through their roots? ALL SOME NONE ?

11. What portion of their food do bean plants absorb through their leaves and stem? ALL SOME NONE ?

12. Let H represent an atom of hydrogen and Cl represent an atom of chlorine. Draw a picture to show how you think the atoms are bonded together for the reactants and products in the following equations:

$$H_2 + Cl_2 \dashrightarrow 2HCl$$

Your picture

$H_2 + Cl_2$ $\longrightarrow$ $2HCl$

13. Try to write sentences explaining the relationships among the following sets of terms. Write sentences including two terms if you do not feel that all three belong together.

a. respiration, photosynthesis, energy

b. photosynthesis, sunlight, food

c. respiration, energy, food

d. glucose, food, energy

9-11. This series of questions is designed to check on students' . mmitment to photosynthesis as the *only* source of food for plants. Even many students who otherwise seem to understand the process fairly well oft n say that plants absorb some of their food from the environment.

12. The purpose of this question is to help instructors check student understanding of chemical formulas. Students lacking this understanding cannot appreciate the chemical conversions in respiration and photosynthesis. We have found that students can generate an amazing variety of chemical structures even for such simple molecules as H_2, Cl_2, and HCl.

13. These questions are especially useful when this test is used as a post-test. Since students often memorize isolated facts, these questions test the understanding of photosynthesis and respiration as a whole. Some students may be unable to link all three concepts together in a single sentence. Others may link them together incorrectly.

For each set of words, there are one or more obvious sentences which describes their relationship. Most students who fail to produce those sentences do not understand the relationships.

III. Materials for Lecture or Discussion with Commentary

This section contains a series of copy-ready masters for use as overhead transparencies and student handouts.

1. The overhead transparencies may be used as lecture supplements, or as a basis for discussion in lecture or recitation sessions.

2. The student handouts may be discussed in lecture or recitation or used by students as study guides.

Each sheet is designed to address one or several key concepts and/or to confront important critical barriers. They are found in copy-ready form on the left pages, with commentary explaining the purpose of the sheet on the right.

Contents

Matter and Energy

Matter

-Is the "stuff" that the universe is made of.

-Changes form, but is never created or destroyed in biological systems (Conservation of Matter).

-Consists of atoms that are bound together to form molecules.

-Atoms are never created or destroyed in biological systems, but molecules can be.

Energy

-Is whatever changes matter or moves it around.

-Changes form, but is never created or destroyed in biological systems (Conservation of Energy).

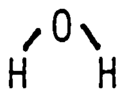
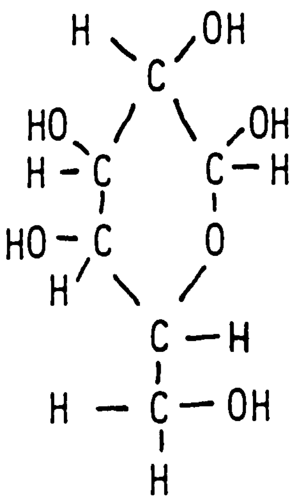
-Has many forms, including light, heat, and motion.

-Can be stored in certain molecules (chemical potential energy) and released when chemical bonds are broken.

Commentary

One problem many students have in understanding respiration and photosynthesis is that they possess unclear concepts of energy and the distinction between energy and matter. The purpose of this overhead is to clear this confusion by contrasting the two. Although students may be able to recite that energy "is the capacity to do work," this definition usually has no intuitive meaning for them. Unless the concepts of matter and energy are clear, students will be unable to understand respiration as an energy-releasing process and photosynthesis as an energy-storing process. In addition, the relevance of matter cycles and energy flow may escape them.

The Molecules of Photosynthesis and Respiration

Structure	Chemical Formula	Common Name
	H_2O	water
O=C=O	CO_2	carbon dioxide
O=O	O_2	oxygen
	$C_6H_{12}O_6$	glucose

Commentary

This overhead transparency presents three representations of the molecules, reactants, and products in the processes of respiration and photosynthesis. For students possessing a basic understanding of atoms and chemical bonds, this transparency serves to link the structures, chemical formulas and common names of these molecules. Most students, however, lack this understanding.

We therefore suggest that this transparency supplement discussion of the laboratory exercise, presented on page S-19, "Photosynthesis and Respiration Molecular Models." We have found that the process of assembling and taking apart molecular models makes the representations of those molecules on this transparency more comprehensible to many students.

Respiration

1. What is respiration? Respiration can be defined in three different ways:

Definition	Comments
a. Medical definition. Respiration is a process taking place in the lungs, in which oxygen (O_2) is absorbed into the blood and carbon dioxide (CO_2) is released into the air.	Biologists do not use this definition, although it is acceptable in medicine and in normal English usage.
b. Broad biological definition. Respiration is the process by which food (usually represented as glucose: $C_6H_{12}O_6$) is used in all living cells to provide energy for cellular processes. Anaerobic respiration takes place without oxygen. Aerobic respiration produces much more energy, but it can proceed only if oxygen is available.	This definition is the one used in this course.
c. Narrow biological definition. Some biologists use the term fermentation to describe anaerobic respiration, and use the term respiration only to describe a part of the aerobic process.	This definition is used in many textbooks.

2. Why is respiration necessary?

Respiration is the process by which chemical energy in food molecules such as glucose is converted into a form useful to living cells (phosphate bonds in ATP molecules).

Notice that the answer does not explain why breathing is necessary. Breathing makes oxygen molecules available so that body cells can engage in respiration.

3. What chemical changes occur during respiration?

Aerobic respiration is a multistep process in which glucose molecules are broken down and combined with oxygen. The end products are water and carbon dioxide: $C_6H_{12}O_6 + 6O_2 \text{ --- } 6CO_2 + 6H_2O$. The energy released during this process is used to construct 38 molecules of ATP. These in turn are broken down when the cell needs energy.

a. Food (glucose) and oxygen are both essential inputs to aerobic respiration. Respiration stops if either is not available. Thus starvation and suffocation are alike in that both kill people by stopping cellular respiration.

b. The inputs to respiration include a high energy organic molecule (glucose). The products are low-energy inorganic molecules (water and carbon dioxide).

4. Where do the glucose and oxygen come from?

The ultimate source of both food and oxygen is photosynthesis by green plants, though the oxygen may stay in the atmosphere for a long time, and the glucose produced by photosynthesis may be converted to many different molecules as it passes through the food chain.

Commentary

By directly contrasting students' naive conceptions concerning respiration with the scientific conceptions, this sheet is designed to confront students with the errors in their thinking.

1. What is respiration?

   The answer explains that, in biological terms, respiration is *not* breathing, and describes respiration in terms of its biological function: providing energy for life.

2. Why is respiration necessary?

   Students are often not used to thinking in terms of functional relationships. Students whose answer to this question would be "in order to stay alive" are exposed to a more fundamental reason for the necessity of respiration. In addition, the comments on this question explain the link between breathing and respiration.

3. What chemical changes occur in respiration?

   Questions 3 and 4 together present respiration as both a chemical process in which matter is transformed and a metabolic process in which energy is transformed.

4. Where do the glucose and oxygen come from?

   This question provides students with a link between photosynthesis and respiration and links both to the ecological carbon cycle.

Photosynthesis

1. What is photosynthesis?

Photosynthesis is the process by which green plants (and other autotrophs) use light energy to produce food (glucose) from water and carbon dioxide.

2. What is food?

Answer

Biologists use the term <u>food</u> to describe glucose and other organic molecules that can be used by living things as sources of energy.

Comment

Nonbiological uses of the term <u>food</u> are usually much broader and less precise. Plant food (fertilizer), for instance, is not food in the biological sense.

3. What chemical changes occur during photosynthesis?

Photosynthesis is a multistep process in which water and carbon dioxide are converted to glucose (food) and oxygen:

$$6CO_2 + H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2.$$

The inputs to photosynthesis are both low-energy inorganic molecules; the products include high-energy organic molecules such as glucose.

4. Why do plants need light?

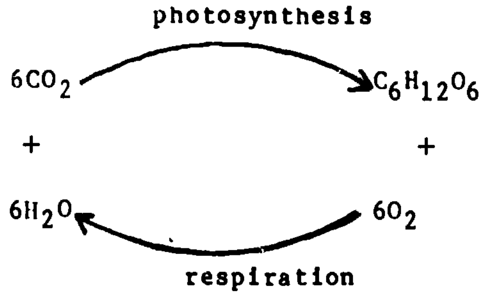
Photosynthesis is a process by which low-energy inorganic molecules are converted to high-energy organic molecules; this can happen <u>only</u> if light supplies the needed energy.

Plants left in the dark starve to death. They cannot make food without light.

5. What happens to the food and oxygen produced by photosynthesis?

The chemical energy in the food is released and made available to cells through the process of respiration. Sometimes this takes place in the plant cells themselves, sometimes it takes place in the cells of animals or other organisms that eat the plants (or animals that eat the animals that eat the plants, or. . .).

Notice now the <u>matter</u> involved in photosynthesis and respiration cycles endlessly:



However, this cycle can continue only as long as sunlight provides fresh <u>energy</u>. The energy is never recycled.

Commentary

1. What is photosynthesis?

   The purpose of this student handout is to contrast naive conceptions of photosynthesis with scientific conceptions.

2. What is food?

   Most students' conceptions of food are vague and imprecise. To some, food is "anything that is taken in or needed." To others "food is energy." In order for students to understand the significance of photosynthesis (i.e., the process by which plants make food), they must understand the scientific conception of food (i.e., organic molecules from which energy can be extracted for life processes). The scientific conception of food includes the function of food for living things (providing energy) while the naive conceptions discussed above do not consider food's functional significance.

3. What chemical changes occur during photosynthesis?

   A common student strategy is memorizing of formulas without attempting to understand them. The answer to this question provides an explanation (in terms of the *function* of the molecules) of the chemical formula for photosynthesis. In addition, by identifying the *role* photosynthesis plays in the life of a plant (making food), it encourages students to think in terms of functions.

4. Why do plants need light?

   This question encourages students to think about the function of photosynthesis and the role light plays in this process. Since many students answer this question, "because they all die without it," this answer is designed to provide an explanation of why plants die without light.

5. What happens to the food and oxygen produced by photosynthesis?

   This question provides a link between photosynthesis and respiration. It also is designed to help students link what they are learning to the carbon cycle, and, more generally, to energy flow and matter cycling in ecosystems.

Substances Needed by Plants and Animals

Substance	Needed for: Plants	Needed for: Animals	How Obtained: Plants	How Obtained: Animals
O_2 (oxygen)	respiration	respiration	absorbed from atmosphere by leaves, stem, roots	absorbed from atmosphere by lungs
Minerals	maintaining body functions	maintaining body functions	absorbed from soil by roots	contained in food
Food	providing energy, which is released by respiration	providing energy, which is released by respiration	made in leaves (photosynthesis)	taken in (by eating)
H_2O (water)	providing fluid balance making food	providing fluid balance	absorbed from soil by roots	taken in (by drinking)
CO_2 (carbon dioxide)	making food	not needed	absorbed from atmosphere by leaves	-------------
Sunlight	as an energy source to make food	not needed as an energy source	from sunlight falling on leaves	-------------

Commentary

This overhead transparency and/or student handout pinpoints basic similarities in, and differences between, plants and animals, both in the way they obtain essential substances and in the function the substances serve for the organism.

1. Both plants and animals extract energy for life from high-energy organic molecules (food).

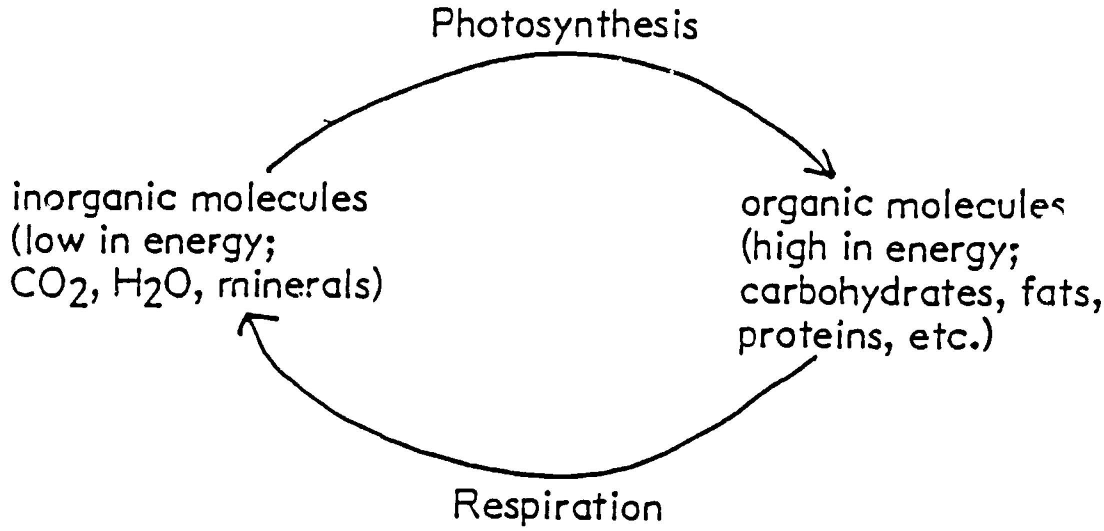
2. In both plants and animals the energy-extracting process is the same (respiration). Both types of organism require oxygen for the process. This is in contrast to the student naive conception that animals "breathe in" oxygen, but plants "breathe in" carbon dioxide instead.

3. Plants obtain required inorganic substances from the soil, but animals obtain these along with their food. These inorganic substances do *not* provide energy. This is in contrast to the naive conception that plants obtain at least some of their food and energy from the soil.

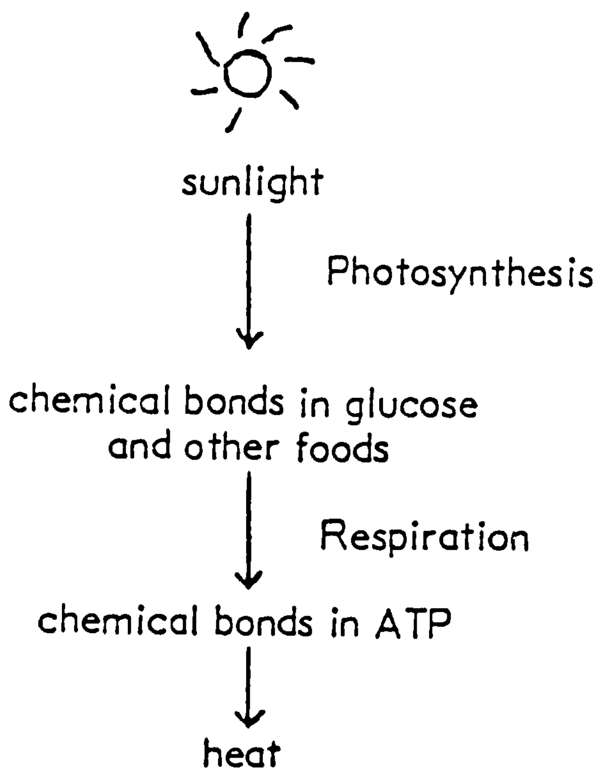
4. Animals obtain all their high-energy organic molecules (food) by consuming them. Plants obtain all their food by making it from inorganic molecules and sunlight via photosynthesis.

5. The function of carbon dioxide, water, and sunlight for plants is to serve as the raw materials from which food can be made via photosynthesis. Animals do not need carbon dioxide, and the functions of water and sunlight are different for plants and animals.

Matter Cycling in Biological Systems



Energy Flow in Biological Systems



Commentary

This overhead transparency aids students in seeing the connections between photosynthesis and respiration and in understanding the basis of matter cycles and energy flow. The essential points illustrated are

1. The basic difference between matter and energy, which many students have difficulty seeing.

2. The cycling and conservation of atoms, as they are incorporated into low-energy and high-energy molecules.

3. The necessity of an energy input to the cycling process.

4. The flow, and degradation to heat, of energy through these processes.

This sheet emphasizes the importance of photosynthesis and respiration to natural ecosystems. It can be used to help students make connections between their learning in ecology and their learning about photosynthesis and respiration.

IV. Laboratory Activities and Commentary

This section contains suggested laboratory activities. As in previous sections, pages on the left are student handouts; right-hand pages contain information for instructors.

We believe that it is especially important for students to think about and answer the questions at the end of each handout. These questions require them to use their knowledge of respiration and photosynthesis to explain what they have observed. Many students will benefit from postlab discussions of these questions.

This section contains three laboratory lessons, as follows:

Respiration and photosynthesis: Molecular models (pages 20-24)

Photosynthesis and food storage in coleus plants (pages 25-26)

Respiration and breathing rate (pages 27-29)

Each lesson should take one to two hours in all. The lessons can be broken into sections if your laboratory periods are short. For instance, we have often done the respiration and photosynthesis molecular models activities during separate laboratory periods.

Respiration and Photosynthesis: Molecular Models

Materials

1. Styrofoam balls--3 different colors (red, blue, and white--for example)
2. Toothpicks--2 different colors (yellow and blue--for example)

1. Introduction

Plants make food by a series of chemical reactions collectively called photosynthesis. Photosynthesis occurs within the cells of plants and is not directly observable. In this exercise you will simulate photosynthesis using styrofoam balls and toothpicks.

There are 93 different kinds of atoms that occur in nature. In this exercise you will be using three different kinds of atoms: carbon atoms, hydrogen atoms, and oxygen atoms.

Styrofoam balls represent atoms in this exercise:

1. Red balls represent carbon atoms.

2. White balls represent oxygen atoms.

3. Blue balls represent hydrogen atoms.

In nature several atoms can become joined together to form molecules. The forces that hold the atoms together in a molecule are called chemical bonds. In this exercise you will use toothpicks to represent the chemical bonds holding the atoms together.

You will notice that there are two different colors of toothpicks: yellow toothpicks represent low-energy bonds; blue toothpicks represent high-energy bonds. As the name indicates, high-energy bonds (such as carbon to carbon, and carbon to hydrogen bonds) contain a large amount of energy. Much energy is needed to form these bonds. Much energy is released when high-energy bonds are broken. Low-energy bonds do not need as much energy to form.

Commentary

Rationale. The chemical formulas of respiration and photosynthesis are often meaningless to students. This exercise is designed to increase student understanding of chemical processes.

Students will learn the processes of respiration and photosynthesis by, first, making a model of a glucose molecule using models of carbon dioxide and water, then breaking the glucose molecule down to re-form carbon dioxide and water. Students will also gain an understanding of energy transformations through the use of different colored toothpicks to represent low-energy and high-energy chemical bonds.

This laboratory activity may be performed in two parts, covering respiration and photosynthesis separately.

II. Carbon Dioxide and Water

In order to make one molecule of food (glucose), plants use six molecules of carbon dioxide and six molecules of water:

1. Using the red and white styrofoam balls and yellow toothpicks (low-energy bonds), construct 6 carbon dioxide molecules. Each CO_2 molecule contains one carbon atom and two oxygen atoms. Each kind of atom has a specific number of bonds that it can form with other atoms. In order to make stable molecules, each kind of atom must be joined to other atoms by the correct number of bonds. Each carbon atom must be joined to other atoms by four bonds. Each oxygen atom must be joined to other atoms with two bonds Throughout this exercise, keep in mind that, although you are using toothpicks to represent chemical bonds, these bonds are more like a force holding atoms together. It makes no sense to have a toothpick (bond) sticking out from a ball (atom) unless it is attached to another atom.

All the bonds in the carbon dioxide molecule are low-energy bonds. Use the yellow toothpicks to connect the atoms.

2. Using the white (oxygen) and blue (hydrogen) styrofoam balls, construct six water molecules. Each water molecule has two hydrogen atoms and one oxygen atom. The atoms are bonded to each other by low-energy bonds (yellow toothpicks). Each hydrogen atom has one bond (toothpick) and, again, each oxygen atom has two bonds (toothpicks).

3. Have your laboratory instructor check your water and carbon dioxide molecules before proceeding.

4. You have now made the basic molecules that plants use to make food.

   a. Where in the plant are carbon dioxide and water combined to make food? ____________________

   b. How does the water get to the leaves? ____________________

   c. How does the carbon dioxide get in the leaves? ____________________

III. Photosynthesis

Keep in mind that the following process occurs within the leaves of plants. A ray of light strikes the chloroplast and the plant begins to make food.

1. Remove the oxygen atoms (and the bonds) from your carbon dioxide molecules.

2. Make a ring with 5 carbon atoms and 1 oxygen atom. The sixth carbon atom sticks out from the ring. Use the blue toothpicks to connect the carbon atoms (Carbon-to-carbon bonds are high-energy bonds. Much energy is required to form these bonds.) Set the oxygen atoms aside (See Figure 1).

3. Split the water molecule in half, so that you have an -H part, and an -OH part.

4a. Students should recognize that this question refers to the process of photosynthesis, which occurs mostly in the leaves of plants, within cells, in the chloroplasts.

4b. Students should recognize that plants absorb water through their roots and transport the water to the leaves.

4c. Students should recognize that carbon dioxide enters the leaves from the air through small holes in the leaves that are called stomates.

1-6. This describes a sequence of steps for assembling the glucose molecule from CO_2 and H_2O. The steps are not those taken by plants in the actual manufacture of glucose.

4. Connect one -H and one -OH to each carbon atom in the carbon ring (as in Figure 1). Carbon to hydrogen bonds are also high-energy bonds, so use the blue toothpicks.

5. Connect the oxygen atoms together in pairs, using the yellow toothpicks (low-energy bonds). You should have <u>6</u> molecules of oxygen (O_2).

6. You now have made the products of photosynthesis, glucose (food) and oxygen.

7. How many carbon atoms does the glucose molecule contain? ______ _____

   How many hydrogen atoms does the glucose molecule contain? ____________

   How many oxygen atoms does the glucose molecule contain? ______________

   What is the chemical formula for glucose? ______________

8. Where does the energy come from that the plant uses to make the high-energy bonds in glucose?

9. What now happens to the glucose molecule? (There are a number of possibilities.)

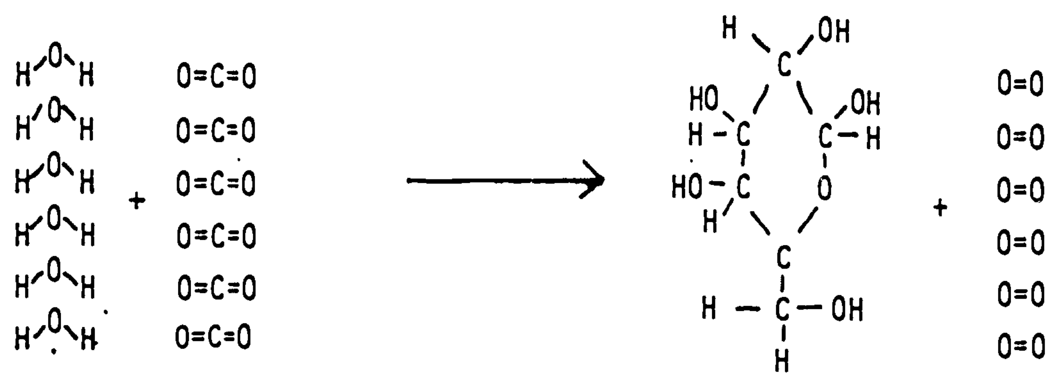


Figure 1. Chemical Changes in Photosynthesis

10. Show your glucose molecule to your lab instructor before proceeding.

11. Write a simple balanced equation for photosynthesis.

7. The sequence of questions is intended to assure that students will see the relationship between the model they have constructed and the representation of glucose as a chemical formula.

8. Notice that the focus of the questions changes from *matter* in Question 7 to *energy* in this question. Your students may have trouble making this shift and therefore might answer with statements about matter rather than correctly identifying sunlight as the source of energy.

9. Students should recognize that the plant may

   a. Store the glucose molecule in the form of starch

   b. Break down the glucose molecules to supply energy

   c. Convert the molecule to something that the plant needs, or

   d. Not do anything with the glucose molecule because it may be eaten by an animal.

11. The purpose of this question is to remind students of the relationship between the activity they have just done and the chemical equation as they commonly see it written:

$$6CO_2 + 6H_2O \text{ ---------> } C_6H_{12}O_6 + 6O_2$$

IV. Respiration

1. The process by which food is broken down to yield energy for life processes is called respiration. The energy yielded comes from energy stored in high-energy bonds. Identify these high-energy bonds in your glucose molecule. Where did the energy come from to make these bonds?

2. Cellular respiration requires 1 glucose molecule and 6 oxygen molecules. Note that this is the exact number of oxygen molecules produced by photosynthesis.

3. First, split the glucose molecule in half so that you have 2, three-carbon molecules. Remove the blue toothpicks that connected the two halves. By removing these high-energy bonds, you are releasing energy, making it available for life processes.

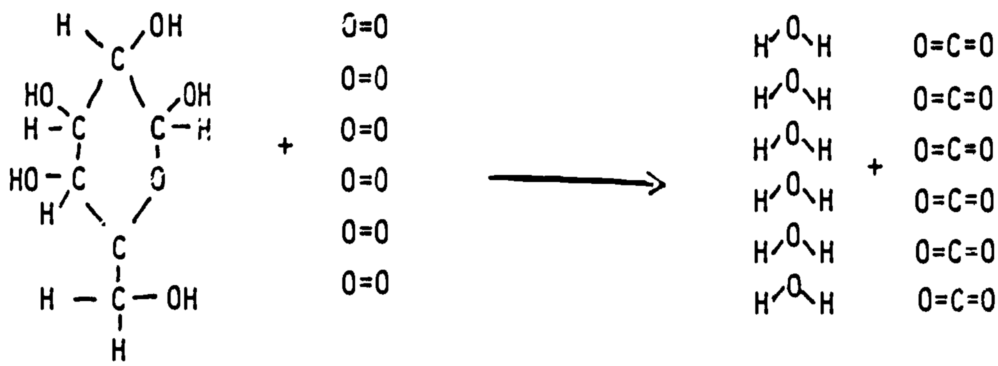


Figure 2. Chemical Changes in Respiration

4. Take the hydrogen atoms and the -OH atoms off the carbon atoms. Take the extra oxygen atom off the ring. Remove the toothpicks. Make sure you understand that, by breaking high-energy bonds, you are releasing energy which will be used for life processes.

5. Join the -OH and hydrogen atoms together with low-energy bonds (yellow toothpicks) to form six water molecules.

6. Completely separate the carbon atoms by removing the remaining high-energy bonds (blue toothpicks). Keep in mind, you are releasing energy.

7. Split the oxygen molecules in half and attach 2 oxygen atoms to each carbon atom to form 6 carbon dioxide molecules. Remember, use low-energy bonds (yellow toothpicks).

8. You have now formed the products of cellular respiration, carbon dioxide and water.

9. Write a simple, balanced equation for respiration.

1. Students should recognize that the energy came fro. sunlight and was incorporated into the glucose molecules through the process of photosynthesis. It is important for students to distinguish among:

   --the *source* of the energy (sunlight)

   --the *process* by which energy is captured (photosynthesis), and

   --the source of *matter* (water and carbon dioxide)

   Note that this question asks about the source of energy; the other answers are wrong.

9. Th purpose of this request is to make sure that students associate their manipulation of the molecular module with both the written molecular structures in Figure 2 and the chemical equation:

$$C_6H_{12}O_6 + 6O_2 \text{ --------> } 6CO_2 + 6H_2O$$

10. Note that the products of cellular respiration are exactly the molecules required for photosynthesis. Why do you think this is important?

11. Assume the energy I am using to write this sentence came from the carrots I ate for dinner last night. Trace the energy in a ray of sunlight from the point of it penetrating the carrot leaf to it being made available to me in my muscle cell. Be sure to identify all the processes involved and where each process occurs.

10. The purpose of this question is to introduce the concept of matter cycling.

Students should be able to recognize the recycling of carbon, hydrogen, and oxygen as essential to continuance of life. Students should understand that these atoms are used and reused, but never destroyed. Molecules, on the other hand, are constantly being formed and torn apart.

11. This question emphasizes the concept of energy flow through food chains.

Students should be able to recognize that energy in sunlight is used by the carrot plant to make a glucose molecule (the process of photosynthesis). When the carrot is eaten, the glucose molecule is absorbed into the body and transported to the muscle cell. Energy is made available to the cell through cellular respiration, the process of breaking down the glucose molecule.

Again, it is important for students to note that the paths taken by energy and matter through the ecosystem are *not* the same, although both energy and matter are passed from one organism to another through the food chain.

Photosynthesis and Food Storage in Coleus Plants

Materials

1. Two coleus plants
2. Hot plates: one per lab table
3. Beakers: 2 sizes. The smaller beaker should fit inside the larger beaker without tipping over. One set per lab table
4. Forceps: one or two per lab table
5. Small dishes, petri plates, or finger bowls: 2 per lab table
6. Iodine: Lugol solution
7. 70% ethyl alcohol
8. Potatoes, bread, sugar, hamburger, butter

Procedure

1. Available to you are several different types of food: hamburger, sugar, bread, potatoes, and butter. Obtain a small portion of each food. Drop a few drops of iodine on each type of food. Observe that iodine turns dark when dropped on some of the food.
   Which foods caused the iodine to turn dark? ______________________

   ____

   What substance in these foods causes the iodine to turn dark? __________

   ____

2. For the rest of this laboratory exercise you should work in teams of two to four students.

3. Plug in your hot plate. Turn the temperature to 400°F.

4. Set up two "double boiler" systems as follows:

   a. You have four beakers on the table in front of you. Fill the two larger beakers 1/3 full with tap water.

   b. Fill the two smaller beakers 1/3 full of 70% ethyl alcohol (available from your laboratory instructor)

   c. Place the smaller beakers inside the larger beakers.

   d. Put the two sets of beakers on the hot plate.

5. There are two plants available to you. One plant has been in the dark for two weeks. The other has been in the light for 10-14 days. Obtain one leaf from each of these plants. Make a small tear in the leaf obtained from the plant in the dark. This will enable you to tell the two leaves apart later.

6. Place one leaf into each of the beakers containing the alcohol. Boiling the leaves in alcohol removes chlorophyll. Boil the leaves until they turn white (about 15 minutes). Make sure all the alcohol does not evaporate. Add more alcohol if necessary (Be careful--alcohol is flammable!)

Commentary

Preparation

Two weeks before this exercise is scheduled, two plants should be obtained. One plant should be placed in a dark area, such as a cupboard. The second plant should be placed in bright light. Suggested plants are coleus plants, poinsettias, or any other dicot not possessing a waxy cuticle.

Rationale

This laboratory exercise requires students to think about the nature of food and the source of food for plants. They will observe that plant leaves kept in the light possess starch granules, whereas those kept in the dark do not. They should be able to explain their results in the following manner:

1. Plants store food in the form of starch.

2. A plant's energy needs require that food be constantly used as an input to respiration.

3. Plants are also able to produce food, but only if light energy is available for the process of photosynthesis.

In answering questions in the laboratory handout, students must think about metabolic processes inside the plant body, and they must also think of *food* as a source of stored chemical energy. This way of thinking will be difficult for students who are accustomed to thinking of light as simply something plants need or for students who do not clearly associate food with chemical energy storage.

Answers to Questions

1. Which foods caused the iodine to turn dark? What substance in these foods causes iodine to turn dark?

   Students should observe that iodine turns dark when placed on the potato and the bread and does not turn dark when placed on any of the other foods. Students should ask themselves what potatoes and bread contain that the other foods do not? Students should recognize that the substance that causes iodine to turn dark is starch. If they do not, tell them.

7. When the chlorophyl has been removed, carefully take the leaves out of the alcohol with forceps. Turn off your hot plate.

8. Place the leaves in the dishes on your table.

9. Cover each leaf with several drops of iodine solution.

10. Wait a few minutes and observe any color change.

Questions

1. How are the two leaves different?

2. How do you think that the starch in the leaf from the plant in the light was produced?

3. What happened to the starch grains in the leaf from the plant in the dark?

4. How is putting a plant in the dark like starving an animal?

5. What in our bodies has the same function as the starch grains in the plant?

1. Students should observe that the leaf obtained from the plant kept in the dark did not turn dark, while the leaf from the plant in the light did turn dark. Students should conclude that leaves from the plant kept in the light contained more starch than leaves from the plant in the dark.

2. Students should recognize that the plant kept in the light used light energy to make food and that this food is stored in the form of starch.

3. Students should infer that, when deprived of light, the plant kept in the dark was unable to make food and was forced to break down stored starch to meet its energy needs.

4. Students should recognize that in both cases the organism is forced to use (break down) stored food to supply energy needs.

5. Students should recognize that plants store reserve food in the form of starch while people (and other animals) store reserve food in the form of fat. See page S-16 for student handout that addresses this issue.

Energy Requirements and Breathing Rate

Materials

1. Inspirator-expirator apparatus
2. Straws
3. 125 ml Ehrlenmeyer flasks - 2 per student
4. Phenolphthalein, indicator solution

I. Using the Inspirator-Expirator Apparatus

1. The flasks on your table contain a red solution (phenolphthalein) that turns colorless in the presence of large amounts of carbon dioxide. Locate the inspirator-expirator apparatus on your table (two Ehrlenmeyer flasks connected by plastic tubing). Place a straw over the Y-connector. Steadily inhale and exhale through the straw. Notice that the air you inhale is bubbled through one flask, while the air you exhale is bubbled through the other. Continue inhaling and exhaling for several minutes.

2. What happened to each of the two solutions?

3. What does this observation indicate?

4. Each molecule of carbon dioxide in your exhaled breath contains one atom of carbon and two atoms of hydrogen.

   What substances are the carbon atoms coming from? ______________________

   What substances are the oxygen atoms coming from? ______________________

5. What parts of the body are they coming from?

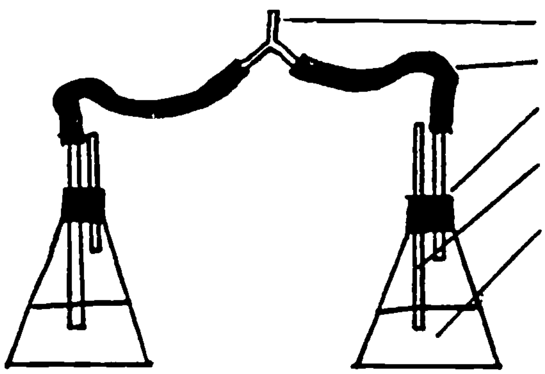
6. How did the carbon dioxide molecules get into your exhaled breath?

Commentary

Preparation

1. Indicator solution (Mix phenolpthalein with water; add NaOH until solution turns pink).

2. Inspirator-expirator apparatus. Add about 100 ml of indicator solution to the Ehlenmeyer flask; construct the apparatus according to the following diagram:



Note that the flexible tubing is connected to the long piece of rigid tubing in one flask and the short piece in the other flask.

3. Fill the two small flasks with about 40 ml each of phenolphthalein solution for each student (or have students do this themselves before Part II of the laboratory exercise).

Rationale

Students will observe that exhaled air contains more carbon dioxide than inhaled air. They will observe that the amount of carbon dioxide in exhaled air increases with increased exercise.

Students should infer that the source of the carbon dioxide is glucose, which is broken down by the process of cellular respiration in order to supply energy. Students will infer that increased exercise requires increased energy supply and, therefore, an increased rate of cellular respiration.

In order to answer the questions in the laboratory handout correctly, students will have to:

1. Use the chemical formula for respiration correctly: $C_6H_{12}0_6 + 602 \text{ -----> } 6CO_2 + 6H_20$.

2. Think of respiration as a process by which food is broken down in the cells to provide energy.

3. Think of breathing as a process by which oxygen is made available to the cells and carbon dioxide is taken away, rather than as something identical with respiration.

Answers to Questions (page S-26)

2. What happened to each of the two solutions?

   Students will observe that the liquid in the flask through which they exhaled changed from red to colorless, while the liquid in the flask through which they inhaled remained red.

3. What does this observance indicate?

   Students should conclude that exhaled air contains more CO_2 than inhaled air. Note that it is incorrect to conclude that the exhaled has *is* CO_2. It is also incorrect to conclude that when people breathe, oxygen is changed to CO_2.

4. What substances are the carbon atoms coming from?

   What substances are the oxygen atoms coming from?

   Students should recognize that the source of the carbon atoms is food (glucose), which is being broken down through the process of respiration to provide energy. Some of the oxygen atoms in exhaled CO_2 also come from food that is broken down, with the remainder coming from inhaled oxygen. For the purposes of this laboratory, it is important only that the students recognize that some of the inhaled oxygen is exhaled as a component of CO_2.

5. What parts of the body are they coming from?

   Students should recognize that food is being broken down by the process of cellular respiration *in every living cell* in the body. Students should understand that *all* living cells require energy and that the process of cellular respiration provides the necessary energy.

6. How did carbon dioxide molecules get into your exhaled breath?

   Students should recognize that CO_2, produced by cellular respiration, is taken from the cells to the lungs by the circulatory system.

II. Effects of Exercise

1. You should work in teams of two. One of you should act as observer and record data for the other. When you have completed this exercise, switch roles and repeat it.

2. Count your normal breathing rate for 30 seconds. Record this in the data chart.

3. On your table are two small flasks, each containing 40 ml of the red indicator solution. Remember, this solution turns clear in the presence of CO_2. The more CO_2 added to the solution, the faster it turns clear.

4. Inhale deeply. Then, steadily exhale through into the solution in one of the beakers. Record the amount of time it takes for the solution to turn clear.

5. Now exercise for two minutes by jogging in place.

6. Immediately after you stop exercising, inhale deeply, and again exhale into the red solution in the second beaker. Record the time it takes for the solution to clear in the data chart.

7. Again, count your breathing rate for 30 seconds. Record this time in the chart.

DATA CHART

	Before Exercise	After Exercise
Breathing Rate (30 seconds)		
Time taken for solution to clear		

8. Why do you need oxygen?

9. What happens to your normal breathing rate after you exercise?

10. Why does this happen?

11. What differences did you observe in the time it took the indicator solution to turn clear before exercise and after exercise?

12. What does this indicate?

13. How would you explain your results?

14. Where in your body is the additional CO_2 coming from?

Answers to Questions

8. Why do you need oxygen?

Students should recognize that oxygen is needed in order for cellular respiration to occur. Cellular respiration supplies living things with energy. If the students answer this question by saying that they need oxygen "in order to breathe" or "in order to stay alive," they are missing the point of this question. They are making statements about the effects of oxygen deprivation while failing to recognize the metabolic role oxygen plays in maintaining life (i.e., supplying energy through the process of cellular respiration).

9. What happens to your normal breathing rate after you exercise?

Students will observe that breathing rate increases with exercise.

10. Why does this happen?

Students should be able to correlate an increased breathing rate with an increased demand for energy. Students should recognize that breathing is a process that supplies cells with the oxygen that is necessary for cellular respiration. They should understand that cellular respiration supplies living cells with energy. Students may also recognize that breathing also functions in removing CO_2, a product of respiration, from the cells. Students should be able to correlate increased exercise with an increased demand for energy.

Again, students who say simply that people need more oxygen when they exercise are missing the point of this question. These students are failing to recognize the function of O_2 as an input to the process of cellular respiration.

11. What differences did you observe in the time it took the indicator solution to turn clear before exercise and after exercise?

Students should observe that it took *less* time for the indicator solution to clear after they had exercised.

12. What does this indicate?

Students should infer that exhaled air contained more CO_2 after exercise than before exercise.

13. How would you explain your results?

Students should recognize that CO_2 produced by the process of cellular respiration supplies energy to living things. Students should be able to correlate increased exercise with increased demand for energy to increased rates of cellular respiration and, therefore, to increased CO_2 production. As in Questions 8, 10, and 11 above, students whose answers do not refer explicitly to cellular respiration or energy use by cells are missing the point.

14. Where in your body is the additional CO_2 coming from?

Students should recognize that since all living cells require energy, all living cells undergo cellular respiration and produce CO_2. However, during exercise, *muscle cells*, due to increased demand for energy, are producing more CO_2 through an increased rate of cellular respiration.

V. Problem Sets

The following section includes questions on respiration and photosynthesis organized into two problem sets. The questions give students a chance to use newly acquired scientific conceptions to solve problems. Also, you can evaluate student responses to assess how well students have replaced naive conceptions with scientific conceptions.

Suggested Use for Problem Sets

Problem Set 1 contains questions relating primarily to respiration, and Problem Set 2 focuses on the nature and use of food for plants and animals. Both problem sets can be done by students independently, then checked by the instructor and/or discussed in class. The problems can also be adapted for use as test questions.

These problems are difficult for students because they require students to organize their newly acquired knowledge into a coherent scheme. Many students will need to discuss the questions in class after attempting to answer them.

Problem Set 1: Respiration

1. a. Here is a list of methods often used by people who want to lose weight:

   --sitting in saunas
   --doing aerobic exercise
   --cutting calories (eating less)

   Which of these methods do you think would result in long-term weight loss?

   b. When you lose weight, you lose fat. Where do the atoms that make up the fat molecules go?

   c. Why will exercising more cause you to lose weight?

   d. Why will eating less cause you to lose weight?

2. a. What is the difference between breathing and respiration?

   b. How are breathing and respiration related?

3. Humans give off carbon dioxide in the air they exhale.
   a. Where in our bodies is the carbon dioxide coming from?

   b. In which of the following situations would you expect to find CO_2 being produced?

   --live yeast in a sugar solution
   --dead yeast in a sterilized sugar solution
   --live grasshoppers
   --live earthworms
   --a rose plant
   --a dog

Commentary

1. This set of questions is designed to start students thinking about the process of respiration as an energy conversion. The questions are asked with reference to subjects that students are familiar with (i.e., dieting and weight loss). Answers to Questions 1c and 1d are critical to student understanding. Answers such as, "when dieting, one *uses* stored fat" or "exercise burns calories" are insufficient. Students should be able to recognize the relationship between the energy demands of an organism and the rate of respiration. In addition, students should recognize that when food intake is insufficient to fully supply the inputs of respiration, the body relies on stored food reserves (fat) to supply these inputs.

   Part 1c addresses the conservation of matter in the process of respiration. Many students do not understand that fat molecules are made of atoms, which cannot be destroyed. They instead visualize fat as being "burned with nothing left over. This question also encourages students to see the relationship between the respiration process and the concentration of CO_2 in exhaled breath.

2. The purpose of this pair of questions is to directly confront the naive conception that respiration *is* breathing and to encourage understanding of the true nature and function of respiration. In addition, Part 2b, by asking how respiration and breathing are related, encourages understanding of the vital role that breathing plays in respiration (i e., providing oxygen for the process).

3a. This question addresses the process of respiration as a chemical conversion. In addition, the conservation of matter (atoms) is addressed. Many students view the chemistry of respiration as oxygen being converted to carbon dioxide. Students should recognize that since atoms cannot be changed or destroyed, the carbon in CO_2 must be coming from somewhere. They should recognize the source of the carbon atoms as glucose and the processes by which the carbon atoms are liberated from glucose molecules and incorporated into CO_2 molecules as respiration.

3b. This question addresses the subject of where respiration takes place. Students holding the naive conception that respiration *is* breathing view respiration as occurring only in the lungs of land animals. Students must recognize that, due to the essential energy-providing function of respiration, the process necessarily occurs in all aerobic organisms.

4. Assume you had two hamsters. One ran on an exercise wheel almost constantly. The other spent most of its time sitting in a corner. If both hamsters ate the same amount of food and their weight was identical to begin with, which one (if either) would you expect to weight more after two weeks?

   Why?

5. The process of cellular respiration requires glucose and oxygen and produces carbon dioxide and water. Cellular respiration is occuring right now in my muscle cells, supplying the energy it takes to write these sentences.

   a. Assume a glucose molecule starts as starch in a piece of bread that I ate. Trace this glucose from my mouth to my muscle cell.

   b. Trace the path of an oxygen molecule from the air to my muscle cell.

   c. What is the path a water molecule takes from my muscle cell to the outside?

   d. Trace the path a carbon dioxide molecule takes from my muscle cell to the outside.

6. a. How do animals obtain energy from food?

   b. How do plants obtain energy from food?

4. This question addresses the process of respiration as an energy conversion. It is designed to help students better understand the flow of energy within organisms. Students holding naive conceptions exhibit no awareness of this idea. Most students will correctly predict which hamster will be heaviest. However, it is important to examine students' explanations of why this occurs critically. Students should recognize that increased activity results in increased demands for energy. The only way these increased energy demands can be met is by increased rates of respiration, with the result that more food in converted to CO_2 and water. We do not feel that answers referring to "burning" or "using" food or fat, without reference to energy demands or what becomes of the matter in the food, are adequate.

5. This set of questions is designed to help students understand the conservation of matter between the organism and the environment. In addition, it helps students to understand how the physiology and anatomy of an organism are shaped by the need to acquire inputs to and eliminate the products of respiration.

6. The purpose of this question is to help students understand the basic function of respiration as extracting usable energy from food. Students often are able to recognize this function for animals, but view photosynthesis as the energy-providing process in plants. Students must understand that respiration is the only process performed by living things that converts energy in food to a usable form and, therefore, is performed by all living things.

Problem Set 2: Food for Plants and Animals

1. a. How do animals get food into their bodies?

   b. How do plants get food into their bodies?

2. a. Do humans need water to survive? ____________

   b. Would a human survive if given water only? ____________

   c. What does food provide that water does not?

3. a. Do plants need water to survive? ____________

   b. Would a plant survive if placed in the light and given plenty of water? ____________

   c. Would a plant survive if placed in the dark and given plenty of water? ____________

   d. What is the function of light to the plant?

4. a. Here is a list of things you might provide to a pet dog that you wanted to keep in good health:

   water   rabies vaccination   dog food   worm capsules   table scraps

   Circle the ones you consider to be food for the dog.

   b. Here is a list of things you might provide to a rose bush that you wanted to keep in good health:

   light   water   fertilizer   soil   bug spray

   Circle the ones you consider to be food for the rose bush.

   c. What are the criteria you used to decide which of the items in the lists above were food.

Commentary

This series of questions addresses the source of food and the nature of food for plants and animals. Without the basic understanding that food consists of organic molecules which are capable of providing energy for life processes, students may not be able to grasp the significance of photosynthesis and respiration.

1. This question contrasts methods used by plants and animals to obtain food. Many students believe that plants obtain food, at least in part, as animals do, from outside sources. Recognition that plants manufacture all of their food via photosynthesis is essential to student understanding of matter cycles and energy flow.

2. This question points out essential differences between food substances and nonfood substances taken in or needed by organisms. Students should recognize that, although water is essential for life, it does not provide the energy necessary for life processes.

3. Students should be able to recognize that although water is a nonfood substance and does not supply energy, plants, unlike animals are able to survive if supplied with water and kept in the light. Students should recognize that this survival is due to the fact that plants kept in the light are manufacturing all of their food via photosynthesis and that light provides the vital energy input required for the photosynthetic process. Students should understand that keeping a plant in the dark is similar to starving an animal in that the organism is then deprived of food.

4. Correct answers are dog food and table scraps for part a; *none* of the substances listed for part b are food for the rose bush.

   This set of questions deals with the nature of food and the source of food for plants. Students holding naive conceptions often view food as anything that is needed or taken in by organisms. In addition, they may also view the primary food source for plants as fertilizer (which is often advertised as "plant food"). The presentation of this question is such that it allows students to see that not everything taken in by animals constitutes food (i.e., rabies vaccine, worm capsules). Therefore it is easier for students to understand that substances taken in by plants do not constitute food (i.e., fertilizer). In addition, by asking students to list the criteria they used to decide which substances were food, the question reveals whether students are using a definition of food that is linked to the concept of energy. This scientific definition of food is in contrast to the vague definition held by students possessing naive conceptions.

5. a. Imagine that you take a potted plant and place it on the window sill. Next to it you put a hamster in a cage. If you provide both organisms with nothing but water, what would happen to the hamster and to the plant?

--after a couple of days?

--after a couple of weeks?

b. Where is the plant getting its food from?

6. a. Now consider a second experiment. Both the hamster and the plant are placed in the dark. Both are given water, the hamster is given hamster food, and the plant is given "plant food" (fertilizer). Which organism would you expect to live longer?

____

b. Explain your predictions.

7. Think about structures that animals and plants possess that are specialized for taking in food. Circle the structures below that you think fit this description.

The claws and beak of an eagle

The scales of a fish

The leaves of a tree

The trunk of an elephant

The roots of a grass plant

The ears of a donkey

The flowers of a rose

5-6. This series of questions address the role of photosynthesis in plant growth and development. Students holding naive conceptions view light as necessary for plant survival but believe that food, at least in part, comes from outside sources.

By contrasting plants with animals (which students are often more familiar with), students are led through a logical argument to the conclusion that plants make all of their own food and that he function of light is to provide an energy input to the food-making (photosynthetic) process.

7. This question assesses student understanding of the source of food for plants. The key items in this list are the plant structures. Since plants do not take in foo', none should be circled. Students possessing the incorrectly naive conception that food is at least partially taken in from outside sources tend to circle such plant structures as leaves and roots.