

The Absorption of Solar Energy

SPN LESSON #8

TEACHER INFORMATION

LEARNING OUTCOME:

Students are able to describe:

- the subatomic and atomic physical interactions that occur between radiation and matter leading to the absorption of radiation energy;
- the selective interactions between various wavelengths of radiation and the absorbing material;
- the mechanisms of energy transfer and conversion;
- the specific energy transfers occurring during photosynthesis;
- the structure of chlorophyll molecules; and
- the location of chlorophyll within chloroplast organelles.

In addition, students are able to interact successfully with a simplified model of photosynthesis that explores the relationship between energy transfer and the chemical reactions that produce energy-containing foods in green plants.

LESSON OVERVIEW:

Three short laboratory activities deal with:

- physical factors controlling the absorption of solar radiation,
- paper chromatography of the pigments in green plants.
- microscopic examination of plant cells and chloroplasts.

Students investigate:

- absorption of solar energy and mechanisms and physical phenomena that make absorption possible.
- factors that control physical interactions between electromagnetic radiation and the materials that radiation encounters.

Students focus on the following topics:

- electromagnetic spectrum
- atomic and subatomic interactions that comprise absorption
- gradational difference between transparency and opaqueness

- energy absorptions that do and do not convert to heat energy transfers and increased temperature
- transfer of that energy within the chloroplasts and the eventual increase in chemical bonding energy within food molecules. (A pencil-and-paper model of photosynthesis helps students identify the location and nature of solar energy absorption.)

GRADE-LEVEL APPROPRIATENESS: This Level II Living Environment and Physical Setting lesson is intended as an enrichment experience for students in grades 5–8, but is also appropriate for use at higher grade levels.

MATERIALS

Part 1: The Absorption of Radiation Energy in General

Lab Activity #1: Color and the Absorption of Sunlight (see Part 1, page 8.6, in student section)

9 Tin cans (such as soup cans) of the same size painted with flat paint. Each can should be painted only one color. Six cans should be colors of the rainbow: violet, blue, green, yellow, orange, and red; the other three should be painted chartreuse, black, and white.

9 Styrofoam tops to fit tightly inside cans—slit to allow insertion of thermometer

9 Thermometers

9 Graduated cylinders

Container of water at room temperature

Part 2: Photosynthesis

Lab Activity #1: Separating the Pigments Found in Leaves (see Part 2, page 8.2, in student section)

Leaves collected by students

Small juice jars

Covers for jars

Rubbing alcohol

Filter paper strips: 1 inch x 8 inches

Water bath: shallow pan (with drain outlet) with hot tap water

Masking tape

8–inch wooden dowel

Lab Activity #2: Finding Chlorophyll in Leaves (see Part 2, page 8.3, in student section)

Microscopes

Glass slides and cover slips

Eloдея plants in water (available from pet stores)

SAFETY

Part 1, Lab Activity #1: Color and the Absorption of Sunlight

The Absorption of Solar Energy

Living Environment, Physical Setting; Level II

8.2

Isopropyl rubbing alcohol can be harmful if mishandled or misused. Carefully follow all warnings given on the container.

Hot water above 150°F can quickly cause severe burns. Be sure to warn the students to be careful near the water bath.

TEACHING THE LESSON

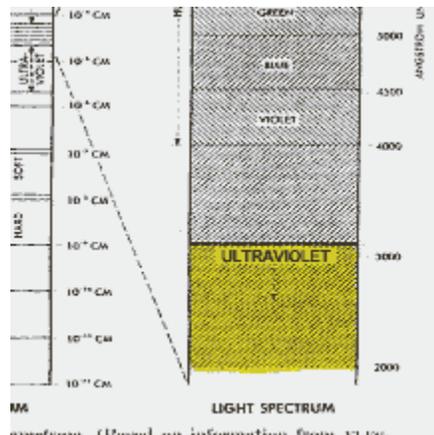
This lesson is divided into two parts designed to be taught sequentially. Each part helps students explore the absorption of electromagnetic radiation and contains lab activities that foster firsthand observations.

- Part 1, The Absorption of Radiation Energy in General, is meant to simplify current thinking on the actual physical interactions that occur during absorption. It can be used for small group work followed by discussion sessions in class and/or it can be used for homework. The lab activity embedded in this part requires initial setup time for the teacher. Consider that the students might paint the metal cans in class as a pre-lab activity.
- Part 2, Photosynthesis, explores the somewhat complicated energy transfers that take place during photosynthesis. Students are expected to interpret a model that shows the complexities of this essential-to-life process in a simplified way. Once again, this might be best delivered through small work groups with frequent reconvening as a class for discussion and clarification. The two lab activities embedded in this part provide students with an opportunity to determine the presence and distribution of chlorophyll.
- Each of the lab activities for this lesson requires a 40-minute lab period. Additionally, Part 1 and Part 2 each require a period for completion and a period for review. If all components of the lesson are completed, seven 40-minute periods will be needed.

ACCEPTABLE RESPONSES FOR DEVELOP YOUR UNDERSTANDING SECTION

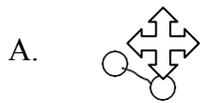
Part 1: The Absorption of Radiation Energy in General

1. Because we see certain individual wavelengths as individual colors
2. 10^{-6} centimeters
3. The shorter the wavelength, the greater the frequency
4. They should be the same, since energy cannot be created or destroyed.
5. Because radiation has the properties of both a wave and a particle
6. Window glass must be transparent to wavelengths of visible light.
7. The sketch should show a series of circles connected by wavy arrows moving to the right.
8. violet
9. red
10. refraction is caused that is greater in the wavelength of light changed the most in velocity, the violet
11. The visible light is separated into bands of color resembling the rainbow.
12. (on next page)

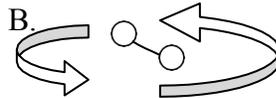


The UV greater than 3100A is reradiated

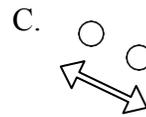
13.



Translational



Rotational



Vibrational

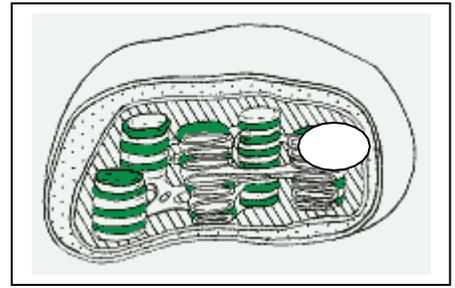
14. They have higher temperature.

Lab Activity #1: Color and the Absorption of Sunlight

1. Usually the black can
2. Usually the white can
3. The cans that absorb the most sunlight gain the most heat energy and increase in temperature the most.
4. So that each can have the same amount of water to heat
5. To reflect more sunlight in the summer and absorb more sunlight in the winter
6. To keep them cooler in the warm climate

Part 2: Photosynthesis

1. Chlorophyll a and chlorophyll b
2. Chlorophyll a absorbs more sunlight in the violet and red parts of the solar spectrum. Chlorophyll b absorbs more sunlight in the blue and orange parts of the solar spectrum.
3. Green and yellow
4. Carotenoids
5. Orange because they absorb violet, blue, and green



Develop Your Understanding

1. It looks like stacks of pancakes.
2. Carbon, hydrogen, oxygen, magnesium
3. Carbon and hydrogen
4. Double lines mean double bonds (two shared electrons)
5. Electromagnetic radiation
6. Student's circle should be drawn around one of the cut-open thylakoids as shown above.
7. It escapes into the atmosphere as a waste product of photosynthesis.
8. They replace the electrons that were kicked free by the absorption of sunlight energy.
9. The hydrogen ions would make the inside space acidic.
10. They pass through the membrane through structure 9 to the main part of the chloroplast.
11. The hydrogen ions from inside the pancake stack to the 'dark reaction' section of the chloroplast
12. CO₂ and NADPH
13. From the atmosphere
14. Electrons and hydrogen ions

DEVELOP YOUR UNDERSTANDING (A SUMMARY)

1. (1) The splitting of water molecules
(2) Pumping hydrogen ions out of the pancake
(3) Making NADPH from NADP⁺ and H⁺
2. ATP, NADPH, CH₂O
3. (1) Sunlight is converted into flowing electrons (electricity).
(2) Electricity is converted to chemical bonding energy in NADPH.
(3) Electricity is converted to chemical bonding energy in ATP.

ADDITIONAL SUPPORT FOR TEACHERS

SOURCE FOR THIS ADAPTED LESSON

This is not an adapted lesson

BACKGROUND INFORMATION

The information presented in this lesson is meant to be self-explanatory. The essential theme in Part 1 should be that the energy of radiation is selectively transferred to specific receivers depending on the wavelength of the radiation. For much of visible light and the surrounding infrared and ultraviolet light, these receivers are the electrons of atoms.

Typically the energy is re-emitted as these electrons drop from excited states back toward their normal states. At other times, some or all of the absorbed energy is transferred within the atom resulting in one of the three types of motion discussed in the exercise. This

transfer is heat energy, which ultimately increases the kinetic energy of the atom and can be measured as an increase in temperature.

Part 2 attempts to simplify the complexity of photosynthesis without getting into the molecule counting of the Krebs cycle. The loosely bound electrons surrounding the magnesium atom in the chlorophyll molecule absorb radiation and are conducted along the **light-harvesting complex**, which starts a chain reaction of events. This flow of electrons is essentially the flow of electricity, which powers the several chemical reactions collectively known as photosynthesis. The reading cited below provides abundant information on both of these topics.

REFERENCES FOR BACKGROUND INFORMATION

Carroll, Mark: *Organelles*, The Guilford Press, 1989.

McGraw-Hill Encyclopedia of Science and Technology, 1960.

Scott, Andrew: *Molecular Machinery*, Basil Blackwell Ltd, 1989.

Williams, R. and Frausto da Silva, J.: *The Natural Selection of the Chemical Elements*, Oxford University Press, 1996.

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www.nyserda.ny.gov

(STUDENT HANDOUT SECTION FOLLOWS)

Name _____

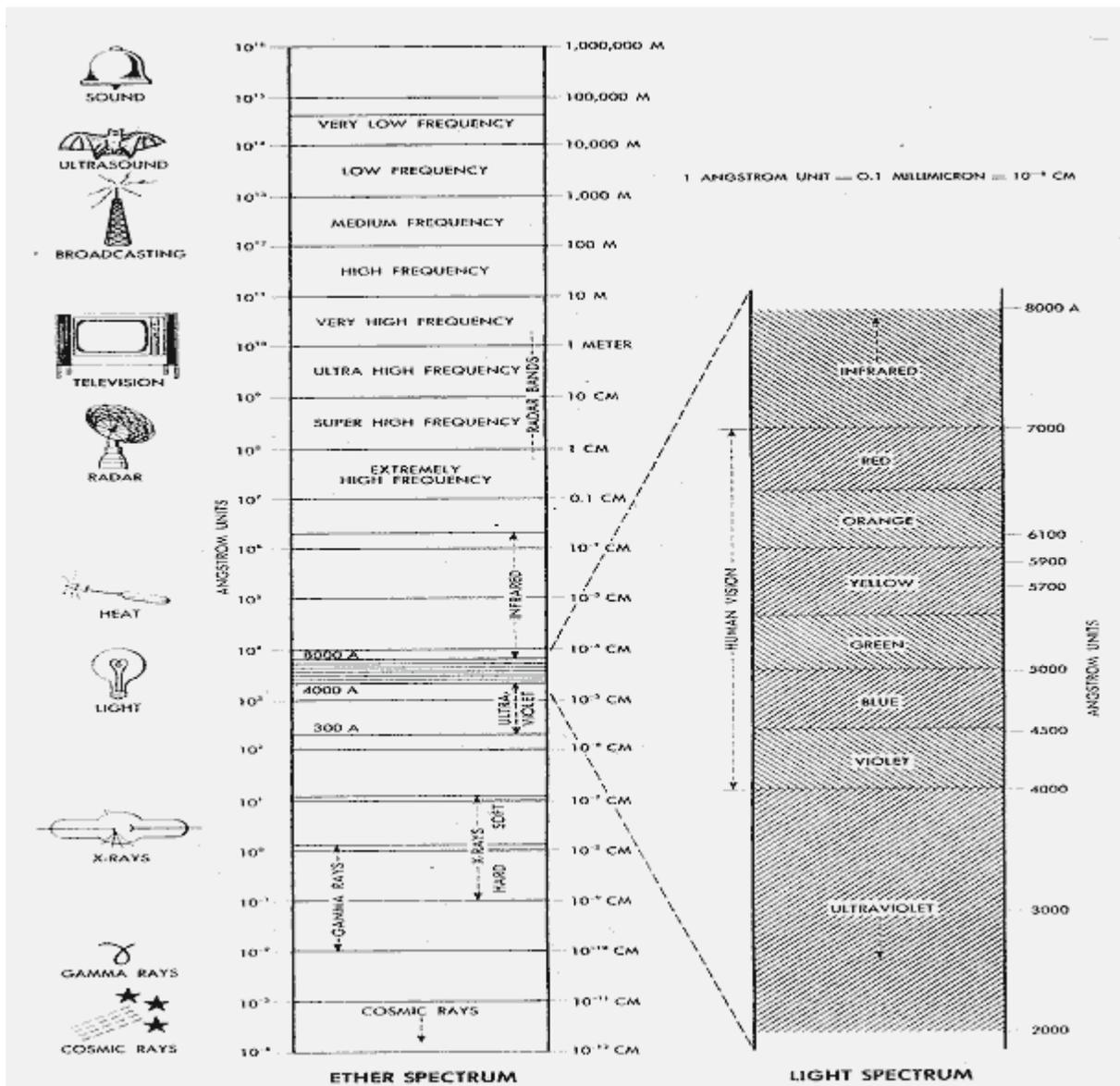
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The Absorption of Solar Energy

Part 1: The Absorption of Radiation Energy in General

The Solar Spectrum

Solar energy consists of a continuum (a series of values that change without a gap from one into another). This continuum ranges from very short to very long wavelengths of electromagnetic radiation. The chart on the next page shows the names that represent the various sections of this continuum of natural radiation.



1. On the chart above, use appropriate-colored pencils to color the labeled parts of the spectrum that are visible to humans. Why are the visible parts of the spectrum labeled as colors?
2. What is an Angstrom unit?
3. What is the relationship between wavelength and frequency?

Absorption

The absorption of electromagnetic energy is a process usually described by its results: it is described as where the energy goes. The energy of the wave or photon is captured by an electron and converted into some form of chemical, heat, or vibrational energy, while the radiation itself is weakened in intensity. Since we are dealing with the interaction of such small objects (microscopic waves or photons, electrons, atoms, and molecules), describing the actual process of absorption is difficult; what is presented here is a model of what we think happens.

4. How does the amount of energy lost by the radiation while passing through a substance compare to the amount of heat or vibrational energy gained by the substance?
5. Why is electromagnetic radiation described as either a wave or a photon?

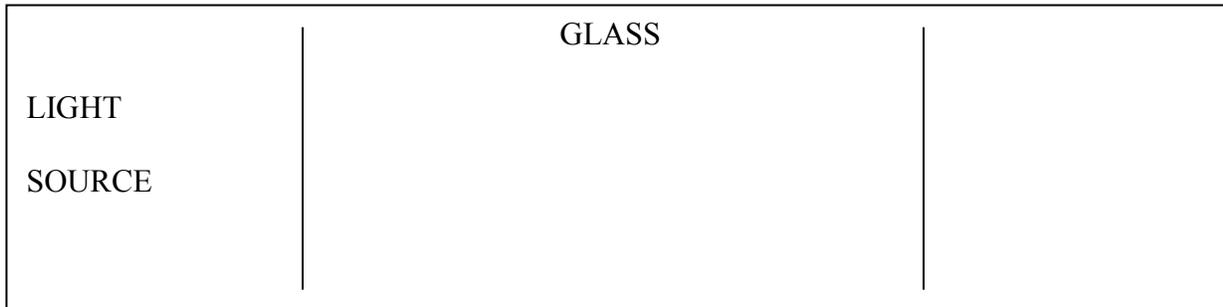
Transparency and *opaqueness* are general terms to describe the endpoints of a continuum of absorbency from 0% to 100%. Most materials—that is, the atoms and molecules present in them—absorb some of the radiation striking or passing through. No known substance has proven to be either completely transparent or completely opaque to all wavelengths of radiation. Depending on their chemical composition, substances exhibit selective absorption of narrow bands and/or whole sections of the radiation spectrum. Window glass is a good example of this phenomenon. Most of us consider glass to be transparent because we can see through it.

6. Since we can see through window glass, what does that indicate about its transparency?

Even though the wavelengths of visible light do pass through glass, scientists have determined that light slows to approximately 65% of the speed of light during this process. How can this be, if light is said to always travel at a constant speed called the “speed of light”? What happens to the light while passing through the glass? Strangely enough, the explanation is that the visible light waves appear to slow down because they are absorbed! Then, they are reradiated in the same direction in which they were traveling. This absorption-reradiation process is almost instantaneous. The light only stops briefly while trapped by an atom of the glass and then goes on its way at the constant speed of light until it encounters another atom within the SiO_2 molecules of the glass.

Make a sketch to represent the stop-and-go transparency of glass in the space below. Use a wavy line for radiation and a circle for the atoms of glass. Remember that most of the “space” occupied by an atom IS empty space.

7.



While passing through window glass, shorter wavelengths of visible light are slowed slightly more than the longer wavelengths.

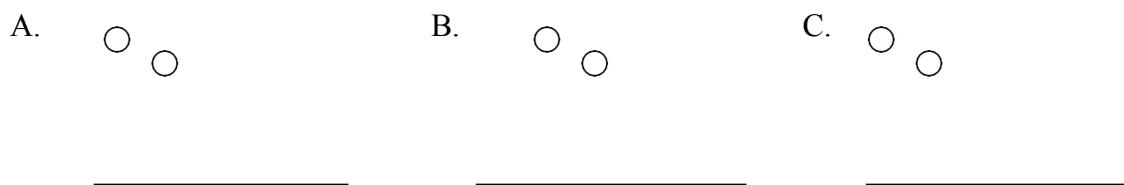
8. Which color of light is slowed the most?
9. Which is slowed the least?
10. What do these variations in the change of velocity in different colors cause?
11. What happens when visible light passes through a prism?

All of these exciting things happen to visible light traveling through glass, but the glass interacts with ultraviolet (UV) light quite differently. Generally, UV with wavelengths less than 3100 Å are absorbed and not reradiated as UV. Instead, the vibrational energy is internalized and becomes what is collectively called **internal energy**. Internal energy takes many forms, all of which involve some sort of increased motion of the atoms and molecules of the glass. In other words, the kinetic energy of the particles within the glass increases. This increase in kinetic energy takes three different forms:

- **Translational** energy involves the side-to-side or back-and-forth motion of the molecules.
- **Rotational** energy is the rate of spin of the molecules.
- **Vibrational** energy is the movement of the atoms within molecules or a molecular structure.

We recognize the increase in the average translational kinetic energy as an increase in temperature. We call the transfer of energy from the captured light to any of these types of internal motions “heat energy.”

12. On the radiation chart above, shade in the section of ultraviolet radiation on the light spectrum on the right that is absorbed by glass. What happens to the UV radiation having wavelengths greater than 3100 Å?
13. In the diatomic (two-atom) air molecules below, use arrows to show the movement involved in the three types of kinetic energy described above that provide the movement measured as temperature. Label each type of energy.



Mechanisms of Absorption

A, or perhaps THE, major site of radiation absorption is the electrons that are located outside the nucleus of atoms of a material. Scientist Max Planck realized that this absorption occurred only at very specific wavelengths, which represented very specific amounts of energy—the shorter the wavelength, the greater the energy. This amount of energy became known as a quantum of energy, and Planck’s theory as the quantum theory. Some of the time this absorbed energy is reradiated as in the case of transparent glass molecules. Most of the time this energy is held by the molecules and atoms and transferred from the electrons to rotational and vibrational energy. When molecules collide, this energy may then become translational energy.

14. How do we recognize the presence of molecules with greater translational energy?

An example of the specific absorption of radiation by electrons explains what happens to ultraviolet radiation approaching Earth’s surface in the atmosphere:

Ultraviolet (UV) radiation entering the upper atmosphere is in the range of 2000–4000 Å. The upper atmosphere absorbs out UV in the range of 2000–2900 Å, which is the most energetic of the UV radiations. Oxygen in the outer part of Earth’s atmosphere absorbs the shorter wavelengths of electromagnetic radiation from X-rays through UV. In turn, some of the oxygen is converted into ozone (O₃) that will also absorb UV in the 2000–2500 Å range. Of the UV reaching Earth’s surface, 10% is in the range of 2900–3200 Å that interacts with human skin to cause tanning and/or sunburning. The remaining 90% of the UV reaching Earth is in the range of 3200–4000 Å and is the lowest energy UV (adapted from Chemheritage.org).

Lab Activity #1: Color and the Absorption of Sunlight

Materials:

- 9 Tin cans (such as soup cans) of the same size painted with flat paint. Each can should be painted only one color. Six cans should be colors of the rainbow: violet, blue, green, yellow, orange, and red; the other three should be painted chartreuse, black, and white.
- 9 Styrofoam tops to fit tightly inside cans—slit to allow insertion of thermometer
- 9 Thermometers
- 9 Graduated cylinders
- Container of water at room temperature

Procedure:

1. Work in groups set up by your teacher.
2. Select a colored can, graduated cylinder, and thermometer.
3. Carefully measure 25 cubic centimeters (mL) of room-temperature water in the graduated cylinder and pour it into the can.
4. Place the Styrofoam on a can and inset the thermometer so that its bulb is touching the bottom of the can. Wait until everyone in the class is ready, and then record the initial thermometer reading in the chart below.
5. When your teacher tells you to do so, place your can along with those of the other groups in a place where they each will receive equal amounts of sunlight.
6. Read the temperature of the water in your can every 15 minutes for $\frac{1}{2}$ hour and record the temperature readings in the chart below.

Time	Start (0)	15 minutes	30 minutes
Temperature			

7. Determine the total change in temperature that occurred in your colored can.

_____ °C

8. Make a bar graph of the class results from this investigation.

4. Why was it important to put exactly 25 mL of water in your colored can? Why was it important that each group measured the water in the same way?

5. Why do people recommend that we wear light colors in the summer and dark colors during the winter?

6. In places like southern California, people use light-colored paints on the outside of their dwellings. Why?

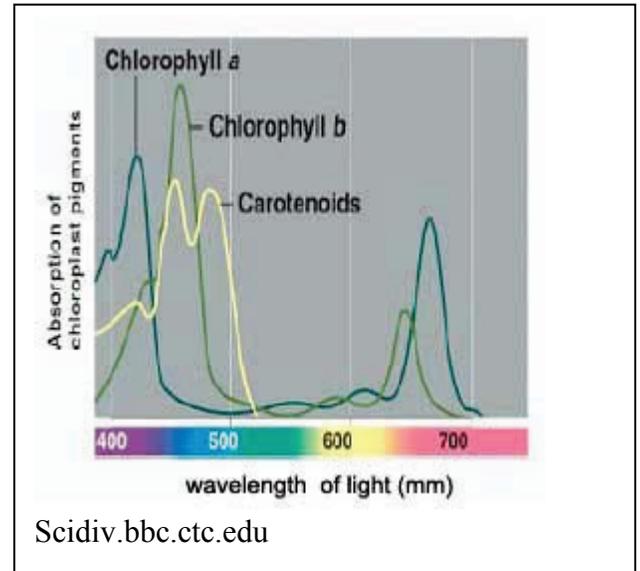
Name _____

Date _____

The Absorption of Solar Energy

Part 2: Photosynthesis

One of the more important types of light absorption, essential to nearly all life-forms on Earth, occurs mainly in green plants. The leaves of these plants appear green both on the sunny side (when light reflects off them) and on the side away from the sunlight (when sunlight shines through them). Green pigments called chlorophyll, found within the cells of leaves and new-growth stems, absorb most colors of visible sunlight but reflect and transmit the green part of the solar spectrum as shown on the graph to the right. You will notice that chlorophyll comes in two varieties.



1. What are the two types of chlorophyll?
2. Describe two differences in the absorption spectrum of these two types of chlorophyll.
3. Which color or colors of the visible spectrum are least absorbed by the two chlorophylls?

One other group of pigments found commonly in green plants is shown on the graph.

4. What is the name of this pigment group?
5. Based on their absorption graph, what color do you think carotenoids would produce in leaves if chlorophylls weren't present?

Lab Activity #1: Separating the Pigments in Leaves

Materials:

Leaves collected by students
Small juice jars
Covers for jars
Rubbing alcohol

Filter paper strips: 1 inch x 8 inches
Water bath: shallow pan (with drain outlet) with hot tap water
Masking tape
8-inch wooden dowel

Procedure:

1. Work in groups of two to three students.
2. Each group of students should collect two to three leaves from a tree (note: each group should select a different type of tree).
3. Identify the type of tree and its location.

Tree: _____

Location: _____

SAFETY NOTE:

Isopropyl rubbing alcohol can be harmful if mishandled or misused. Carefully follow all warnings on the label or given by your teacher.

4. Cut the leaves into very small pieces and put them into glass jars labeled with the name of the tree and student group.
5. Add enough rubbing alcohol to each jar to cover the leaves. Using a section of wooden dowel, carefully grind the leaves and alcohol mixture.
6. Cover the jars loosely with lids and place the jars carefully in a water bath (shallow tray containing 1 inch of hot tap water).
7. Keep the jars in the water bath for at least 30 minutes, or longer, until the alcohol has become colored (the darker the better). Twirl each jar gently about every five minutes or so.
8. Obtain a strip of filter paper and write your group name in pencil in the last ½ inch at one end.
9. Remove your jar from the water bath and uncover it. Place the strip of filter paper into the jar so that the unlabeled end is approximately ½ inch into the alcohol. Bend the other end over the top of the jar and secure it with tape.
10. Place the jar in a quiet location for at least ½ hour.
11. When bands of color appear on the filter paper, remove the paper from the jar and let dry. Tape the strip to the space provided on the next page. Label the color bands.

SAFETY NOTE:

Hot water above 150°F can quickly cause severe burns. Be careful near the water bath.

LEAF COLOR STRIP:

The golden pigments near the top of the chromatogram are the **carotenes**. You will probably have two bands of lighter yellow **xanthophyll** pigments in the middle of the chromatogram, with the bright green (grass green) **chlorophyll a** immediately below the lower **xanthophyll** layer. **Chlorophyll b** is a more olive green layer immediately below the chlorophyll a layer. You may also see some grayish leaf breakdown products in the xanthophyll regions of the chromatogram.

Lab Activity #2: Finding Chlorophyll in Leaves

Materials:

Microscopes

Glass slides and cover slips

Elodea plants in water

Procedure:

1. Work in groups of two students.
2. Carefully bring a microscope to your workstation.
3. Remove a leaf from the *Elodea* plant and place it on a microscope slide with a few drops of water. Cover with a cover slip.
4. Observe the leaf through the microscope. Draw and describe what you see.

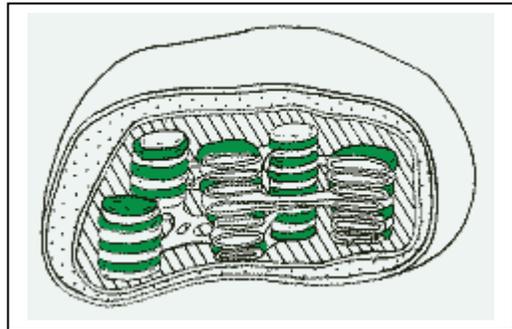
SAFETY NOTE:

Handle the microscope with care. Always carry it with two hands. Always focus it according to your teacher's instructions.

DEVELOP YOUR UNDERSTANDING

Even though leaves look green all over to our eyes, you have seen through the microscope that this is not the case. Chlorophyll is not randomly distributed throughout the cell; it is concentrated in small green cell organelles called chloroplasts. These structures, in some form, are thought to have been in existence for billions of years, probably first as independent organisms and later incorporated into green plants as chloroplasts, as we now know them. They may have been responsible, along with a type of blue-green algae known as stromatolites, for changing the composition of Earth's early atmosphere into one that contained enough oxygen to support non-photosynthesizing organisms (such as us).

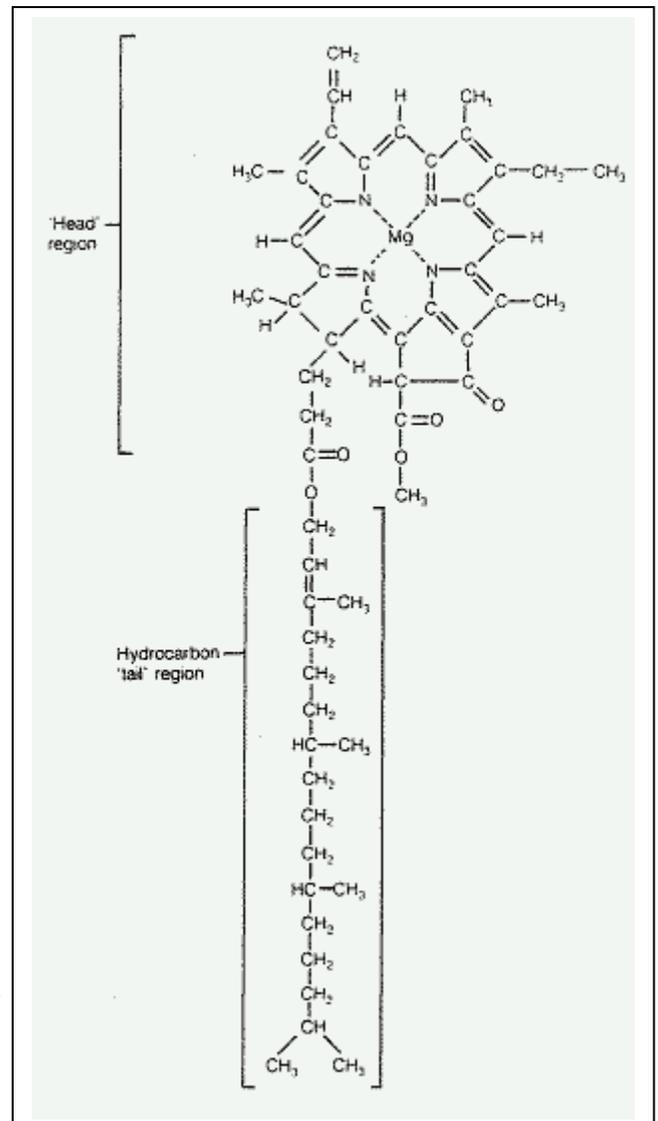
Even within the chloroplasts, the complex "blueprint" of life specifies where chlorophyll is located. As you can see in the cutaway view of a chloroplast that is shown to the right, a chloroplast has a definite internal arrangement of its parts.



1. Describe this internal structure.

The stacked structures, which look like stacked pancakes, are the sites of sunlight absorption, and this absorption starts the food-making process of photosynthesis. The "pancakes" are actually fluid-filled sacs surrounded by a membrane. It is within these membranes that thousands of chlorophyll molecules are located.

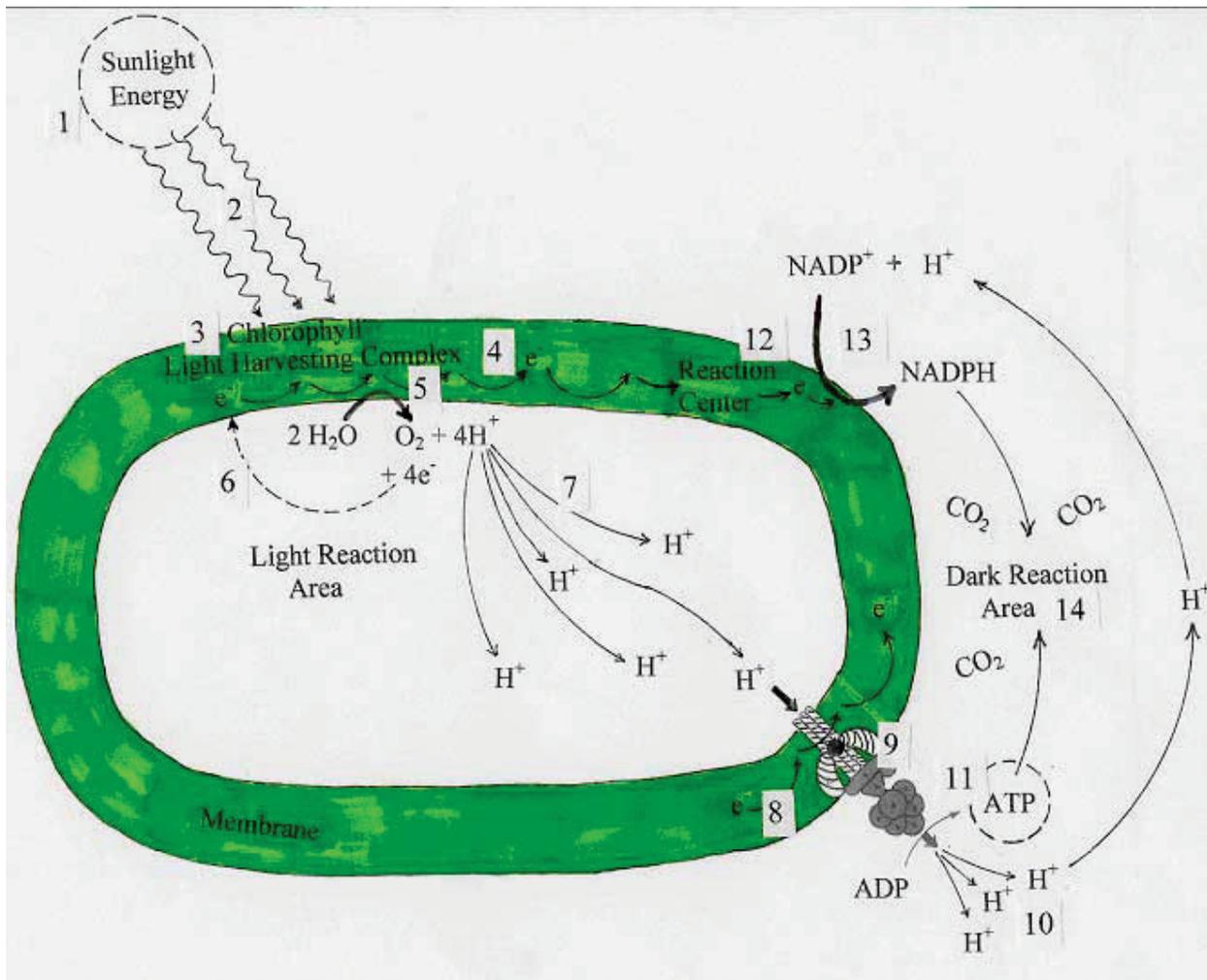
To gain appreciation for the complexity of life that we often take for granted, let's start with the chlorophyll molecule itself. As organic molecules go, this is a fairly simple chemical structure. You can see what is considered simple for yourself in the structural diagram to the right.



2. Name the various elements found in this molecule.
3. Which two elements are most abundant?

4. Why are some atoms in chlorophyll represented as being connected with double lines and others connected with single lines?

The “head” region of the molecule is the section where sunlight energy is absorbed. The “tail” region anchors the chlorophyll molecules into a complex called the light harvesting complex, or LHC for short. LHC is composed of both chlorophyll and protein molecules. Several of these chains of molecules are found in the membranes of each pancake within the stacks that are within the chloroplasts. Find the LHC within the membrane in the cross-sectional view of the pancake below.



5. What type of energy transfer do the wavy arrows shown at #2 in this diagram represent?
6. Go back to the chloroplast diagram at the beginning of this section and circle a similar cutaway view of the enlarged pancake above.

Each LHC contains approximately 300 chlorophyll molecules and acts like an antenna to intercept the wavelengths of electromagnetic energy [#3]. As usual, the absorbed radiation excites an electron to a higher energy level, but here is where the difference occurs. The electron, instead of dropping immediately back down from its excited state and emitting radiation or lingering in the excited state until the energy is dissipated as heat, gets whisked off down the pancake membrane along the light harvesting complex [#4]. Given the abundance of chlorophyll molecules, a multitude of electrons are moving down each LHC each second. The removal and transfer of these electrons creates an electrical imbalance, which drives one of the important

subprocesses of photosynthesis: the splitting of water molecules that are present in the cell [#5] into oxygen gas (O_2) and hydrogen ions (H^+).

7. From your prior knowledge of photosynthesis, what happens to this oxygen gas?

8. Free electrons (e^-) are another product of the splitting of the water molecules. What happens to these electrons? Follow the dashed arrow going left to find out.

9. Notice how the inside of the sac fills with H^+ ions from this process. How does this affect the pH of this region?

10. Where do these H^+ ions go from the inside of the sac?

The fancy structure at #9 is a membrane-piercing protein structure. These structures are found throughout the pancake membranes, but only this one is shown for simplicity's sake. This structure acts as a pump, once again powered by the flow of electrons along yet another LHC as shown by #8.

11. What material does this structure appear to pump, and from where to where?

This movement allows a second major process to take place in photosynthesis: the changing of an ADP molecule to an ATP molecule as shown at #11. This chemical change adds a high-energy phosphate group to the ADP molecule, which finally traps the sunlight energy in the chemical bond. The energy in the ATP molecule supplies the energy for most chemical changes within living organisms. In this case it is used to complete photosynthesis, which occurs in the area outside the pancake labeled "Dark Reaction Area."

12. Besides the ATP molecule, what other substances move to the dark reaction area?

13. Where has the carbon dioxide come from?

14. What two substances from within the pancake structure help make NADPH molecules?

The processes of the dark reaction combine the hydrogen from the NADPH with CO₂ to form simple sugar-building molecules, CH₂O, thereby transferring the trapped sunlight energy from the ATP molecules to sugar molecules. You are familiar with sugar molecules as food for the living organism that contains the chloroplasts and the organisms that eat this organism.

DEVELOP YOUR UNDERSTANDING: SUMMARY

1. The flow of the excited electrons of absorbed sunlight energy drives three processes in the internal membranes of chlorophyll. Describe these three processes.

(1)

(2)

(3)

2. Name three molecules involved in photosynthesis that at some point hold the energy that was originally received from the Sun.

(1)

(2)

(3)

3. Describe three energy transformations that take place in the photosynthesis interactions shown in the diagram above.

(1)

(2)

(3)