
Photosynthesis
and
Respiration

Summary Questions

1. What is the First Law of Thermodynamics?

2. What is the Second Law of Thermodynamics?

3. Within an ecosystem, approximately what percent of sunlight energy is converted into plants?

4. Within an ecosystem, from the plant energy conversion onward, what is the percent of each subsequent energy conversion?

5. Write the equation for photosynthesis.

6. Write the equation for respiration.

7. Which has more electron energy: $C_4H_6O_4$ or $C_4H_4O_4$?

8. What are the products of anaerobic respiration?

9. Where in the cell does aerobic respiration occur?

10. Compare the amounts of ATP produced.

Aerobic = ____________ ATP

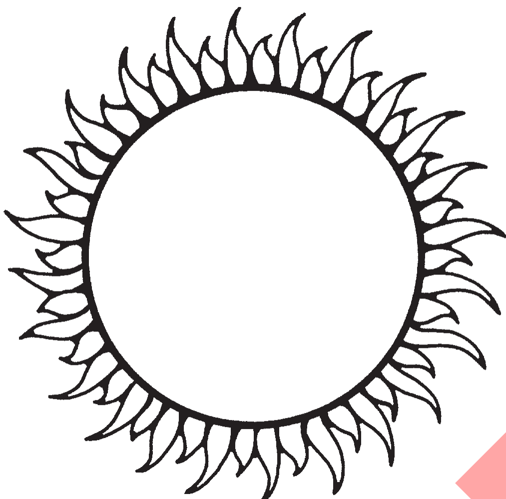
Anaerobic = ____________ ATP

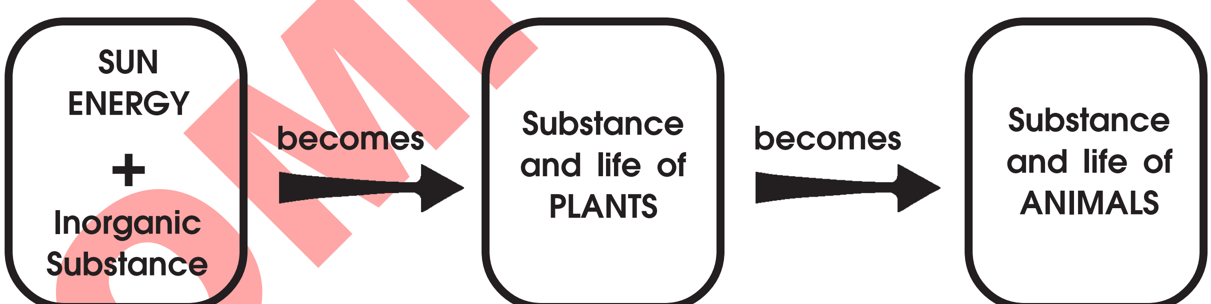
PHOTOSYNTHESIS AND RESPIRATION

INTRODUCTION

Physicists have developed two ways of describing the universe: One of these is energy, and the other is matter. Matter is anything that has mass and occupies space. Energy is non-material, travels in waves, and has the capacity to change matter.

Life can be described from both of these points of view. Life is an assemblage of atoms and molecules. It is also an energy process. The following Activities present highlights of energy conversions and substance changes in living systems.





ACTIVITIES

ACTIVITY #1

"ENERGY"

Energy can move and change matter, and can exist in different forms. Some of these forms include heat, light, electrical, chemical, and mechanical energy. In addition to describing the form of energy, we can measure the *amount* of it. The amount of energy can be measured using various experimental methods. For example, we can estimate the amount of heat energy in a flame by observing how fast that flame can "move" water molecules (heat them up).

LAWS OF THERMODYNAMICS

Several basic principles of energy change have been discovered. Two of these, the First and Second Laws of Thermodynamics, are of particular value in understanding life processes.

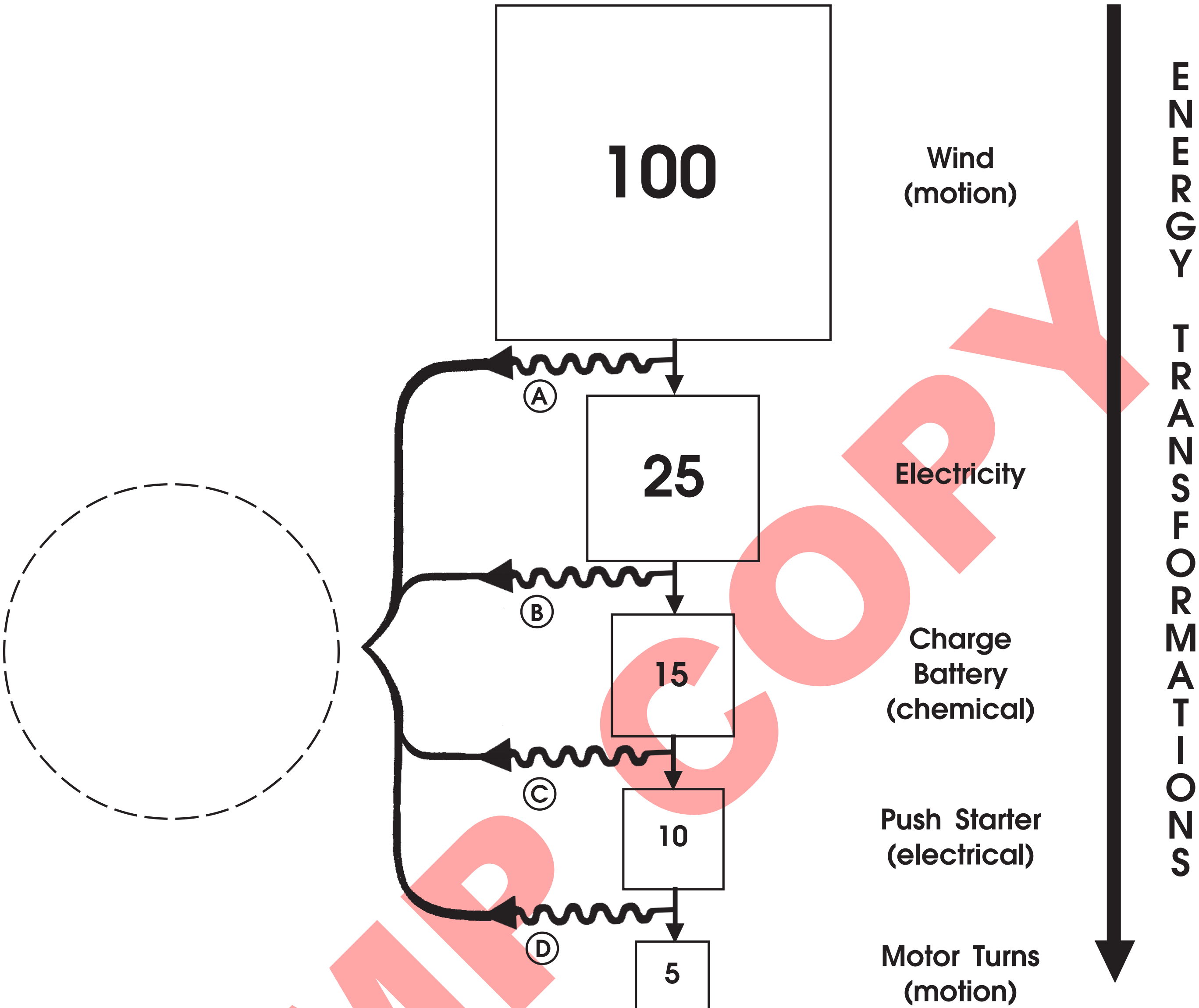
First Law of Thermodynamics

The amount of energy does not change; only the form of energy changes.

Second Law of Thermodynamics

Heat is always produced whenever one form of energy is converted into another form.

Imagine that the Engineering Department decided to build a campus wind generator for capturing and storing energy in batteries that could be used later to run electric motors. The size of the energy boxes in the diagram on the next page represents the amount of energy available at each step along the way. The numbers in the boxes represent energy units.



? QUESTION

1. What form of energy is represented by Ⓐ, Ⓑ, Ⓒ, and Ⓓ?
   Write the name of this form of energy inside the circle on the left side of the diagram.

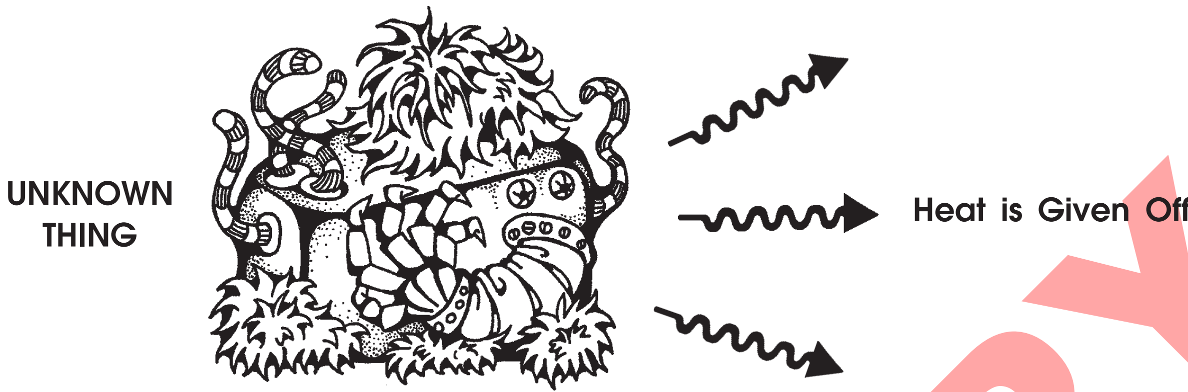
2. Which Law of Thermodynamics is used to answer question #1?

3. Using the First Law of Thermodynamics, calculate the amounts of energy released at . . .
   Ⓐ ____________ Ⓑ ____________ Ⓒ ____________ Ⓓ ____________.

4. What is the total amount of heat in the big circle? ________________________

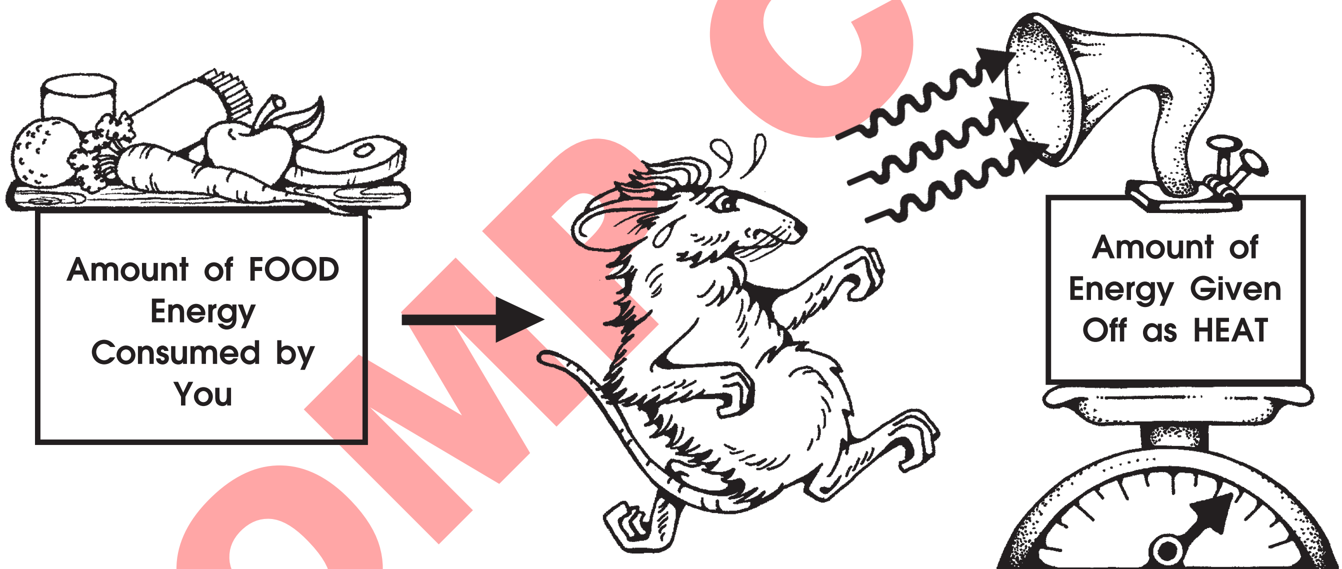
5. A biology student who learned about the Laws of Thermodynamics, suggested that the school's Engineering Department should have designed a wind machine that directly turned the campus motors. How would her suggested change improve efficiency?

6. Imagine there is an "unknown thing" giving off heat. What can we conclude is going on inside the "unknown thing"?



ENERGY IN ANIMALS

We can measure the amount of energy in food. Also, there are machines designed to record the heat that an organism gives off during the day. Assume that the *size* of the boxes in the diagram below represents the amounts of energy for one day.



? QUESTION

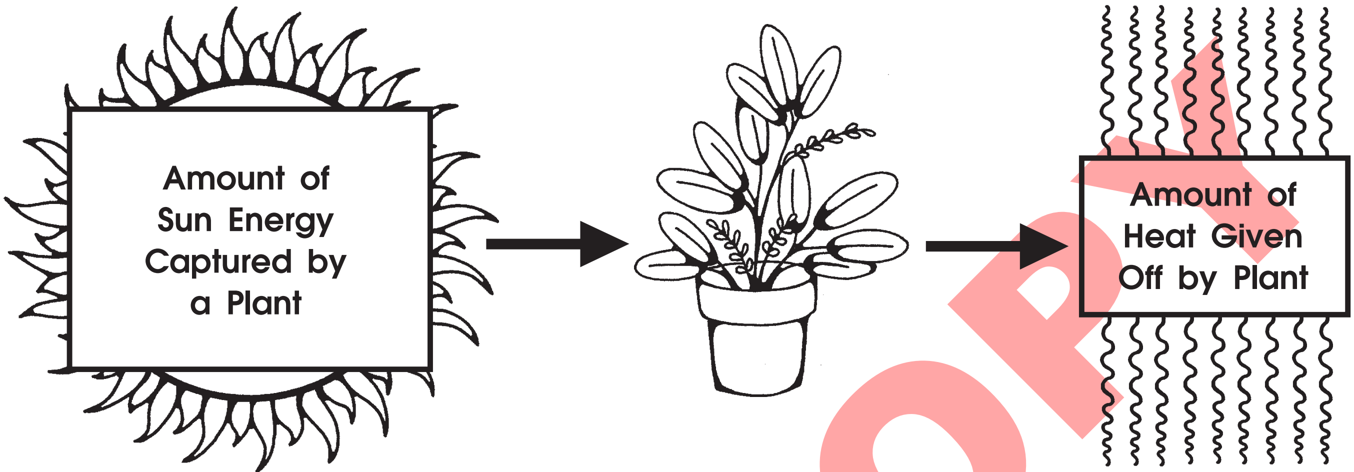
1. Use the First Law of Thermodynamics to analyze the energy diagram above. What is obvious about the amounts of energy represented in the diagram?

2. Where is the rest of the energy?

The process of FOOD ENERGY ⟶ YOU ⟶ HEAT is called ***Respiration***. We will outline the substances that are changed during respiration in Activity #3.

ENERGY IN PLANTS

We can measure both the amount of light energy absorbed by a plant during a day and the amount of heat released by the plant. Assume that the size of the boxes represents amounts of energy.



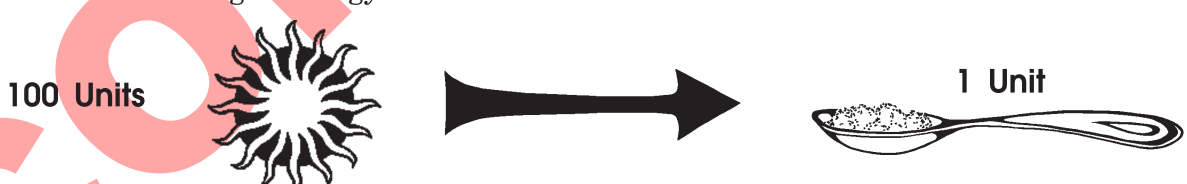
? QUESTION

Considering the First Law of Thermodynamics, where is the rest of the energy?

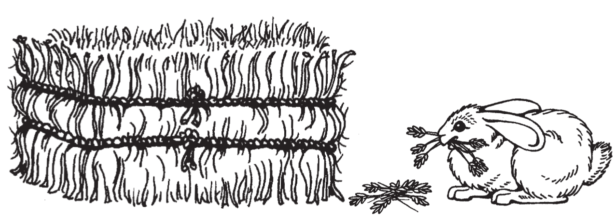
The process of SUN ENERGY ⟶ PLANT is called ***Photosynthesis***. We will describe the substances that are changed during photosynthesis in Activity #2.

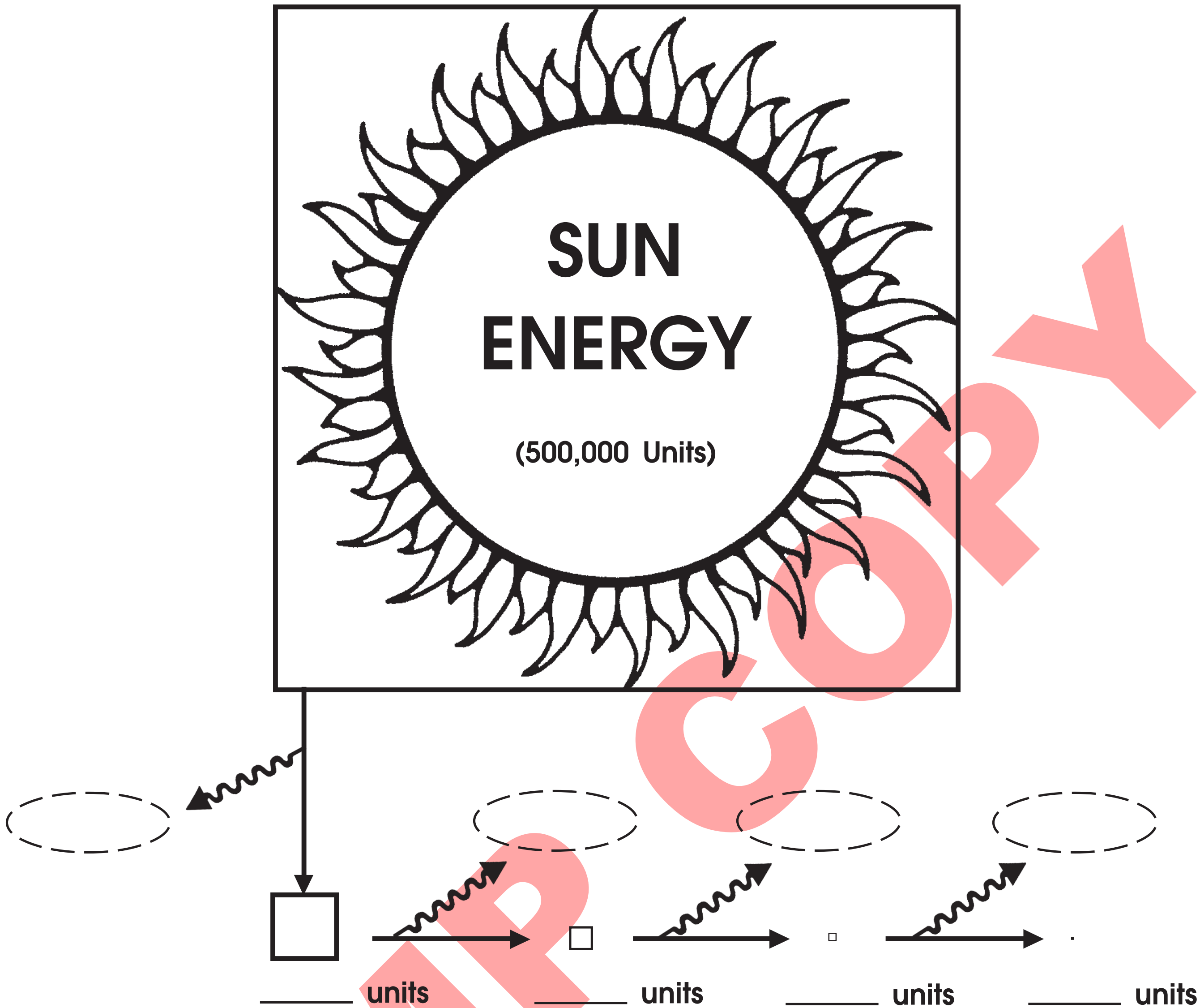
ENERGY IN ECOSYSTEMS

The Laws of Thermodynamics help us to understand conversions of energy within ecosystems. Energy of sunlight is first converted into the chemical energy of plants. This conversion occurs with about 1% efficiency. This means that photosynthesis requires about 100 units of sun energy to produce one unit of sugar energy.



The animal that eats plants is called a ***herbivore***. The animal that eats herbivores is called the ***first carnivore***. The ***second carnivore*** eats the first carnivore, and so on. At each step from the plant outward, the energy conversion efficiency is about 10%. (For example, 100 kg of plant are required to produce 10 kg of rabbit.) The diagram on the next page shows the amounts of energy at each food level in the ecosystem.





? QUESTION

1. Each of the four boxes represents a food level. Write the name of each food level (from plants ⟶ second carnivores) below the boxes.

2. Starting with 500,000 units of sunlight energy, calculate and record the number of energy units (on the lines below each box) for each of the energy levels in the diagram.

3. What form of energy is given off during the conversion from one ecosystem level to the next? ***Hint:*** Remember the Second Law of Thermodynamics.

4. Record the amount of energy (question #3) given off at each step in the ecosystem diagram. (Put your answers in the dotted ovals at the ends of the wavy arrows.)

5. Assume that humans are the second-level carnivores, and that each energy unit in their level represents 25 people. How many people can be supported in the ecosystem?

6. Assume that we eat herbivores only. As first-level carnivores, how many humans can now be supported in the ecosystem?

7. If we ate plants only, how many humans could be supported by the ecosystem?

8. If we ate plants only, what would happen to the amounts of energy available for the other herbivores and carnivores in the ecosystem?

9. Let's look at energy conversion another way. It takes about 0.5 kg of meat to support a human for one day. Assuming that beef is the only available nutrient, how much meat energy (kilograms of meat) will it take to get you to 20 years old?

10. How much plant energy (kilograms of plant) will it take to feed the beef that gets you to 20 years old? (Refer to question #9.)

11. Your digestive system is very efficient at digesting meat, but is not as efficient at getting all of the available nutrition from plants. Now, assume that you were raised on plants instead of meat. Plant material has about 40% of the per-kg food value as meat. How much plant energy would it take to get you to 20 years old?

Do you get the general idea of how the Laws of Thermodynamics give us a better understanding of ecosystems?

The next Activities present how matter is changed by energy in both photosynthesis and respiration.

ACTIVITY #2

"PHOTOSYNTHESIS"

Activity #1 presented photosynthesis from the energy perspective. In this Activity we consider the changes in *substances* (matter) during photosynthesis.

HISTORICAL DISCOVERY PROCESS

The chemical changes that occur during photosynthesis have been investigated for the past 300 years. The general highlights of these discoveries help us to understand the basic process of photosynthesis.

Three centuries ago people wondered where plants came from. They knew that plants grew out of the ground, but *how* that happened was a complete mystery to them. The first step in answering the question was to plant a small tree in a large pot supported off the ground. They did this so that the soil of the container was separated from the soil of the earth. Only the dirt in the pot was available to the plant.

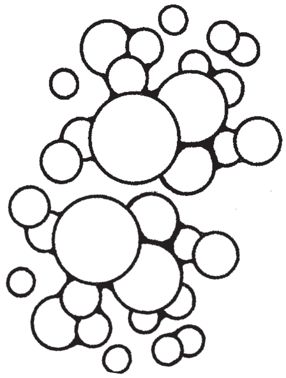
The people cared for the plant during one year. At the end of the year the small tree had gained 100 kg. (*The actual data from this experiment have been changed to simplify the discussion.*)

? QUESTION

1. What do you think the experimenters considered as two possible sources for the substances (matter) that became incorporated into new tree growth? (This experiment was performed nearly 300 years ago. People didn't know very much about chemistry, and air was thought to be a non-substance.)

________________________ ________________________

2. When the experimenters measured the weight of the two substances (question #1) given to the plant, they found 35 kg of one and 2 kg of the other. Where do you think they thought the rest of the plant's weight came from?



People guessed that there must be some invisible substance in light or somewhere else that was added to the plant. It took another century for humans to discover the chemical makeup of air. Once humans invented accurate scales, they could measure small changes in the weight of air.

Experimenters put a plant into a sealed jar with air that had been weighed. After the plant was exposed to light for a few hours, the air lost weight. They had discovered another source of matter for the new plant growth—the air! The basic equation for photosynthesis was complete:

CO_2 + H_2O + a little soil —Light Energy→ New Plant Tissue + O_2

heavy air | $C_6H_{12}O_6$ and its variations | light air

? QUESTION

1. Look at the molecular formula for plant tissue. Where does the carbon come from?

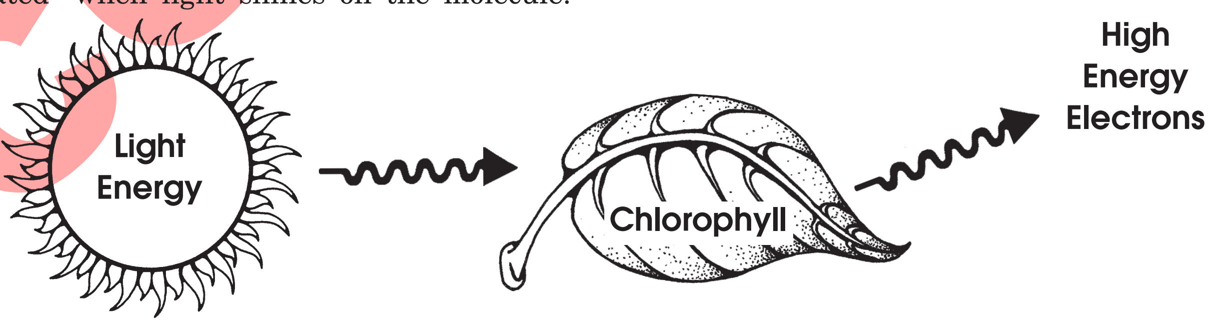
2. Where does the hydrogen in $C_6H_{12}O_6$ come from?

3. When radioactive isotopes of oxygen atoms are put into CO_2 molecules and the plant is allowed to photosynthesize, only new plant tissue ($C_6H_{12}O_6$) is radioactive and the oxygen gas given off is not radioactive. Draw a dotted line in the photosynthesis equation to show where the oxygen atoms in CO_2 go.

4. Draw a dotted line in the equation to show where the oxygen atoms in H_2O go.

CHLOROPHYLL

All chemical reactions involve changes in the *electrons* of atoms. The key to photosynthesis is a special molecule called ***chlorophyll***. This large and complex molecule has electrons that become "activated" when light shines on the molecule.



This reaction is unusual because most substances only heat up when exposed to sunlight; that is, their electrons aren't "activated" by light energy. But the electrons in chlorophyll are activated by light, and this electron energy is used to make new plant tissue ($C_6H_{12}O_6$).

? QUESTION

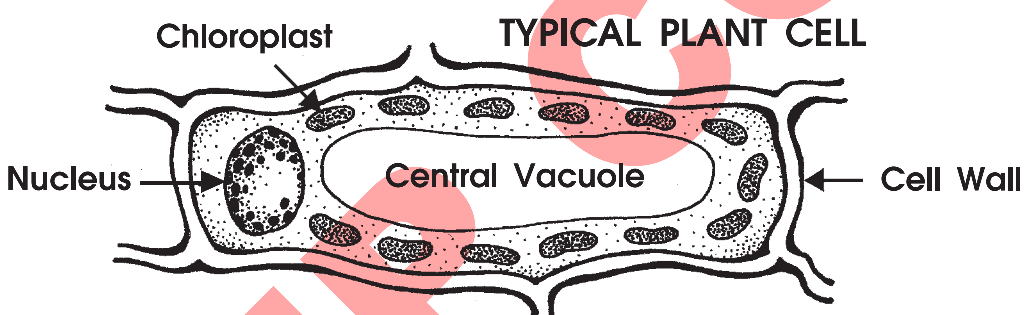
1. Sunlight contains all of the colors of light in the visible spectrum. Which color do you see reflecting from the surface of plants?

2. Which two primary colors do you *not* see when looking at the plant leaves?

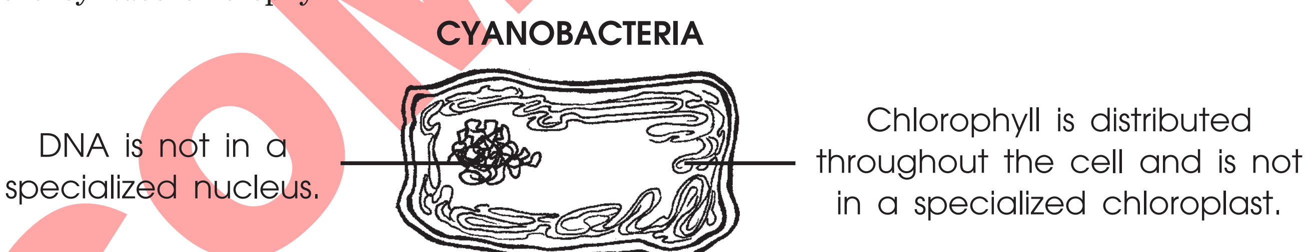
3. Which colors of light probably activate the electrons of the chlorophyll molecule? Explain.

CHLOROPLASTS

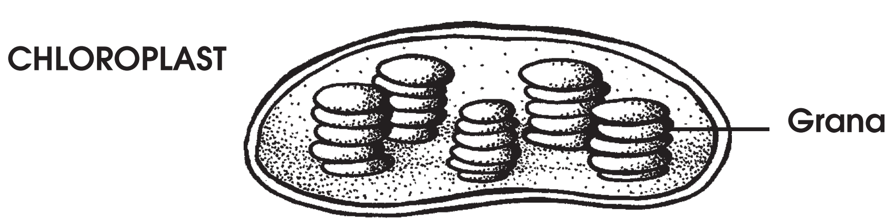
All of the unicellular algae and multicellular plants are eukaryotic and have specialized organelles called ***chloroplasts***. The chloroplasts contain chlorophyll and enzymes for the photosynthesis process.



The exceptions to this rule are the photosynthetic bacteria (cyanobacteria). They are prokaryotic; that is, they don't have cell organelles like chloroplasts. However, cyanobacteria *do* photosynthesis, and they *have* chlorophyll.



The chloroplast has many specialized structures. Stacks of discs, called ***grana,*** contain the chlorophyll and act like photoelectric cells. When light shines on these grana, the electrons of the chlorophyll are "activated." This is the first stage of photosynthesis.



The second stage of photosynthesis involves the building of sugar molecules from carbon dioxide and water. These two ingredients will not combine unless chemical energy is provided. That energy comes from the "activated" electrons in the chlorophyll reaction. Sugar molecules are made in the fluids of the chloroplasts that surround the grana.

Simple sugars made during photosynthesis are modified into all of the other organic molecules needed by the plant.

Simple Sugars
- → **Starch** (for later energy supply)
- → **Cellulose** (for cell walls)
- → **Amino Acids** → **Proteins** (for enzymes and structural materials)
- → **Nucleotides** (for DNA and RNA)
- → **Oils** (for cell membranes and energy storage)

? QUESTION

1. When light energy shines on chlorophyll, the light energy is transformed into . . .

Light Energy → **Chlorophyll** → ______________ **Energy**

2. Some biologists refer to the two parts of photosynthesis as the light reactions and the synthesis reactions. Which part do you think that they call the light reactions?

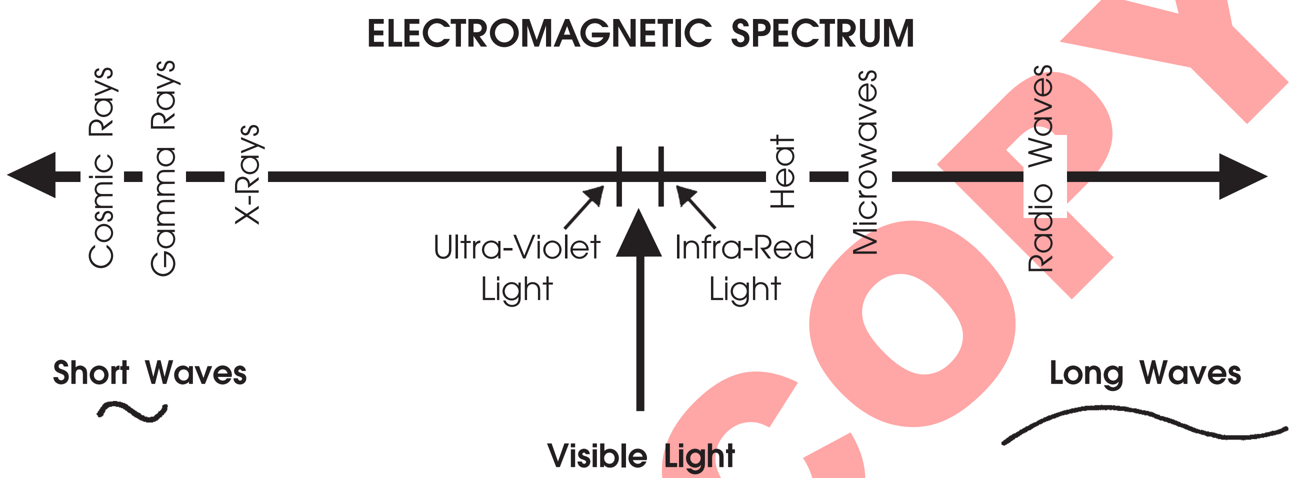
3. Which part of photosynthesis do you think they call the synthesis reactions?

4. The synthesis reactions happen in the daytime, but are sometimes called "dark reactions" because light energy is not directly required. What kind of energy is required to run the synthesis reactions?

Where does that energy come from?

CHARACTERISTICS OF LIGHT

Our description of energy includes anything that is non-material, travels in waves, and having the capacity to move and change matter. There are many different kinds of energy, and each has its characteristic *wavelength*. When all of these energy waves are arranged on a scale from short waves to long waves, that scale is called the ***electromagnetic spectrum***.



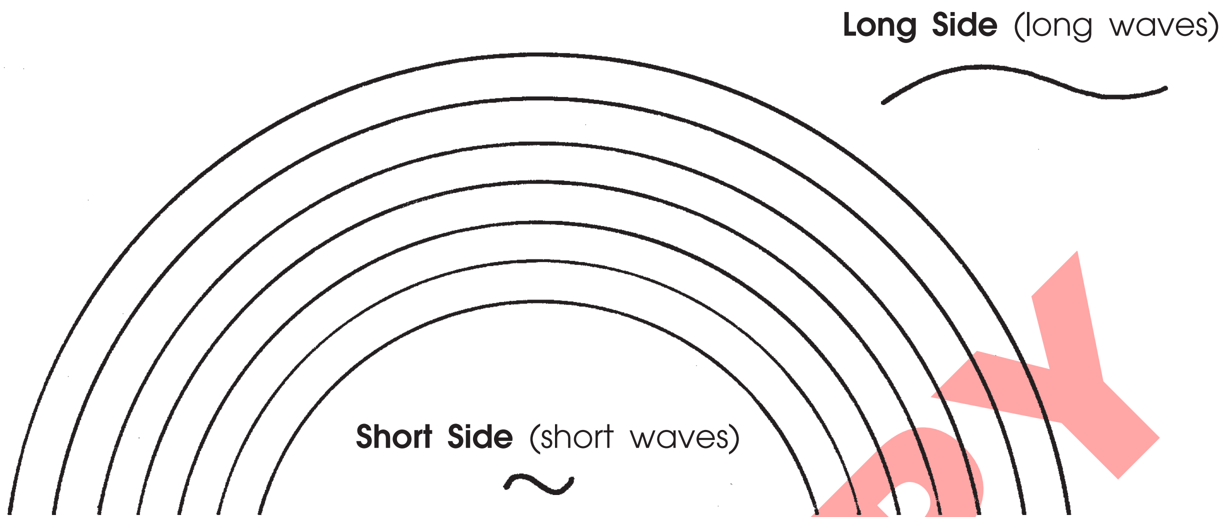
You can see that visible light is only a very small slice of the electromagnetic spectrum. An important feature of electromagnetic energy is that shorter waves have more energy than longer waves. This is the key to understanding why only a narrow segment of waves in the electromagnetic spectrum is ideal for biological reactions like photosynthesis and vision. Some people humorously refer to this idea as the "Goldilocks" principle—the wavelength has to be "just right."

The energy waves just shorter than violet light are called ***ultra-violet***, and the waves just longer than red light are called ***infra-red***.

Ultra-violet waves are damaging to life. These waves have too much ____________. The molecules exposed to ultra-violet waves become over-activated and are chemically changed or destroyed.

The molecules exposed to infra-red waves are "warmed up," but these waves do not have enough ____________ to activate electrons (essential for biochemical reactions).

White light (visible light) is made of different wavelengths of energy (different colors). You can remember where the various colors occur in the visible light spectrum by recalling the image of a rainbow in your mind.



? QUESTION

1. Which color is on the short side of the rainbow?

2. Which color is on the long side?

3. Which color is about in the middle?

4. Put these colors in the rainbow diagram above. (The long side of the rainbow is the longer wavelength.)

5. Which color do you see when you look at plants? (The color that you *see* is the color that plants do *not* use in photosynthesis.)

6. Which two primary colors do you *not* see when looking at a plant? (These are the two wavelengths of energy that plants mostly use for photosynthesis, so they are *absorbed* by the plant rather than reflected back.)

________________________ ________________________

There is much more to photosynthesis than is covered in this Activity. You will have to get those details from lecture or your textbook.

ACTIVITY #3

"RESPIRATION"

Respiration was presented from the energy perspective in Activity #1. In this Activity we consider the changes in substances (matter) during cellular respiration. Respiration is the chemical breakdown of food molecules, converting food energy into usable energy (ATP) for the cell.

HISTORICAL DISCOVERY PROCESS

Investigation of the chemical changes during respiration coincided with experimental revelations about photosynthesis. The earliest experiments on respiration were performed about 300 years ago, and involved both plants and animals.

EARLY EXPERIMENTS

Mouse in a sealed jar → **Mouse dies in an hour or so**

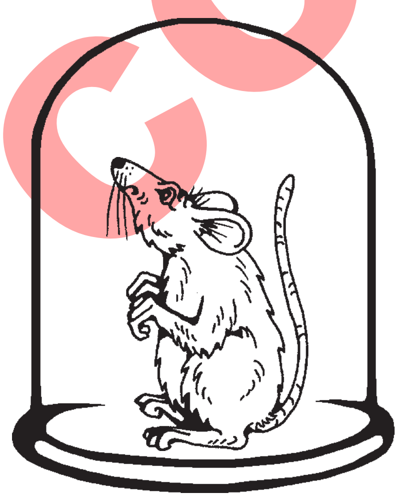
Mouse in a sealed jar with a large plant in the light → **Mouse lives just fine**

Mouse in a sealed jar with a large plant in the dark → **Mouse dies in an hour or so**

These early experiments revealed several facts:

- There was something in the air that animals needed to live.
- Somehow plants were able to "regenerate" the air that animals needed.
- Light was necessary for plants to "regenerate" the air.

Later experiments measured changes in the weight of substances during respiration.



← **Mouse in a sealed jar with enough air but no food**

Experimental Results:
Mouse loses weight.
Mouse produces water.
Air gets heavier.

? QUESTION

1. Based on this experiment, where did the weight of the mouse go? __________ and __________

2. The air started out light in weight. What was the substance of that air? (Refer to "light air" in Activity #2.)

3. The air ended up heavier in weight. What was the substance of that air? (Refer to "heavy air" in Activity #2.)

4. Write the molecular formulas for each substance in this basic equation for respiration below. (Use the same formula for mouse tissue that we used for plant tissue in Activity #2.)

Mouse Tissue + Light Air ⟶ Water + Heavy Air

5. Radioactive isotope experiments have shown that atoms of carbon, oxygen, and hydrogen are rearranged just like in photosynthesis, only the equation is in reverse. (Refer to the photosynthesis equation in Activity #2.) Draw a dotted line in the respiration equation (question #4) to show where the carbon atoms in the food molecule go.

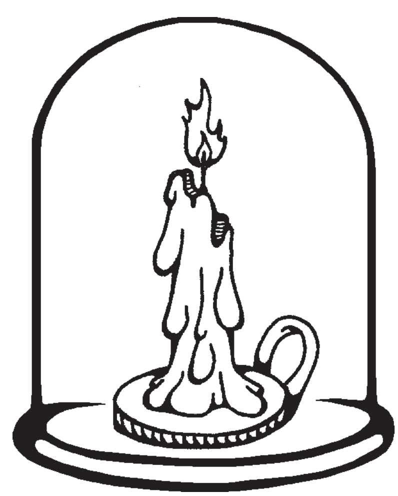
6. Draw a dotted line in the respiration equation to show what happens to the oxygen atoms in the air that we breath.

7. Where do the oxygen atoms in CO_2 come from? (Show this with another dotted line in the respiration equation.)

RESPIRATION COMPARED TO A BURNING CANDLE

Experimenters discovered that a burning candle is the same basic chemical process as animal respiration. The burning of any substance is called ***combustion***.

$$\text{Candle} + O_2 \longrightarrow CO_2 + H_2O$$



? QUESTION

1. Respiration is the opposite of ________________.

2. Which must have evolved first—animals that required oxygen or the process of photosynthesis?

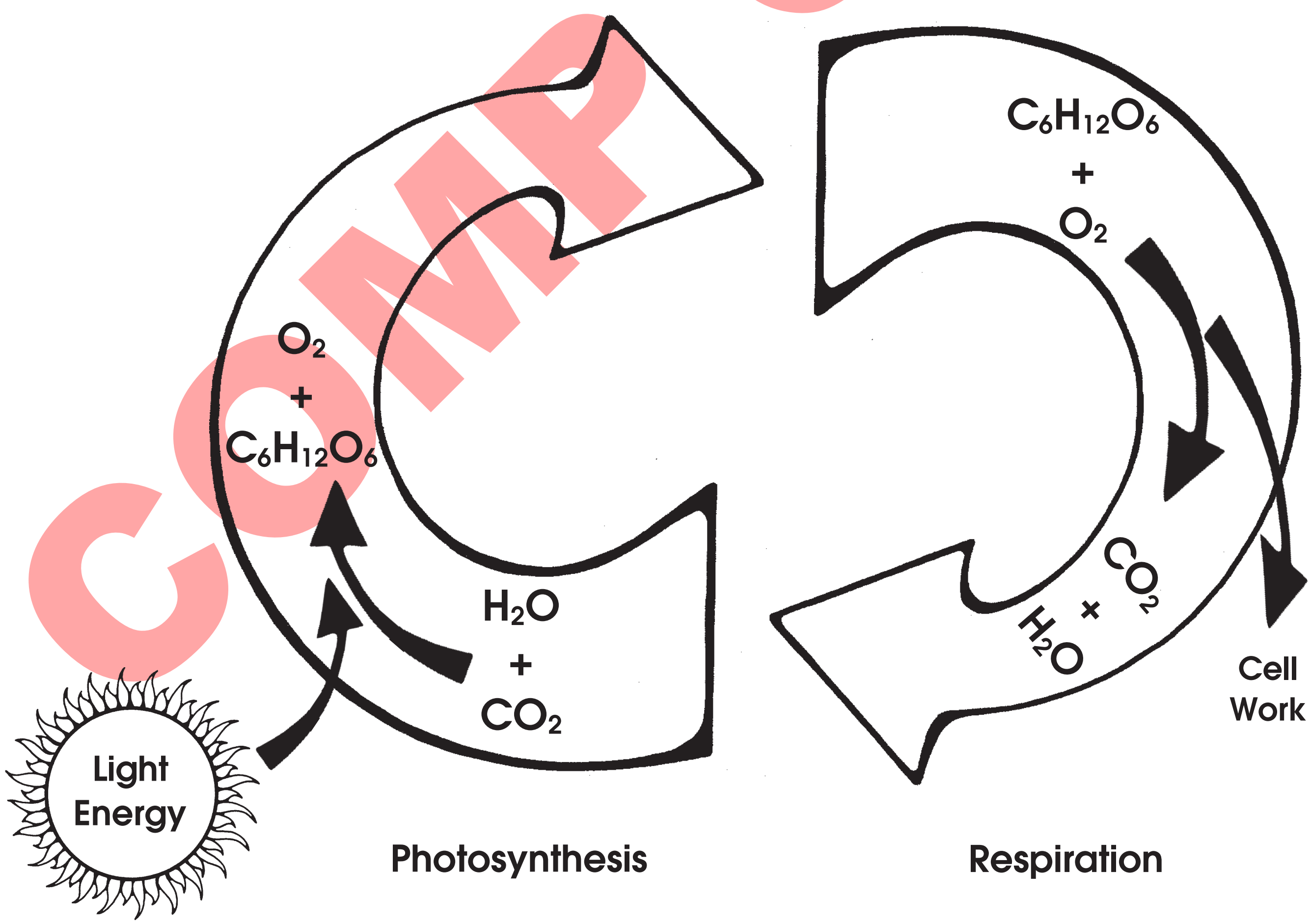
3. Assume that all oxygen in the atmosphere came from photosynthesis. Knowing this, what has been happening faster—respiration or photosynthesis?

4. Evidence suggests that the early atmosphere of our planet was very high in CO_2. Based on your answer to question #2, where did the CO_2 go?

5. If your answer to question #3 is true for this planet, then where is all the "extra" plant material that hasn't burned or been eaten? (***Hint:*** think of two major resources.)

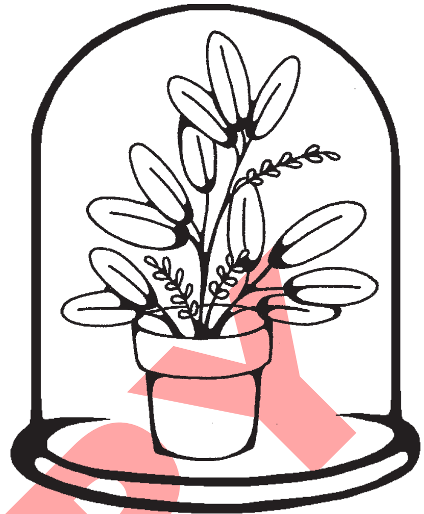
________________________________ ________________________________

6. If all the resources referred to in question #5 were burned, what change would happen in the atmosphere?



DOES RESPIRATION HAPPEN IN PLANTS?

Plant in a sealed jar in the dark →



Experimental Results:
Plant loses weight.
Plant produces water.
Air gets heavier.

Conclusion:
Plants do respiration.

? QUESTION

A house plant was kept one month in each of three rooms in the house. Compare the intensity of photosynthesis and respiration by the plant in each of the rooms.

In room #1 the plant lost weight and started to die. ______________________________

In room #2 the plant gained weight. ______________________________

In room #3 the plant survived but didn't gain weight. ______________________________

CHEMICAL BREAKDOWN OF FOOD

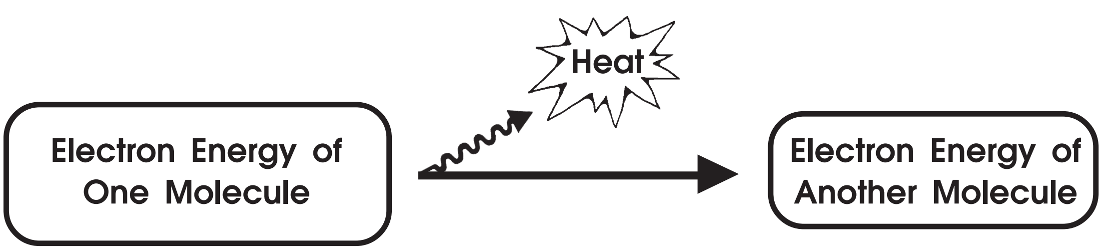
Using a few basic rules about chemical reactions, you can understand much about respiration.

Rule: Electrons have energy.

Rule: Sometimes electrons can move from one molecule to another.

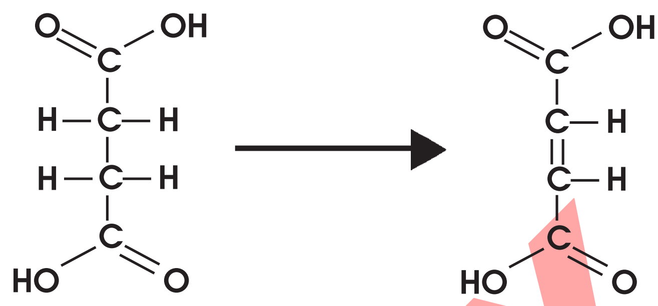
Rule: Whenever hydrogen atoms are added to or removed from a molecule in a chemical reaction, assume that the number of electrons also changes (one hydrogen added = one electron added).

Rule: The Second Law of Thermodynamics applies to situations in which the electron energy of one molecule is transformed into the electron energy of another molecule.



? QUESTION

1. In the reaction shown, is the molecule gaining or losing energy?



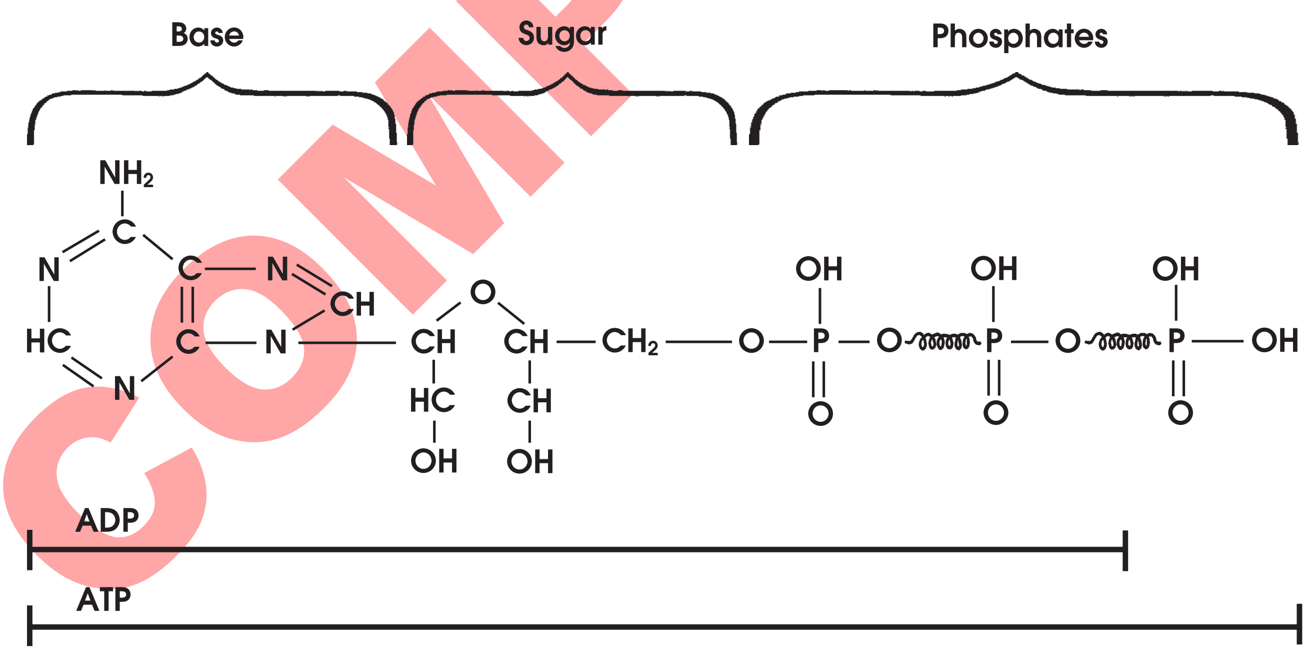
2. Which has more electron energy—$C_6H_{12}O_6$ or $6CO_2$? ____________

3. How many electrons are removed from sugar during respiration—$C_6H_{12}O_6 \rightarrow 6CO_2$?

____

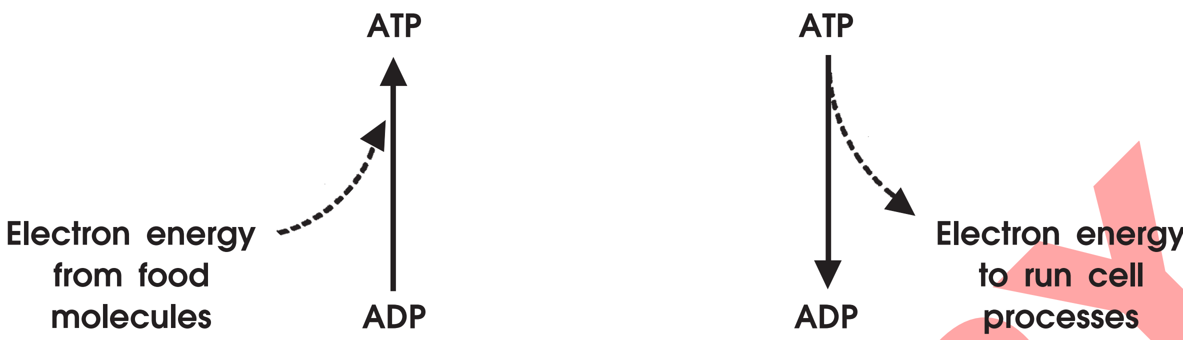
4. Cells need a special molecule called ATP to do the work of life. Assume that the energy of one electron from food ($C_6H_{12}O_6$) can be transformed into the energy in 3 ATP molecules. How many ATP molecules are generated during the breakdown of one sugar molecule during respiration? (Refer to your answer for question #3.) ____________

ATP



ATP (adenosine triphosphate) is a special high-energy molecule in the cell. This molecule can also exist in a low-energy form called ADP (adenosine diphosphate). ATP has more high-energy electrons than ADP. That extra electron energy comes from food molecules.

ATP delivers high-energy electrons to other energy-requiring processes in the cell. The two processes (ADP $\longrightarrow$ ATP and ATP $\longrightarrow$ ADP) create an energy exchange system in the cell.



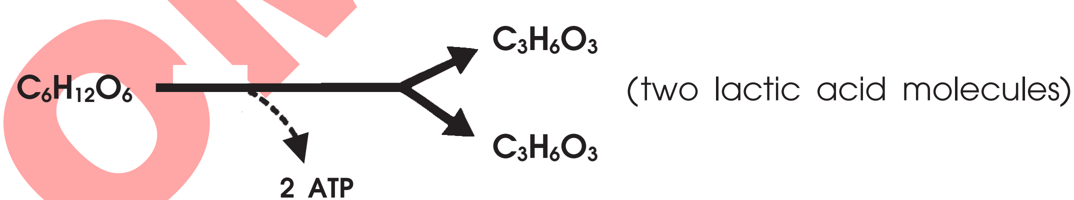
AEROBIC AND ANAEROBIC RESPIRATION

You concluded previously that cells requiring oxygen for respiration must have evolved after photosynthesis. We know that some chemical reactions can happen without oxygen. So, could there have been a form of respiration that might have existed before photosynthesis? The answer is yes. Respiration can occur without oxygen, and there were primitive cells living by this process before photosynthesis evolved.

Respiration without oxygen present is called ***anaerobic*** (without air). Respiration with oxygen is called ***aerobic***. Aerobic respiration occurs inside a specialized organelle called the ***mitochondrion***, whereas anaerobic processes (also called *fermentation*) are associated with other membranes in the cytoplasm.

The sugar molecule is only partially broken down during anaerobic respiration. Have all high-energy electrons been removed from the sugar molecule below? ____________

Anaerobic Respiration in Human Muscles



The energy of two ATP molecules is generated when sugar is "split" into the two lactic acid molecules. These two ATP molecules are the *only* energy captured from the food molecule during anaerobic respiration. High-energy electrons remain in the lactic acid. This means that anaerobic respiration is very *inefficient* compared to aerobic respiration. (***Remember:*** In question #4 under "Chemical Breakdown of Food," you calculated that 36 ATP are generated during aerobic respiration.)

In humans, anaerobic respiration happens for short periods of time only in the skeletal muscles. During strenuous exercise, this maintains metabolism when oxygen is temporarily depleted. Other organs of your body are incapable of anaerobic respiration, and their cells begin to die when oxygen is used up.

? QUESTION

Complete the following table comparing aerobic and anaerobic respiration.

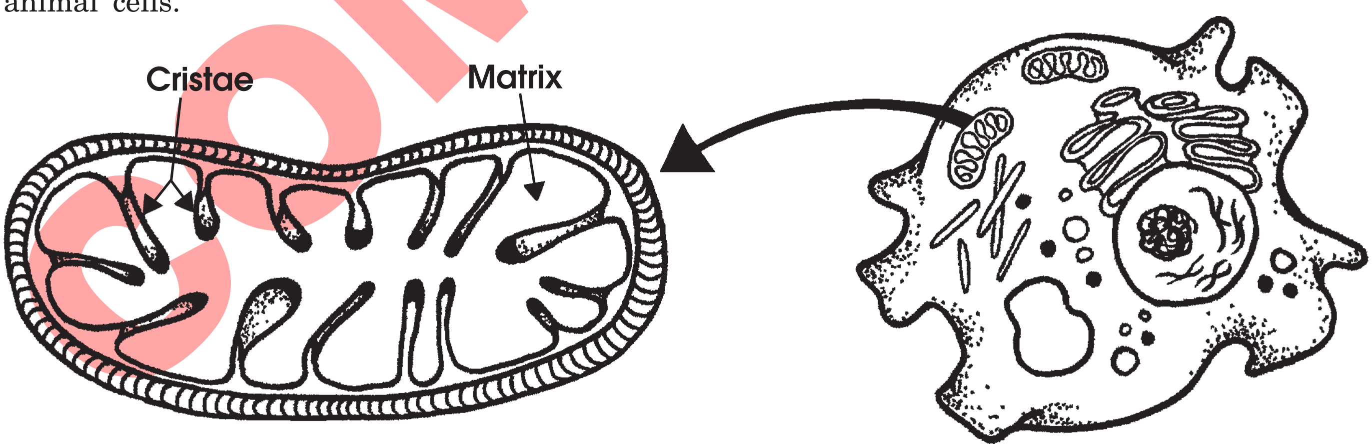
Comparisons	Aerobic	Anaerobic
Is oxygen necessary?		
Which came first on the planet?		
What are the end products?		
How much ATP energy is generated?		
Where in the cell does it happen?		

MITOCHONDRIA

Aerobic respiration is the process in living organisms that extracts electron energy from the chemical bonds in food (organic molecules), and converts that energy into a more useful form of energy (called ATP) to run cell activities. This cell process uses oxygen and produces carbon dioxide. The complete equation is:

Organic Molecules (food) + Oxygen → Carbon Dioxide + Water, ATP Energy (runs cell processes) + Heat

Aerobic respiration occurs inside the mitochondria, which are cellular organelles in both plant and animal cells.



Mitochondrion

Cell

The mitochondria have a remarkable structure that is somewhat like a factory. The high-energy electrons are stripped off the food molecule in the fluid matrix, and then the energy of those electrons is used to generate ATP energy along the ***cristae*** membranes.

? QUESTION

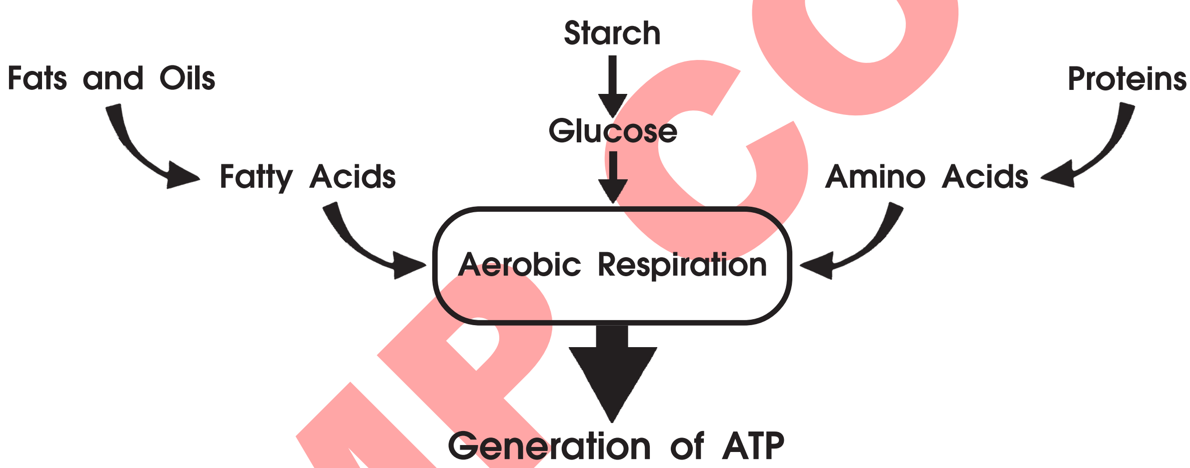
1. Which cells evolved first—eukaryotic or prokaryotic?

2. Which cells have mitochondria—eukaryotic or prokaryotic?

3. Some of the cells of your body have many mitochondria and other cells have few mitochondria. Why would there be differences?

METABOLISM OF NUTRIENTS

Sugar is not the only type of food molecule that can be metabolized during cell respiration. Fats, proteins, and starch are other energy sources for the generation of ATP.



The amount of ATP generated by these nutrients depends on the size of the molecule and the number of high-energy electrons that can be stripped off.

Starches are easy to metabolize because they consist of glucose sugar molecules hooked together.

Proteins must first be broken into amino acids, which are then modified. The nitrogen atoms are broken off the amino acid molecule, and ammonia is produced which is then converted into urea. Urea is dumped into the urine. The part of the amino acid remaining after nitrogen removal can be broken down by aerobic respiration. An amino acid generates about the same amount of ATP energy as does an equal weight of sugar.

Fat molecules have many more high-energy electrons than an equal weight of either sugar or protein. Protein and sugar provide about 4 Calories of energy per gram. Fat provides about 9 Calories of energy per gram. Now you can see why it's so easy for those high-energy electrons to pile up!

? QUESTION

1. What factor determines the amount of energy that can be gained from a nutrient molecule?

2. Which nutrient provides the most ATP energy per molecule metabolized?

3. Urea is one of the substances that gives urine its characteristic smell. Urea in the urine means that you have been metabolizing ________________. (which nutrient)

This completes our discussion of cellular respiration. Your textbook will present many more details about the process, and applications related to health and nutrition.