Chapter 4

Photosynthesis

4.1 Lesson 4.1: Energy for Life: An Overview of Photosynthesis

Lesson Objectives

- Identify the kind of energy which powers life.
- Contrast the behavior of energy to that of materials in living systems.
- Analyze the way in which autotrophs obtain energy and evaluate the importance of autotrophs to energy for all life.
- Explain the relationship between autotrophs and heterotrophs.
- Discuss the importance of glucose to all life on earth.
- Compare the energy-carrying role of ATP to that of glucose.
- Explain the roles of chlorophyll and NADPH as sources of energy for life.
- Summarize the process of photosynthesis and write out the overall chemical equation for photosynthesis.
- Identify reactants, necessary conditions, and products in the chemical equation for photosynthesis.
- Describe the roles of chlorophyll and chloroplasts in photosynthesis.
- Identify the groups of organisms which are capable of photosynthesis.
- Discuss the many reasons photosynthesis is important to humans.

Introduction

All living things require an ongoing source of energy to do the work of life. You often see energy in action on a large scale: a whale breaches, apple blossoms swell and burst, a firefly glows, or an inky cap mushrooms overnight. However, energy works constantly to maintain life on a very small scale as well. Inside each cell of every organism, energy assembles chains of information and constructs cellular architecture. It moves tiny charged particles and giant protein molecules. Moreover, it builds and powers cell systems for awareness, response, and reproduction. All life's work requires energy.

Physics tells us that organized systems, such as living organisms, tend to disorder without a constant input of energy. You have direct, everyday experience with this law of nature: after a week of living in your room, you must spend energy in order to return it to its previous, ordered state. Tides and rain erode your sandcastles, so you must work to rebuild them. And your body, after a long hike or big game, must have more fuel to keep going. Living things show amazing complexity and intricate beauty, but if their source of energy fails, they suffer injury, illness, and eventually death.

Physics also tells us that, although energy can be captured or transformed, it inevitably degrades, becoming heat, a less useful form of energy. This is why organisms require a constant input of energy; the work they must do uses up the energy they take in. Energy, unlike materials, cannot be recycled. The story of life is a story of energy flow – its capture, transformation, use for work, and loss as heat.

Energy, the ability to do work, can take many forms: heat, nuclear, electrical, magnetic, light, and chemical energy. Life runs on **chemical energy** - the energy stored in covalent bonds between atoms in a molecule. Where do organisms get their chemical energy? That depends…

How Do Organisms Get Energy? Autotrophs vs. Heterotrophs

Living organisms obtain chemical energy in one of two ways.

Autotrophs, shown in **Figure** 4.1, store chemical energy in carbohydrate food molecules they build themselves. **Food** is chemical energy stored in organic molecules. Food provides both the energy to do work and the carbon to build bodies. Because most autotrophs transform sunlight to make food, we call the process they use **photosynthesis**. Only three groups of organisms - plants, algae, and some bacteria - are capable of this life-giving energy transformation. Autotrophs make food for their own use, but they make enough to support other life as well. Almost all other organisms depend absolutely on these three groups for the food they produce. The **producers**, as autotrophs are also known, begin **food chains** which feed all life. Food chains will be discussed in the *Principles of Ecology* chapter.

Heterotrophs cannot make their own food, so they must eat or absorb it. For this reason, heterotrophs are also known as **consumers**. Consumers include all animals and fungi and many protists and bacteria. They may consume autotrophs, or other heterotrophs or **organic molecules** from other organisms. Heterotrophs show great diversity and may appear far more fascinating than producers. But heterotrophs are limited by our utter dependence on those autotrophs which originally made our food. If plants, algae, and autotrophic bacteria vanished from earth, animals, fungi, and other heterotrophs would soon disappear as well. All life requires a constant input of energy. Only autotrophs can transform that ultimate, solar source into the chemical energy in food which powers life, as shown in **Figure** 4.2.

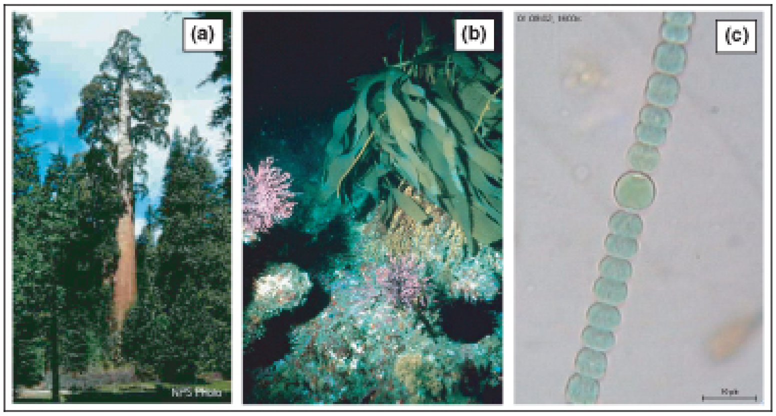


Figure 4.1: Photosynthetic autotrophs, which make food for more than 99% of the organisms on earth, include only three groups of organisms: plants such as the redwood tree (a), algae such as kelp (b), and certain bacteria like this (c).

Photosynthesis provides over 99 percent of the energy supply for life on earth. A much smaller group of autotrophs - mostly bacteria in dark or low-oxygen environments - produce food using the chemical energy stored in **inorganic molecules** such as hydrogen sulfide, ammonia, or methane. While photosynthesis transforms light energy to chemical energy, this alternate method of making food transfers chemical energy from inorganic to organic molecules. It is therefore called **chemosynthesis**, and is characteristic of the tubeworms shown in **Figure** 4.3. Some of the most recently discovered chemosynthetic bacteria inhabit deep ocean hot water vents or "black smokers." There, they use the energy in gases from the Earth's interior to produce food for a variety of unique heterotrophs: giant tube worms, blind shrimp, giant white crabs, and armored snails. Some scientists think that chemosynthesis may support life below the surface of Mars, Jupiter's moon, Europa, and other planets as well. Ecosystems based on chemosynthesis may seem rare and exotic, but they too illustrate the absolute dependence of heterotrophs on autotrophs for food.

Food and Other Energy-Carrying Molecules

You know that the fish you had for lunch contained protein molecules. But do you know that the atoms in that protein could easily have formed the color in a dragonfly's eye, the heart of a water flea, and the whiplike tail of a *Euglena* before they hit your plate as sleek fish muscle? As you learned above, food consists of organic (carbon-containing) molecules which store energy in the chemical bonds between their atoms. Organisms use the atoms of food molecules to build larger organic molecules including proteins, DNA, and fats and

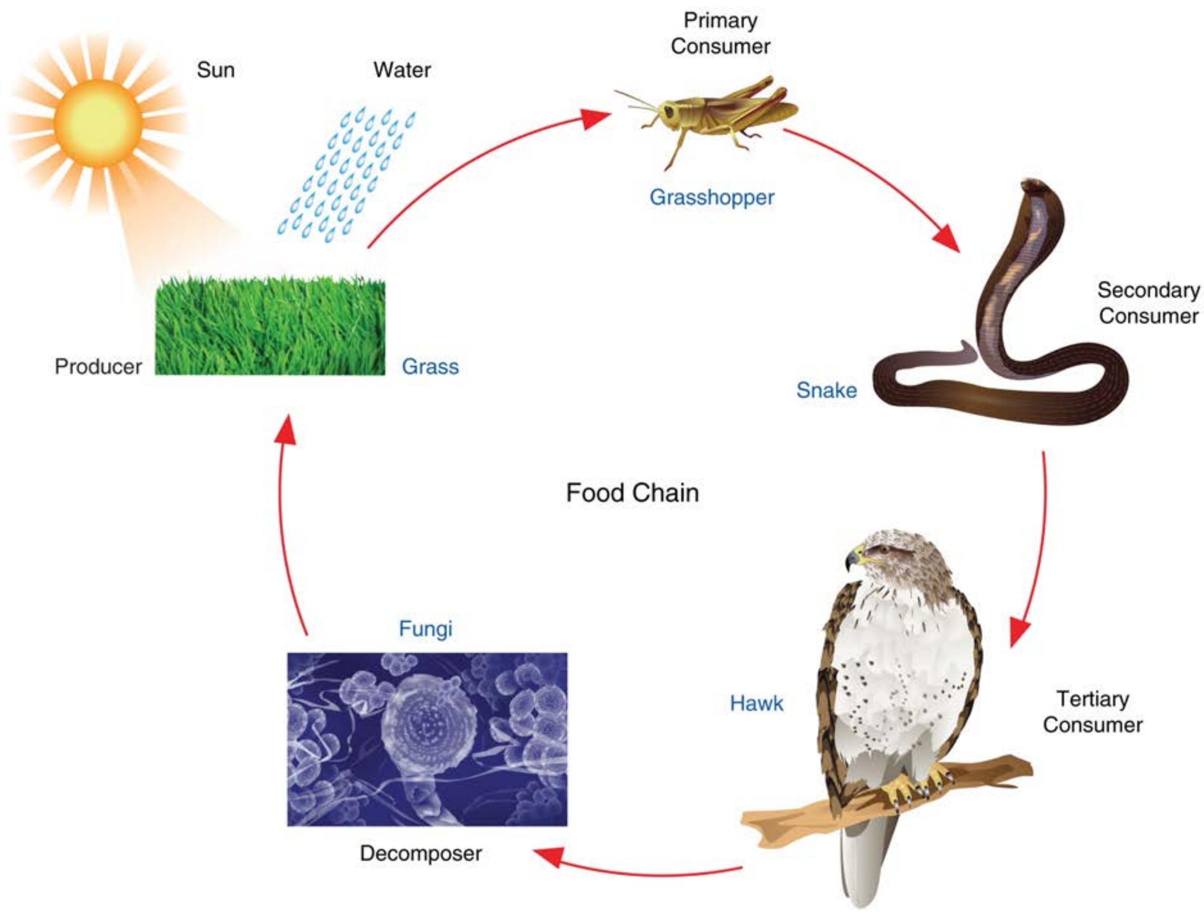


Figure 4.2: Food chains carry energy from producers (autotrophs) to consumers (heterotrophs). 99 percent of energy for life comes from the sun via photosynthesis. Note that only nutrients recycle. Energy must continue to flow into the system.

Figure 4.3: Tubeworms deep in the Gulf of Mexico get their energy from chemosynthetic bacteria living within their tissues. No digestive systems needed! Photo: Charles Fisher

use the energy in food to power life processes. By breaking the bonds in food molecules, cells release energy to build new compounds. Although some energy dissipates as heat at each energy transfer, much of it is stored in the newly made molecules. Chemical bonds in organic molecules are a reservoir of the energy used to make them. Fueled by the energy from food molecules, cells can combine and recombine the elements of life to form thousands of different molecules. Both the energy (despite some loss) and the materials (despite being reorganized) pass from producer to consumer – perhaps from algal tails, to water flea hearts, to dragonfly eye colors, to fish muscle, to you!

The process of photosynthesis, which usually begins the flow of energy through life, uses many different kinds of energy-carrying molecules to transform sunlight energy into chemical energy and build food.

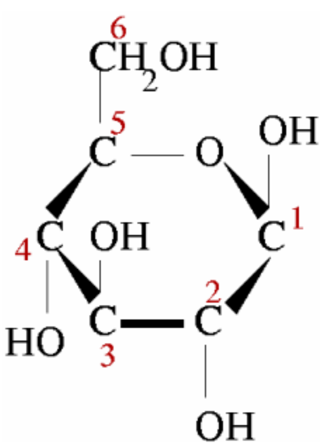
Some carrier molecules hold energy briefly, quickly shifting it like a hot potato to other molecules. This strategy allows energy to be released in small, controlled amounts. An example is **chlorophyll,** the green pigment present in most plants which helps convert solar energy to chemical energy. When a chlorophyll molecule absorbs light energy, electrons are excited and "jump" to a higher energy level. The excited electrons then bounce to a series of carrier molecules, losing a little energy at each step. Most of the "lost" energy powers some small cellular task, such as moving ions across a membrane or building up another molecule. Another short-term energy carrier important to photosynthesis, NADPH, holds chemical energy a bit longer but soon "spends" it to help to build sugar.

Two of the most important energy-carrying molecules are **glucose** and **ATP**, adenosine triphosphate. These are nearly universal fuels throughout the living world and both are also key players in photosynthesis, as shown below.

A molecule of glucose, which has the chemical formula $C_6H_{12}O_6$, carries a packet of chemical energy just the right size for transport and uptake by cells. In your body, glucose is the "deliverable" form of energy, carried in your blood through capillaries to each of your 100 trillion cells. Glucose is also the carbohydrate produced by photosynthesis, and as such is the near-universal food for life.

ATP molecules store smaller quantities of energy, but each releases just the right amount to actually do work within a cell. Muscle cell proteins, for example, pull each other with the energy released when bonds in ATP break open (discussed below). The process of photosynthesis also makes and uses ATP - for energy to build glucose! ATP, then, is the useable form of energy for your cells.

Glucose is the energy-rich product of photosynthesis, a universal food for life. It is also the primary form in which your bloodstream delivers energy to every cell in your body. The six carbons are numbered.



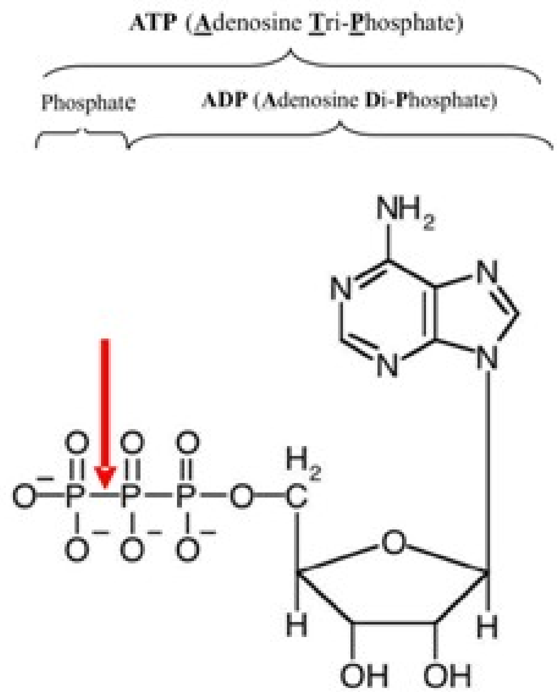
Why do we need both glucose and ATP? Why don't plants just make ATP and be done with it? If energy were money, ATP would be a quarter. Enough money to operate a parking meter or washing machine. Glucose would be a dollar bill (or $10) – much easier to carry around in your wallet, but too large to do the actual work of paying for parking or washing. Just as we find several denominations of money useful, organisms need several "denominations" of energy – a smaller quantity for work within cells, and a larger quantity for stable storage, transport, and delivery to cells.

Let's take a closer look at a molecule of ATP. Although it carries less energy than glucose, its structure is more complex. "A" in ATP refers to the majority of the molecule – adenosine – a combination of a nitrogenous base and a five-carbon sugar. "T" and "P" indicate the three phosphates, linked by bonds which hold the energy actually used by cells. Usually, only the outermost bond breaks to release or spend energy for cellular work.

An ATP molecule, shown below, is like a rechargeable battery: its energy can be used by the cell when it breaks apart into ADP (adenosine diphosphate) and phosphate, and then the "worn-out battery" ADP can be recharged using new energy to attach a new phosphate and rebuild ATP. The materials are recyclable, but recall that energy is not!

How much energy does it cost to do your body's work? A single cell uses about 10 million ATP molecules per second, and recycles all of its ATP molecules about every 20-30 seconds.

A red arrow shows the bond between two phosphate groups in an ATP molecule. When this bond breaks, its chemical energy can do cellular work. The resulting ADP molecule is recycled when new energy attaches another phosphate, rebuilding ATP.



Keep these energy-carrying molecules in mind as we look more carefully at the process which originally captures the energy to build them: photosynthesis. Recall that it provides nearly all of the food (energy and materials) for life. Actually, as you will see, we are indebted to photosynthesis for even more than just the energy and building blocks for life.

Photosynthesis: The Most Important Chemical Reaction for Life on Earth

What do pizza, campfires, dolphins, automobiles, and glaciers have in common? In the following section, you'll learn that all five rely on photosynthesis, some in more ways than one. Photosynthesis is often considered the most important chemical reaction for life on earth. Let's delve into how this process works and why we are so indebted to it.

Photosynthesis involves a complex series of chemical reactions, each of which convert one substance to another. These reactions taken as a whole can be summarized in a single symbolic representation – as shown in the chemical equation below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Enzymes}]{\text{Chloroplast, Chlorophyll}} C_6H_{12}O_6 + 6O_2$$

We can substitute words for the chemical symbols. Then the equation appears as below.

$$\text{Carbon dioxide + water + light energy} \xrightarrow[\text{Enzymes}]{\text{Chloroplast, Chlorophyll}} \text{glucose + oxygen gas}$$

Like all chemical equations, this equation for photosynthesis shows reactants connected by plus signs on the left and products, also connected by plus signs, on the right. An arrow indicating the process or chemical change leads from the reactants to the products, and conditions necessary for the chemical reaction are written above the arrow. Note that the same kinds of atoms, and number of atoms, are found on both sides of the equation, but the kinds of compounds they form change.

You use chemical reactions every time you cook or bake. You add together ingredients (the reactants), place them in specific conditions (often heat), and enjoy the results (the products). A recipe for chocolate chip cookies written in chemical equation form is shown below.

$$\underbrace{\text{Butter + sugar + eggs + flour + chocolate chips}}_{\text{REACTANTS}} \xrightarrow[\text{NECESSARY CONDITIONS}]{\text{375 F, 8—10 minutes}} \underbrace{\text{chocolate chip cookies}}_{\text{PRODUCT}}$$

Compare this familiar recipe to photosynthesis below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Enzymes}]{\text{Chloroplast, Chlorophyll}} C_6H_{12}O_6 + 6O_2$$

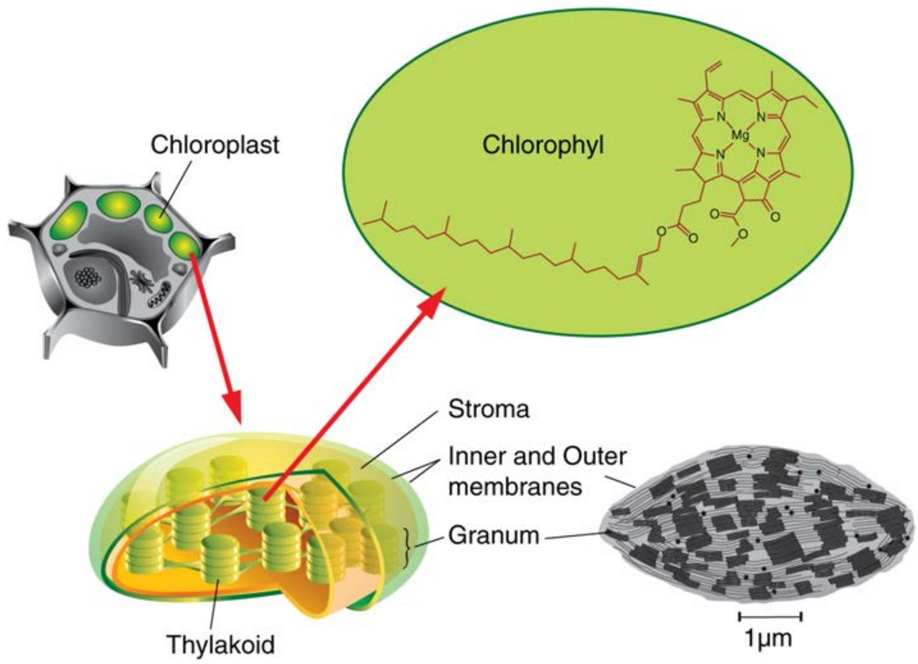
The equation shows that the "ingredients" for photosynthesis are carbon dioxide, water, and light energy. Plants, algae, and photosynthetic bacteria take in light from the sun, molecules of carbon dioxide from the air, and water molecules from their environment and combine these reactants to produce food (glucose).

Of course, light, carbon dioxide, and water mix in the air even without plants. But they do not chemically change to make food without very specific necessary conditions which are found only in the cells of photosynthetic organisms. Necessary conditions include:

1. **enzymes** - proteins which speed up chemical reactions without the heat required for

cooking
2. **chlorophyll** - a pigment which absorbs light
3. **chloroplasts** - organelles whose membranes embed chlorophyll, accessory pigments, and enzymes in patterns which maximize photosynthesis

Within plant cells or algal cells, chloroplasts organize the enzymes, chlorophyll, and accessory pigment molecules necessary for photosynthesis.



When the reactants meet inside chloroplasts, or the very similar cells of blue-green bacteria, chemical reactions combine them to form two products: energy-rich glucose molecules and molecules of oxygen gas. Photosynthetic organisms store the glucose (usually as starch) and release the oxygen gas into the atmosphere as waste.

Let's review the chemical equation for photosynthesis once more, this time at the level of atoms as in the equation below.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Enzymes}]{\substack{\text{Chloroplast} \\ \text{Chlorophyll}}} C_6H_{12}O_6 + 6O_2$$

Look closely at its primary purpose: storing energy in the chemical bonds of food molecules. The source of energy for food is sunlight energy. The source of carbon atoms for the food molecules is carbon dioxide from the air, and the source of hydrogen atoms is water. Inside the cells of plants, algae, and photosynthetic bacteria, chlorophyll, and enzymes use the light energy to rearrange the atoms of the reactants to form the products, molecules of glucose and oxygen gas. Light energy is thus transformed into chemical energy, stored in the bonds which bind six atoms each of carbon and oxygen to twelve atoms of hydrogen – forming a molecule of glucose. This energy rich carbohydrate molecule becomes food for the plants, algae, and bacteria themselves as well as for the heterotrophs which feed on them.

One last detail: why do "6"s precede the CO_2, H_2O, and O_2? Look carefully, and you will see that this "balances" the equation: the numbers of each kind of atom on each side of the arrow are equal. Six molecules each of CO_2 and H_2O make 1 molecule of glucose and 6 molecules of oxygen gas.

Lesson Summary

All organisms require a constant input of **energy** to do the work of life.

- Energy cannot be recycled, so the story of life is a story of energy flow – its capture, transformation, use for work, and loss as heat.

Life runs on **chemical energy**.

- **Food** is chemical energy stored in organic molecules.
- Food provides both the energy to do life's work and the carbon to build life's bodies.
- The carbon cycles between organisms and the environment, but the energy is "spent" and must be replaced.

Organisms obtain chemical energy in one of two ways.

- **Autotrophs** make their own carbohydrate foods, transforming sunlight in **photosynthesis** or transferring chemical energy from inorganic molecules in **chemosynthesis**.
- **Heterotrophs** consume organic molecules originally made by autotrophs.
- All life depends absolutely upon autotrophs to make food molecules.

The process of **photosynthesis** produces more than 99% of all food for life, forming the foundation of most food chains.

- Only three groups of organisms – plants, algae, and some bacteria – carry out the process of photosynthesis.

All organisms use similar energy-carrying molecules for food and to carry out life processes.

- **Glucose** ($C_6H_{12}O_6$,) is a nearly universal fuel delivered to cells, and the primary product of photosynthesis.

- **ATP** molecules store smaller amounts of energy and are used within cells to do work.
- **Chlorophyll** and **NADPH** molecules hold energy temporarily during the process of photosynthesis.

The chemical equation below summarizes the many chemical reactions of photosynthesis.

$$6CO_2 + 6H_2O + \text{light} \xrightarrow[\text{Enzymes}]{\substack{\text{Chloroplast} \\ \text{Chlorophyll}}} C_6H_{12}O_6 + 6O_2$$

- The equation states that the reactants (carbon dioxide, water and light), in the presence of chloroplasts, chlorophyll and enzymes, yield two products, glucose and oxygen gas.
- **Chlorophyll** is a pigment that absorbs sunlight energy.
- **Chloroplasts** are the organelles within plant and algal cells that organize enzymes and pigments so that the chemical reactions proceed efficiently.

In the process of photosynthesis, plants, algae, and blue green bacteria absorb sunlight energy and use it to change carbon dioxide and water into glucose and oxygen gas.

- Glucose contains stored chemical energy and provides **food** for the organisms that produce it and for many heterotrophs.
- Photosynthesized carbohydrates (represented here by glucose) make up the wood we burn and (over hundreds of millions of years) the coal, oil, and gas we now use as fossil fuels.
- Most of the oxygen gas is waste for the organisms which produce it.
- Both CO_2 consumed and O_2 produced affect the composition of earth's atmosphere; before photosynthesis evolved, oxygen was not part of the atmosphere.

Review Questions

1. Compare the behavior of energy to the behavior of matter in living systems.
2. Water and carbon dioxide molecules are reactants in the process of photosynthesis. Does this mean they are "food" for plants, algae, and blue-green bacteria? Use the definition of "food" to answer this question.
3. Compare autotrophs to heterotrophs, and describe the relationship between these two groups of organisms.
4. Name and describe the two types of food making found among autotrophs, and give an example of each. Which is quantitatively more important to life on earth?
5. Trace the flow of energy through a typical food chain (describing "what eats what"), including the original source of that energy and its ultimate form after use. Underline each form of energy or energy-storing molecule, and boldface each process which transfers or transforms energy.

6. Trace the pathway that carbon atoms take through a typical food chain, beginning with their inorganic source.
7. The fact that all organisms use similar energy-carrying molecules shows one aspect of the grand "Unity of Life." Name two universal energy-carrying molecules, and explain why most organisms need both carriers rather than just one.
8. A single cell uses about 10 million ATP molecules per second. Explain how cells use the energy and recycle the materials in ATP.
9. Discuss the importance of photosynthesis to humans in terms of food, fuel, and atmosphere. In what ways could you affect the process of photosynthesis to conserve these benefits?
10. Using symbols, write the overall chemical equation for photosynthesis, labeling the reactants, necessary conditions, and products. Then write two complete sentences which trace the flow of (1) energy and (2) atoms from reactants to products.

Further Reading / Supplemental Links

- Graham Kent, "Light Reactions in Photosynthesis" Animation. Bio 231 Cell Biology Lab, October 2004. Available on the Web at:
- http://www.science.smith.edu/departments/Biology/Bio231/ltrxn.html.
- Illustrator: Thomas Porostocky; Writer: Lee Billings; Map data adapted from MODIS observations by NASA's Terra and Aqua satellites; Graph data and reference: Biology, 4th ed., Neil A. Campbell, Benjamin/Cummings Publishing Company, 1996. "Crib Sheet #10, Photosynthesis." *Seed Magazine,* August 2007. Available on the Web at:
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Vocabulary

ATP Adenosine triphosphate, the energy-carrying molecule used by cells to do work.

autotroph An organism capable of transforming one form of energy – usually light – into the food, or stored chemical energy, they need to do work.

chemosynthesis Process by which a type of autotroph makes food using chemical energy in inorganic molecules.

chlorophyll The primary pigment of photosynthesis.

chloroplast The organelle in plant and algal cells where photosynthesis takes place.

consumers Heterotrophs, which must eat or absorb organic food molecules because they are incapable of producing them.

energy The ability to do work.

food Organic (carbon-containing) molecules which store energy in the chemical bonds between their atoms.

food chain A pathway which traces energy flow from producers through consumers.

glucose The carbohydrate product of photosynthesis; serves as the universal fuel for life.

heat Thermal energy, the energy of vibrations in molecules – the "lowest" form of energy, which cannot easily be used for useful work.

heterotrophs Organisms which must consume organic molecules because they are incapable of synthesizing the food, or stored chemical energy, they need to work.

inorganic molecules Molecules which do not contain carbon (with a few exceptions such as carbon dioxide) and are not necessarily made by living organisms.

NADPH An energy carrier molecule produced in the light reactions of photosynthesis and used to build sugar in the Calvin cycle.

organic molecule A molecule which contains carbon, made by living organisms; examples include carbohydrates, lipids, and proteins.

photosynthesis The process by which plants, algae, and some bacteria transform sunlight into chemical energy and use it to produce carbohydrate food and oxygen for almost all life.

producer An autotroph, capable of synthesizing food molecules; forms basis of food chains.