This caterpillar is busily munching its way through leaf after leaf. In fact, caterpillars do little more than eat, day and night. Like all living things, they need food to provide their cells with energy. The caterpillar will soon go through an amazing transformation to become a beautiful butterfly. These changes require a lot of energy. Like this caterpillar and all other living things, you need energy to power everything you do. Whether it’s running a race or blinking an eye, it takes energy. In fact, every cell of your body constantly needs energy to carry out life processes. You probably know that you get energy from the food you eat, but where does food come from? How does it come to contain energy, and how do your cells get the energy from food? When you read this chapter, you will learn the answers to these questions.

Lesson Objectives
- Identify the kind of energy that powers life.
- State why living things need energy.
- Evaluate the importance of autotrophs for providing energy to all life.
- Describe how autotrophs and heterotrophs obtain energy.
- Define chemosynthesis.
- Compare and contrast glucose and ATP.
- Outline how living things make and use food.
- Outline the stages of photosynthesis.
- Describe the chloroplast and its role in photosynthesis.
- Identify the steps of the light reactions and the Calvin cycle.

Vocabulary
- accessory pigment
- ATP (adenosine triphosphate)
- ATP synthase
- autotroph (aka: producer)
- bioenergetics
- Calvin cycle
- chemosynthesis
- chloroplast
- chlorophyll
- electrochemical gradient
- electron transport chain (ETC)
- energy
- food
- glucose
- grana (granum, singular)
- heterotroph (aka: consumer)
- inorganic molecules
- light reactions
- organic molecules
- photolysis
- photosynthesis
- photosystem
- pigment
- plastids
- stroma
- thylakoid membrane
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 dog wags its tail, a firefly glows in the dark, or a bird flies through the air. 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. 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. Energy, unlike matter, cannot be recycled, so organisms require a constant input of energy. Life runs on chemical 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...

Plants and other autotrophs make food out of “thin air” — at least, they use carbon dioxide from the air to make food. Most food is made in the process of photosynthesis. This process provides more than 99% of the energy used by living things on Earth. Photosynthesis also supplies Earth’s atmosphere with oxygen.

How Do Organisms Get Energy? Autotrophs vs. Heterotrophs

Living organisms obtain chemical energy in one of two ways.

Autotrophs, shown in Figure 4.1 on the next page, 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, or autotrophs, begin the food chains which feed all life. They produce food not only for themselves but for all other living things as well (which are known as consumers or heterotrophs). This is why autotrophs form the basis of food chains, such as the food chain shown in Figure 4.2 on the next page.
Photosynthetic autotrophs, which make food for more than 99% of the organisms on earth, using the energy in sunlight, include only three groups of organisms: plants such as the redwood tree (a), algae such as kelp (b), and certain bacteria (c).

A food chain shows how energy and matter flow from producers (autotrophs) to consumers (heterotrophs). Matter is recycled, but energy must keep flowing into the system. Where does this energy come from???

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 (autotrophs). 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. In Figure 4.2, all of the organisms are consumers except for the grass. What do you think would happen to consumers if all producers were to vanish from Earth?
Chemosynthesis

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. Therefore the process is called chemosynthesis. Some chemosynthetic bacteria live around deep-ocean hot water vents known as “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, giant white crabs, and armored snails pictured in Figure 4.3. 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.

Figure 4.3: (a) Giant tube worms deep in the Gulf of Mexico get their energy from chemosynthetic bacteria living within their tissues, (b) Giant white crabs get their energy by consuming the red plums of giant tube worms, and (c) armored snails feed off of detritus left behind by the other deep-ocean vent creatures. No digestive systems needed!

Food to Energy Molecules: Glucose and ATP

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 whip-like 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 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. Glucose is a simple carbohydrate and is the energy-rich product of photosynthesis that has the chemical formula C₆H₁₂O₆. Its structural formation can be seen in Figure 4.4 below. It stores chemical energy in a concentrated, stable form. In your body, glucose is the “deliverable” form of energy that is carried in your blood through capillaries and taken up by each of your trillions of cells. Glucose is the end product of photosynthesis, and it is the nearly universal food for life.

![Figure 4.4: 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.](image)

ATP (adenosine triphosphate) molecules store smaller quantities of energy, but each releases just the right amount to actually do work within a cell. Its structural formation can be seen in Figure 4.5 below. ATP is made during the first half of photosynthesis and then used for energy during the second half of photosynthesis, when glucose is made. It is also used for energy by cells for most other cellular processes. Muscle cell proteins, for example, pull each other with the energy released when bonds in ATP break open. ATP releases energy when it gives up one of its three phosphate groups and changes to ADP (adenosine di-phosphate [two phosphates]). ATP is the useable form of energy for your cells.

![Figure 4.5: ATP is the useable form of energy for your cells and is a product of the photosynthetic process.](image)
Why Organisms Need Both Glucose and ATP

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. That’s 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.

A molecule of glucose contains more chemical energy in a smaller “package” than a molecule of ATP. Glucose is also more stable than ATP. Therefore, glucose is better for storing and transporting energy. However, glucose is too powerful for cells to use. ATP, on the other hand, contains just the right amount of energy to power life processes within cells. For these reasons, both glucose and ATP are needed by living things.

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 in Figure 4.6, is like a rechargeable battery: its energy can be used by the cell when it breaks apart into ADP (adenosine di-phosphate) 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.

Figure 4.6: The red arrow shows the bond between two phosphate groups in an ATP molecule. When this bond breaks, its chemical energy is released so it 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. It changes light energy into chemical energy and also releases oxygen. Without photosynthesis, there would be no oxygen in the atmosphere. 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 shown below:

\[
6\text{CO}_2 + 6\text{H}_2\text{O} \quad \text{light} \quad \xrightarrow{} \quad \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]

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

Carbon dioxide + water + light energy \rightarrow 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.

\[
\text{Butter} + \text{sugar} + \text{eggs} + \text{flour} + \text{chocolate chips} \quad \rightarrow \quad \text{chocolate chip cookies}
\]

Compare this familiar recipe to photosynthesis below.

\[
6\text{CO}_2 + 6\text{H}_2\text{O} \quad \text{light} \quad \xrightarrow{} \quad \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2
\]

The equation shows that the “ingredients” for photosynthesis are carbon dioxide, water, and light energy. Plants, algae, and photosynthetic bacteria (autotrophs) take in light energy from the sun, absorb molecules of carbon dioxide from the air, and water molecules from their environment and combine these reactants to produce food (glucose) and oxygen. Photosynthetic organisms store the glucose (usually as starch) and release the oxygen gas into the atmosphere as waste.

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

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]

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 does the number ‘6’ precede the CO2, H2O, and O2? 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 CO2 and H2O make 1 molecule of glucose and 6 molecules of oxygen gas.

**Stages of Photosynthesis**

Photosynthesis occurs in two stages, which are shown in Figure 4.7.

1. Stage I is called the **light reactions**. This stage uses water and changes light energy from the sun into chemical energy stored in ATP and NADPH (another energy-carrying molecule). This stage also releases oxygen as a waste product.
2. Stage II is called the **Calvin cycle**. This stage combines carbon from carbon dioxide in the air and uses the chemical energy in ATP and NADPH to make glucose.

![Figure 4.7: The two stages of photosynthesis are the light reactions and the Calvin cycle. Do you see how the two stages are related?](image)
Before you read about these two stages of photosynthesis in greater detail, you need to know more about the chloroplast, where the two stages take place.

**Chloroplasts: Theaters for Photosynthesis**

If you examine a single leaf of the aquatic plant *Elodea*, shown in Figure 4.8, under a microscope, you will see within each cell dozens of small green ovals. These are chloroplasts, the organelles which conduct photosynthesis in plants and algae. Chloroplasts closely resemble some types of bacteria and even contain their own circular DNA and ribosomes. In fact, the endosymbiotic theory holds that chloroplasts were once independently living bacteria (prokaryotes). So when we say that photosynthesis occurs within chloroplasts, we speak not only of the organelles within plants and algae, but also of some bacteria (photosynthetic bacteria do not have chloroplasts, but they contain structures similar to chloroplasts and produce food in the same way.)—in other words, virtually all photosynthetic autotrophs.

![Figure 4.8](image-url)

*Figure 4.8:* On the left is a high power microscopic photo of the chloroplasts found in a single leaf of Elodea, on the right is a picture of the whole Elodea plant.

Each chloroplast contains neat stacks called grana (singular, granum). The grana consist of saclike membranes, known as thylakoid membranes. These membranes contain photosystems, which are groups of molecules that include chlorophyll, a green pigment. The light reactions of photosynthesis occur in the thylakoid membranes. The stroma is the space outside the thylakoid membranes. This is where the reactions of the Calvin cycle take place. Figure 4.9 shows all of these structures and their locations.

![Figure 4.9](image-url)

*Figure 4.9:* A chloroplast consists of stacks of grana made up of saclike membranes called thylakoid membranes surrounded by stroma. The thylakoid membranes contain molecules of the green pigment chlorophyll.
The structures shown in Figure 4.9 work with enzymes and two basic types of molecules—pigments and electron carriers—to carry out the photosynthetic process.

Pigment molecules, are often arranged together with proteins in large, complex photosystems (Figure 4.10), and they absorb specific wavelengths of light energy and reflect others; thus they appear colored. The most common photosynthetic pigment is chlorophyll, which absorbs blue-violet and red wavelengths of light, and reflects green. Accessory pigments absorb other colors of light and then transfer the energy to chlorophyll. These include xanthophylls (yellow) and carotenoids (orange). Figure 4.11 shows the wavelengths absorbed by different photosynthetic pigments.

**Figure 4.10**: The pigment molecule, chlorophyll, appears green because its electrons absorb blue-violet and red light and reflect green, orange, and yellow light. This diagram shows their location in protein molecules of a photosystem within the thylakoid membrane.

**Figure 4.11**: Each kind of pigment absorbs specific wavelengths (colors) of light. Sunlight contains many different wavelengths, which you see when they separate into a rainbow. Not all colors of light are used to make food for life. Most plants, algae, and photosynthetic bacteria appear green because they reflect green wavelengths. Their pigments have absorbed the violet-blue and red wavelengths. The amount of photosynthesis depends on the wavelength of light available.
Electron carrier molecules are usually arranged in electron transport chains (ETCs). These accept and pass along energy-carrying electrons in small steps (Figure 4.12). In this way, they produce ATP and NADPH, which temporarily store chemical energy. Electrons in transport chains behave much like a ball bouncing down a set of stairs – a little energy is lost with each bounce. However, the energy “lost” at each step in an electron transport chain accomplishes a little bit of work, which eventually results in the synthesis of ATP.

![Electron Transport in the Thylakoid Membrane](image)

Figure 4.12: Electron carrier molecules move from photosystem II to photosystem I making NADPH and provide the energy resources needed for ATP to be made in the ATP Synthase complex.

Now that you’ve explored some of the key players and viewed the chloroplast theater, let’s put them together to see how the process unfolds. We will divide the process into two basic sets of reactions, known as the light reactions and the Calvin cycle, which uses carbon dioxide. As you study the details, refer frequently to the chemical equation of photosynthesis. In the first stage, you’ll discover how chloroplasts transform light energy, and why we owe our ability to breathe to plants!

**Photosynthesis Stage I: The Light Reactions**

**Chloroplasts Capture Sunlight’s Chemical Energy...**

The first stage of photosynthesis is called the light reactions. Every second, the sun fuses over 600 million tons of hydrogen into 596 tons of helium, converting over 4 tons of helium (4.3 billion kg) into light and heat energy. Countless tiny packets of that light energy travel 93 million miles (150 million km) through space, and about 1% of the light which reaches the Earth’s surface participates in photosynthesis. Light is the source of energy for photosynthesis, and the first set of reactions which begin the process requires light – thus the name, Light Reactions, or Light-dependent Reactions. During this stage, light is absorbed and transformed to chemical energy in the bonds of NADPH and ATP. You can follow the process in Figure 4.12 as you read about it below.

When light strikes chlorophyll (or an accessory pigment in photosystem II, refer back to Figure 4.10) within the chloroplast, it energizes electrons within that molecule. These electrons jump up to
higher energy levels; they have absorbed or captured, and now carry, that energy. High-energy electrons are “excited.” Who wouldn’t be excited to hold the energy for life?

The excited electrons leave chlorophyll to participate in further reactions, leaving the chlorophyll “at a loss” for electrons; eventually they must be replaced. That replacement process also requires light, working with an enzyme complex to split water molecules. In this process of photolysis (“splitting by light”), H₂O molecules are broken into hydrogen ions, electrons, and oxygen atoms. The electrons replace those originally lost from chlorophyll. Hydrogen ions and the high-energy electrons from chlorophyll will carry on the energy transformation after the Light Reactions are over. The oxygen atoms, however, form oxygen gas, which is a waste product of photosynthesis. The oxygen gas given off supplies most of the oxygen in our atmosphere. Before photosynthesis evolved, Earth’s atmosphere lacked oxygen altogether, and this highly reactive gas was toxic to the many organisms living at the time. Something had to change! Most contemporary organisms rely on oxygen for efficient respiration. So plants don’t just “restore” the air, they also had a major role in creating it!

![Differentiation of Earth](image)

**Figure 4.13:** Photosynthesis has made the Earth’s atmosphere today very different from what it was 2-3 billion years ago, by giving off oxygen gas as waste. The table to the right shows the composition of today’s atmosphere. On the left is an Apollo 17 photograph of Earth.

<table>
<thead>
<tr>
<th>Nitrogen</th>
<th>78.084%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>20.946%</td>
</tr>
<tr>
<td>Argon</td>
<td>0.934%</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.036%</td>
</tr>
<tr>
<td>Water vapor</td>
<td>1%</td>
</tr>
<tr>
<td>Other</td>
<td>0.002%</td>
</tr>
</tbody>
</table>

To summarize, chloroplasts “capture” sunlight energy in two ways. Light “excites” electrons in pigment molecules, and light provides the energy to split water molecules, providing more electrons as well as hydrogen ions.
How Do Chloroplasts Convert Light Energy to Chemical Energy?

Excited electrons which have absorbed light energy are unstable. However, the highly organized electron carrier molecules embedded in chloroplast membranes order the flow of these electrons, directing them through electron transport chains (ETCs). At each transfer, small amounts of energy released by the electrons are captured and put to work or stored. Some is also lost as heat with each transfer, but overall the light reactions are extremely efficient at capturing light energy and transforming it to chemical energy. Below is a summary of the steps of the Light Reactions, as you read them refer to Figure 4.12 on page 99 and follow the process.

Steps of the Light Reactions
The light reactions occur in several steps, all of which take place in the thylakoid membrane of chloroplasts, as shown in Figure 4.12.

• Step 1: Units of sunlight, called photons, strike a molecule of chlorophyll in photosystem II of the thylakoid membrane. The light energy is absorbed by two electrons (2 e-) in the chlorophyll molecule, giving them enough energy to leave the molecule.

• Step 2: At the same time, enzymes in the thylakoid membrane use light energy to split apart a water molecule. This produces:
  1. two electrons (2 e-)
  2. an atom of oxygen (O). This atom combines with another oxygen atom to produce a molecule of oxygen gas (O2), which is released as a waste product.
  3. two hydrogen ions (2H+). The hydrogen ions, which are positively charged, are released inside the membrane in the thylakoid interior space.

• Step 3: The two excited electrons from Step 1 contain a great deal of energy, so, like hot potatoes, they need something to carry them. They are carried by a series of electron-transport molecules, which make up an electron transport chain. The two electrons are passed from molecule to molecule down the chain. As this happens, their energy is captured and used to pump more hydrogen ions into the thylakoid interior space.

• Step 4: When the two electrons reach photosystem I, they are no longer excited. Their energy has been captured and used, and they need more energy. They get energy from light, which is absorbed by chlorophyll in photosystem I. Then, the two re-energized electrons pass down another electron transport chain.

• Step 5: Enzymes in the thylakoid membrane transfer the newly re-energized electrons to a compound called NADP+. Along with a hydrogen ion, this produces the energy-carrying molecule NADPH. This molecule is needed to make glucose in the Calvin cycle.

• Step 6: By now, there is a greater concentration of hydrogen ions—and positive charge—in the thylakoid interior space. This difference in concentration and charge creates what is called a electrochemical gradient. It causes hydrogen ions to flow back across the thylakoid membrane to the stroma, where their concentration is lower. Like water flowing through a hole in a dam, the hydrogen ions have energy as they flow down the electrochemical gradient. The enzyme ATP synthase acts as a channel protein and helps the ions cross the membrane. ATP synthase also uses their energy to add a phosphate group (Pi) to a molecule of ADP, producing a molecule of ATP. The energy in ATP is needed for the Calvin cycle.

By the time Step 6 is finished, energy from sunlight has been stored in chemical bonds of NADPH and ATP. Thus, light energy has been changed to chemical energy, and the first stage of photosynthesis is now complete.
Photosynthesis Stage II: The Calvin Cycle
Making Food “From Thin Air”

You’ve learned that the first, light-dependent stage of photosynthesis uses two of the three reactants - water and light - and produces one of the products - oxygen gas (a waste product of this process). All three necessary conditions are required – chlorophyll pigments, the chloroplast “theater,” and enzyme catalysts. The first stage transforms light energy into chemical energy, stored to this point in molecules of ATP and NADPH. Look again at the overall equation below. What is left?

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{light} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]

Waiting in the wings is one more reactant – carbon dioxide, and yet to come is the star product which is food for all life – glucose. These key players perform in the second act of the photosynthesis, in which food is “made from thin air!”

The second stage of photosynthesis takes place in the stroma (a matrix that contains dissolved enzymes, see Figure 4.14) of the chloroplast and has two parts. First carbon dioxide is “fixed.” Then ATP and NADPH from the Light Reactions provide chemical energy to combine the fixed carbons to make glucose. The reactions of this stage can occur without light, so they are sometimes called light independent or dark reactions. This stage of photosynthesis is also known as the Calvin cycle because its reactions were discovered by a scientist named Melvin Calvin. He won a Nobel Prize in 1961 for this important discovery. You can follow the Calvin cycle in Figure 4.15 on the next page as you read about it in this section.

Figure 4.14 Stage II of photosynthesis, the Calvin cycle takes place in the stroma surrounding the thylakoid membranes of the chloroplasts.

Steps of the Calvin Cycle
The Calvin cycle has three major steps: carbon fixation, reduction, and regeneration. All three steps take place in the stroma of a chloroplast.

• Step 1: Carbon Fixation. Carbon dioxide from the atmosphere combines with a simple, five-carbon compound called RuBP. This reaction occurs with the help of an enzyme named RuBisCo and produces molecules known as 3PG (a three-carbon compound, 3-Phosphoglyceric acid).

• Step 2: Reduction. Molecules of 3PG (from Step 1) gain energy from ATP and NADPH (from the light reactions) and re-arrange themselves to form G3P (glycerate 3-phosphate). This molecule also has three carbon atoms, but it has more energy than 3PG. One of the G3P molecules goes on to form glucose, while the rest of the G3P molecules go on to Step 3.

• Step 3: Regeneration. The remaining G3P molecules use energy from ATP to form RuBP, the five-carbon molecule that started the Calvin cycle. This allows the cycle to repeat.
The Calvin cycle begins with a molecule named RuBP (a five-carbon sugar, Ribulose-1,5-bisphosphate) and uses the energy in ATP and NADPH from the light reactions. Follow the cycle to see what happens to all three of these molecules. Six turns of the cycle produce one molecule of glucose. In this diagram, each black dot represents a carbon atom. Keep track of what happens to the carbon atoms as the cycle proceeds.

You can also watch an animation of the Calvin cycle at this link: http://www.science.smith.edu/departments/Biology/Bio231/calvin.html.

So – how does photosynthesis store energy in sugar? Six “turns” of the Calvin cycle use chemical energy from ATP to combine six carbon atoms from six CO$_2$ molecules with 12 “hot hydrogen atoms” from NADPH. The result is one molecule of glucose, $C_6H_{12}O_6$.

**Why is Carbon Dioxide “Fixed”**

Life on Earth is carbon-based. Organisms need not only energy but also carbon atoms for building bodies. For nearly all life, the ultimate source of carbon is carbon dioxide (CO$_2$), an inorganic molecule. CO$_2$, as you saw in Figure 4.13, makes up .038% of the Earth’s atmosphere. Animals and most other heterotrophs cannot take in CO$_2$ directly. They must eat other organisms or absorb organic
molecules to get carbon. Only autotrophs can build low energy inorganic CO₂ into high-energy organic molecules like glucose. This process is carbon fixation.

Plants have evolved three pathways for carbon fixation. The most common pathway combines one molecule of CO₂ with a 5-carbon sugar called ribulose biphosphate (RuBP). The enzyme which catalyzes this reaction (nicknamed RuBisCo) is the most abundant enzyme on earth! The resulting 6-carbon molecule is unstable, so it immediately splits into two 3-carbon molecules. The 3-carbons in the first stable molecule of this pathway give this largest group of plants the name "C-3."

Dry air, hot temperatures, and bright sunlight slow the C-3 pathway for carbon fixation. This is because stomata, tiny openings under the leaf which normally allow CO₂ to enter and O₂ to leave, must close to prevent loss of water vapor (Figure 4.16). Closed stomata lead to a shortage of CO₂. Two alternative pathways for carbon fixation demonstrate biochemical adaptations to differing environments.

Plants such as corn solve the problem by using a separate compartment to fix CO₂. Here CO₂ combines with a 3-carbon molecule, resulting in a 4-carbon molecule. Because the first stable organic molecule has four carbons, this adaptation has the name C-4. Shuttled away from the initial fixation site, the 4-carbon molecule is actually broken back down into CO₂, and when enough accumulates, RuBisCo fixes it a second time! Compartmentalization allows efficient use of low concentrations of carbon dioxide in these specialized plants.

Cacti and succulents such as the jade plant avoid water loss by fixing CO₂ only at night. These plants close their stomata during the day and open them only in the cooler and more humid nighttime hours. Leaf structure differs slightly from that of C-4 plants, but the fixation pathways are similar. The family of plants in which this pathway was discovered gives the pathway its name, Crassulacean Acid Metabolism, or CAM. All three carbon fixation pathways lead to the Calvin Cycle to build sugar.

![Figure 4.16](image-url): Stomata on the underside of leaves take in CO₂ and release water and O₂. Guard cells close the stomata when water is scarce. Leaf cross-section (right) and stoma (left).
Lesson Summary

- Living things need energy to carry out all life processes. They get energy from food.
- Autotrophs make their own food. Heterotrophs get food by eating other living things.
- Most autotrophs make food using photosynthesis. This process occurs in two stages: the light reactions and the Calvin cycle.
- Some bacterial autotrophs make food using chemosynthesis. This process uses chemical energy instead of light energy to produce food.
- Glucose and ATP are used for energy by nearly all living things. Glucose is used to store and transport energy, and ATP is used to power life processes inside cells.
- Both stages of photosynthesis take place in chloroplasts. The light reactions take place in the thylakoid membranes, and the Calvin cycle takes place in the stroma.
- The light reactions capture energy from sunlight, which they change to chemical energy that is stored in molecules of NADPH and ATP. The light reactions also release oxygen gas as a waste product.
- The reactions of the Calvin cycle add carbon (from carbon dioxide in the atmosphere) to a simple five-carbon molecule called RuBP. These reactions use chemical energy from NADPH and ATP that were produced in the light reactions. The final product of the Calvin cycle is glucose.

References/Multimedia Resources


Textbook resource granted through licensure agreement with the CK-12 Foundation at www.ck-12.org

CK-12 Foundation
3430 W. Bayshore Rd., Suite 101
Palo Alto, CA 94303
USA http://www.ck12.org/saythanks

Except as otherwise noted, all CK-12 Content (including CK-12 Curriculum Material) is made available to Users in accordance with the Creative Commons Attribution/Non-Commercial/Share Alike 3.0 Unported (CC-by-NC-SA) License (http://creativecommons.org/licenses/by-nc-sa/3.0/), as amended and updated by Creative Commons from time to time (the “CC License”), which is incorporated herein by this reference. Complete terms can be found at http://www.ck12.org/terms.