Photosynthesis and Agriculture

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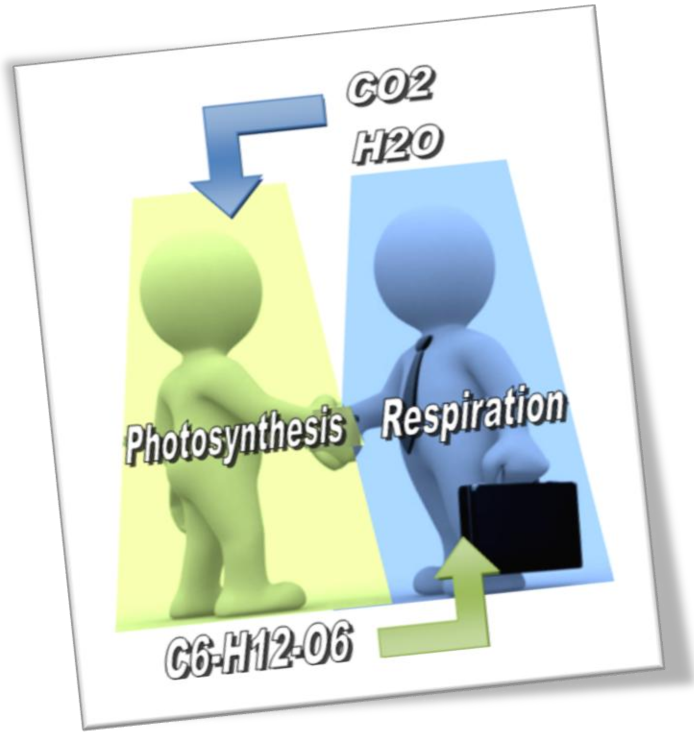

If you recall, all living things power their cells using ATP. ATP is created using hydrogen from sugar atoms. It isn't correct to say that energy is *created*…it is a law of physics that we can neither create nor destroy energy. Rather, it would be more accurate to say that energy has been *transformed*. We simply took the energy trapped in the molecule bonds of sugar and transferred it through a complex series of chemical reactions into another kind of chemical energy – ATP.

This begs the questions – where did the energy in sugar come from? You actually might know the answer already…plants produce sugar in a process called **photosynthesis**. Photosynthesis is a process powered by the sun's rays. What you probably don't now is *how* the sugar is created (even if you think you know, you probably don't understand it completely).

Agriculture is an Energy Industry. All agriculturalists create a useable form of energy in some way, shape, or form. Some harvest the sun's energy indirectly through crops, fruits, and vegetables, which all act like biological solar panels that catch the energy of the sun and convert it into a form we can use. Other agriculturalists harvest the sun's energy even more indirectly by raising animals which consume the chemically-captured energy of the sun. Some agriculturalists help us to preserve energy by producing wool, wood, and cotton. However, all agriculturalists are in the industry of energy.

What is Energy?

This might be a good time to look at what energy actually is…after all, if every agriculturalist harvests energy, then it must be pretty important. Energy is simply the capacity of something to do work. There are many kinds of energy. Movement is **kinetic energy**; for example, a sled going down a snowy hill is able to do so because of kinetic energy. The sleds waiting at the top of the hill have **potential energy**, or stored energy waiting to be released. The ATP that enables your muscles to contract has **chemical energy**, or energy trapped in molecular bonds.

Life on earth is possible because we live close, but not too close, to a constant source of **light energy** – photons from the sun. We are, in fact, the exact right distance from the sun to receive its energy without being killed by it. Go to Venus, and the intense heat would kill you instantly. Skip a planet and head to Mars and you'll find too little energy to perform even the simplest processes of life. Earth is perfectly placed in space for life.

The Rules of Energy

So why does Earth have life when Mars and Venus don't? To understand this, we have to begin with just a few energy rules and concepts.

1. Energy can neither be created nor destroyed. It can only change. The light energy of the sun can be changed to chemical energy in sugar and ATP, which can be turned into moving mechanical energy (such as when your muscles contract). The end result of almost all energy is that it becomes heat. This heat eventually dissipates into space and is no longer usable. So while energy cannot be destroyed, it can be changed.

2. Energy is constantly being turned into a useless form. The process of turning something useful into something useless is called **entropy**. Entropy is really just a measure of how chaotic, disorderly, or useless something is. An abandoned house will start to fall apart over time because of entropy. It is simply becoming less and less orderly until it becomes a pile of rubble and then nothing at all. Unless energy is continuously added to something, entropy will take over and destroy it. The total entropy of the universe is constantly increasing.

3. Energy that can be used is called **Free Energy**. In other words, free energy is something that can be used for work. The more complex something is, the more free energy it takes to offset entropy and prevent a collapse. This might make sense to you – if you stop consuming energy (food), your body will begin to waste away. You need energy to keep something as complex as your body in good running order, free of entropy.

4. Free Energy is simply what is left over after we subtract heat and entropy from the total energy of something. For example, every time you eat something, 90% of the energy in that food is lost as heat from your body. You are only able to use 10% of the energy in anything you eat. This 10% that remains is the free energy.

5. The greater the chaos, instability, or heat in something, the less usable energy that remains. For example, if you throw a log on a fire, the intense heat causes the orderly energy preserved in that log to break down rapidly. That once-stable energy then becomes the heat you feel in a fire. Living organisms want to be as orderly and stable as possible, with few temperature fluctuations. If our bodies increase in temperature even by a few degrees (such as when we have a severe fever), the complex organic molecules (such as our bodies' proteins) will begin to fall apart.

If Free Energy (usable energy) is what remains after we subtract heat and entropy, we could describe this as:

Free Energy = Total Energy – [Heat x Entropy].

With these ideas in mind, it should make more sense to you why Mars and Venus have no life. Venus has way too much heat. Most of the total energy is lost after we subtract this heat. Mars has no life because it has too little energy. The end result in both cases is that there is not enough Free Energy left for the intense demands of living organisms.

We see this same process in Earth's ecosystems. Deserts lack many of the requirements for life because they have too little free energy. The intense heat causes water to evaporate and organic molecules to break down too easily. Only those species with very specific adaptations to overcome these problems can survive. The Arctic and Antarctic face a similar problem as Mars – they receive too little solar energy for enough Free Energy to remain. Again, only those species with very specific adaptations can acquire and preserve enough energy to survive.

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Five Energy Concepts

1. Energy can neither be created nor destroyed, only changed.

2. Entropy is the measure of disorder. Entropy increases unless energy is added.

3. Free energy is useful energy. It can be used for work. Entropy and heat cannot be used for work.

4. Free Energy is what is left from Total Energy after subtracting Heat and Entropy.

5. The more complicated something is, the more energy it takes to prevent entropy from taking over.

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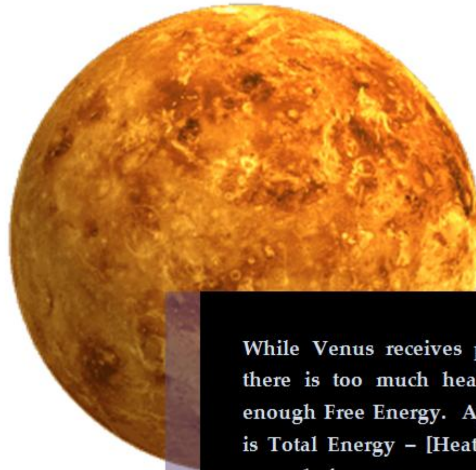
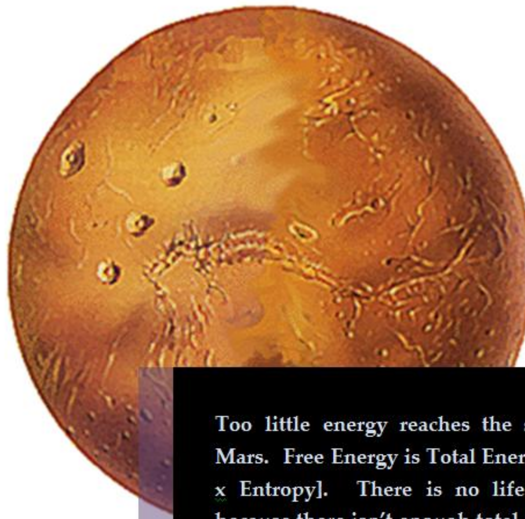
The Sun – The Source of All of Life's Energy

Because most places on Earth receive just the right amount and kind of energy, life can occur. Life on Earth is almost entirely dependent on the sun for its energy supplies. While plants and photosynthetic organisms are the only species to rely directly on the sun, all species rely on the sun for their energy needs, even if it's only an indirect reliance. After all, herbivores are eating the energy of the sun trapped in plants. Carnivores eat the energy of the sun trapped in plants that was passed on to herbivores. All living things need the sun's energy to survive. If the sun's energy is even partially blocked, life will cease to exist. When an asteroid struck the earth 65 million years ago, it kicked up huge clouds of dust that blocked out the sun and ended photosynthesis, wiping out the dinosaurs. Life needs energy, and it gets that energy from the sun.



While Venus receives plenty of energy, there is too much heat for there to be enough Free Energy. Again, Free Energy is Total Energy – [Heat x Entropy]. Not enough free energy remains because too much of it is heat.

However, the sun's energy by itself is not useful to any living organism. Living things cannot use light energy for their own needs – they need to change light energy into another form that can be used. Photosynthesis is the process of converting solar light energy into chemical energy, or sugar.



Too little energy reaches the surface of Mars. Free Energy is Total Energy – [Heat x Entropy]. There is no life on Mars because there isn't enough total energy.

Endothermic and Exothermic Chemical Reactions

Photosynthesis is a series of chemical reactions necessary to create a stable chemical way to store the sun's energy over moderately long periods of time. Chemical reactions can fall into one of two groups – either they absorb energy or they give off energy. For example, burning a log on a fire is an **exothermic** chemical reaction – it gives off energy in the form of heat. Instant cold packs in first aid kits are **endothermic** – they absorb energy. An easy way to remember these two terms is to look at how each begins. *Exo*thermic reactions are where the energy *exits* the molecules, whereas *endo*thermic chemical reactions are where energy goes *inside*.

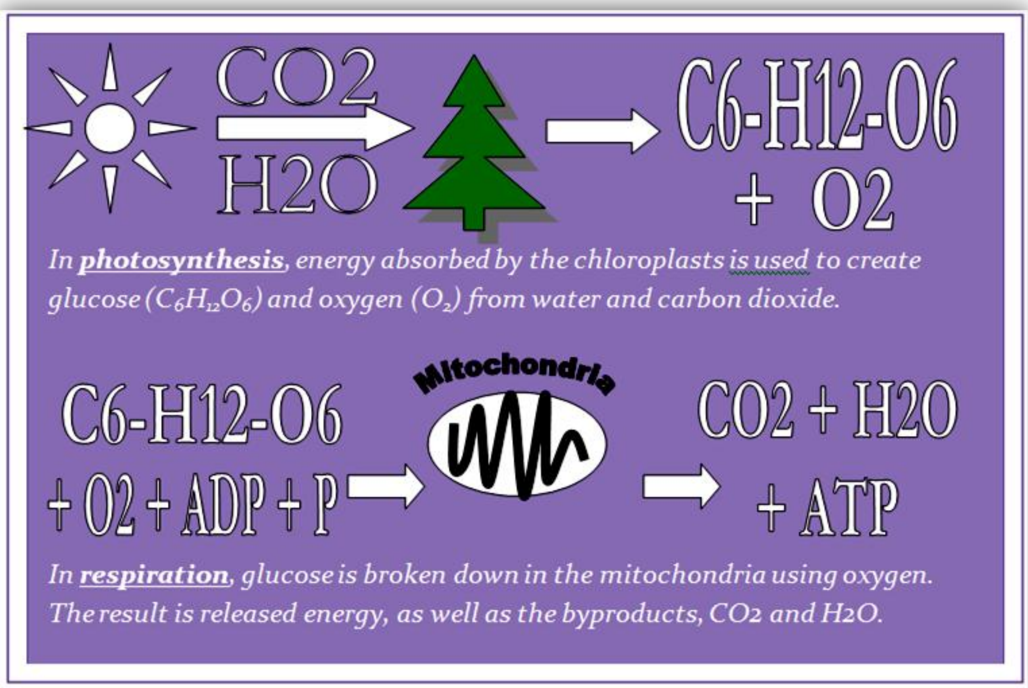
Figure 1 The Thermic Twins, Exo and Endo

Photosynthesis is an *endothermic* reaction. It is absorbing the energy of the sun for later release. Cellular respiration, when sugar is broken down to power ATP production, is *exothermic*. In other words, when sugar is created through photosynthesis, energy is absorbed from the sun in a series of endothermic chemical reactions.

When that sugar is consumed and broken down by the mitochondria of plant cells, animal cells, and other kinds of cells, the energy trapped in the sugar is released in a series of exothermic chemical reactions.

Overview of Photosynthesis

Photosynthesis on the surface seems pretty simple. Plants absorb water (H_2O) from the soil using their roots and carbon dioxide (CO_2) from the air through their leaves. Using the energy of the sun, water and carbon dioxide are combined into a brand new molecule, $C_6H_{12}O_6$, or sugar. Plants may later combine sugar molecules into different lengths of chains to create starches or fibers for fuel and for their plant structures.



When sugar is consumed by a plant or animal, it is broken down into $C_6H_{12}O_6$ once again. The mitochondria strip the hydrogen atoms off of the sugar and use these to power the revolving door ATP synthase structures that create ATP from ADP and P_i. Unused carbon and oxygen that remain from the sugar bond to form CO_2, which is given off by both plants and animals. Hydrogen atoms bond to oxygen that is absorbed by the plant or animal to create water molecules. This CO_2 and H_2O is then reabsorbed by plants and turned back into sugar. Hence, this process is an ever-ongoing cycle between CO_2 and H_2O and $C_6H_{12}O_6$.

Photosynthesis In More Detail

So how is the sugar molecule actually created? This is where it gets a little more complicated, but it's not too bad. First, remember that energy can neither be created nor destroyed. Knowing that, you also have to realize that it takes energy to create sugar. This might seem confusing…why would it take energy to create a changed form of energy? This sort of makes sense if you think about it. For example, gasoline is a form of chemical energy your car uses. However, gasoline isn't found ready to be put into your car…it has to be refined in multiple ways. This refinement process takes energy, and so it takes energy to create the gasoline form of energy.

In the same way, it takes energy to create sugar molecules. Once the energy is created, this energy can be stored until it is needed later. Again, any time a cell needs energy, it has only one option: ATP. So before we can make sugar, we have to make ATP.

Photosynthesis occurs in a cellular structure called the **chloroplast**. Like the mitochondria, the chloroplasts can create their own ATP in a process very similar to the mitochondria.

The first step in creating ATP for making sugar is to get a supply of hydrogen protons (H^+). Plants and other photosynthetic cells use water (H_2O) as their source of hydrogen. Using the energy of the sun and the **chlorophyll** pigment, the H_2O is split into pure oxygen and pure hydrogen. The oxygen is released into the air – it is not needed for this process. The hydrogen is kept so that it can power the ATP Synthase revolving doors inside the chloroplast.

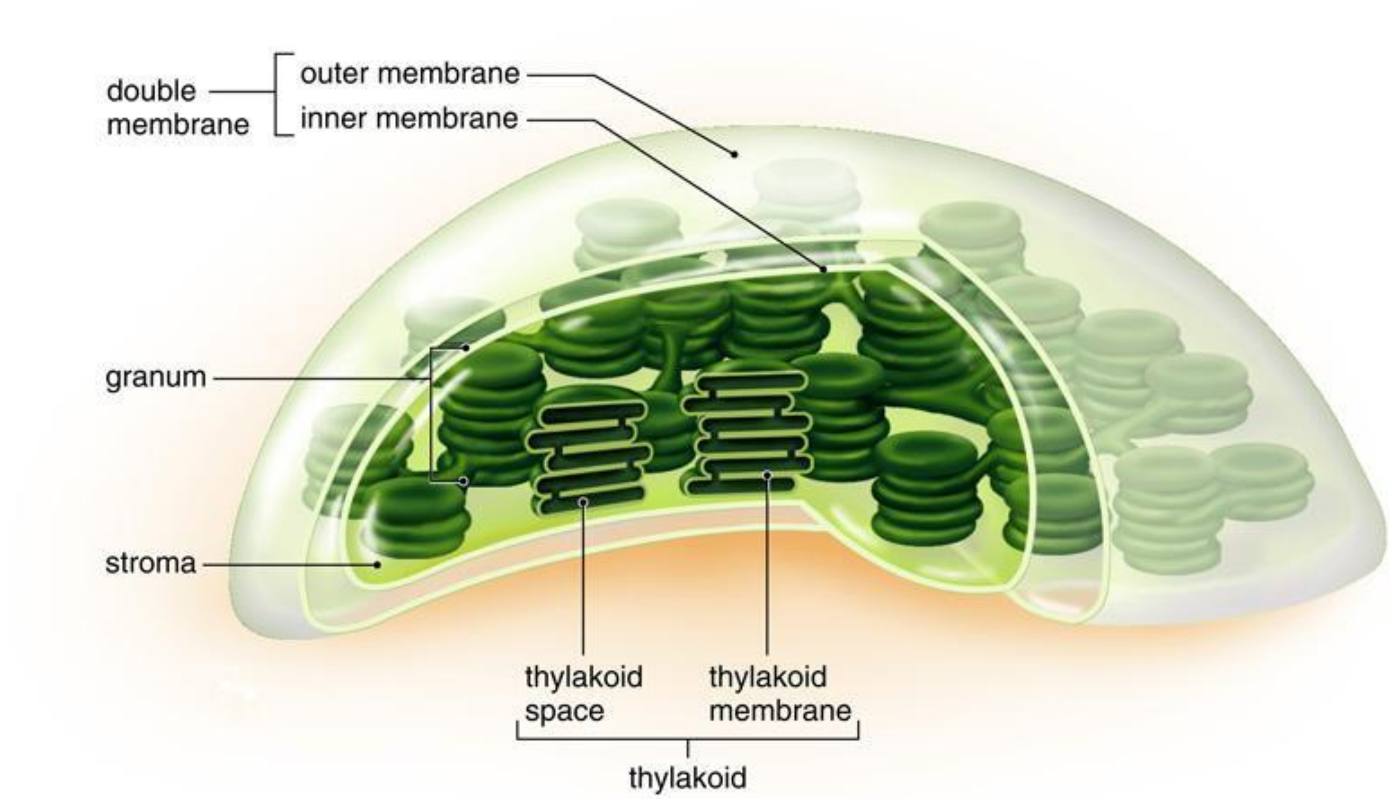


Figure 2 A chloroplast organelle, with grana and individual thylakoids. Chloroplasts use the pigment chlorophyll to split water molecules. The hydrogen from water is stuffed into the thylakoids, where the protons power ATP Synthase pumps. ATP Synthase is used to create ATP, and ATP is used by the chloroplasts to create sugar molecules as well as starches and fiber.

Inside every chloroplast is a structure that looks like a stack of pancakes. These structures are the **grana** (singular: granum). Each "pancake" in the grana is called a **thylakoid**. These thylakoids are stuffed with protons (H^+). Just like in the mitochondria, these protons hate being around each other…they just dread seeing each other no matter where it occurs. Just as before, they want to escape any way possible, and just like before, the only way out of the thylakoid in the grana is through the revolving door, ATP Synthase. As protons go through ATP Synthase, ADP and P_i are combined into ATP.

Once the ATP is made, it can be used to create sugar molecules. ATP in the chloroplast IS NOT used to power the cell. Rather, this ATP is exclusively used to make sugar molecules. The longer the chain of sugars, the more ATP that is needed. In a way, the chloroplast ATP is like a train engine at a rail yard, attaching individual rail cars to each other. Just as train cars will not form trains by themselves and need the engine to put a train together, sugar molecules need the energy of ATP to be turned into simple sugars, starches, and fibers. Without ATP, there can be no sugar molecules and there can be no chains of sugar.

Summary of Photosynthesis

1. H_2O is absorbed by the roots. CO_2 is absorbed by the leaves.
2. H_2O is split into pure oxygen and pure hydrogen using the energy of the sun. The oxygen is released and the hydrogen protons are moved into the chloroplasts.
3. Hydrogen protons are stuffed into the thylakoids (individual pancakes) in the grana (stacks of pancakes).
4. Hydrogen protons leave the thylakoids through the ATP Synthase revolving doors. ATP Synthase turns ADP and P_i into ATP.
5. ATP is used to combine CO_2 and Hydrogen into $C_6H_{12}O_6$, or sugar (glucose). This sugar can be consumed by the plant for energy, or the sugar molecules can be strung together using ATP to create starches and fibers.
6. When sugar is utilized by the mitochondria, CO_2 and H_2O are released and reabsorbed by plants.

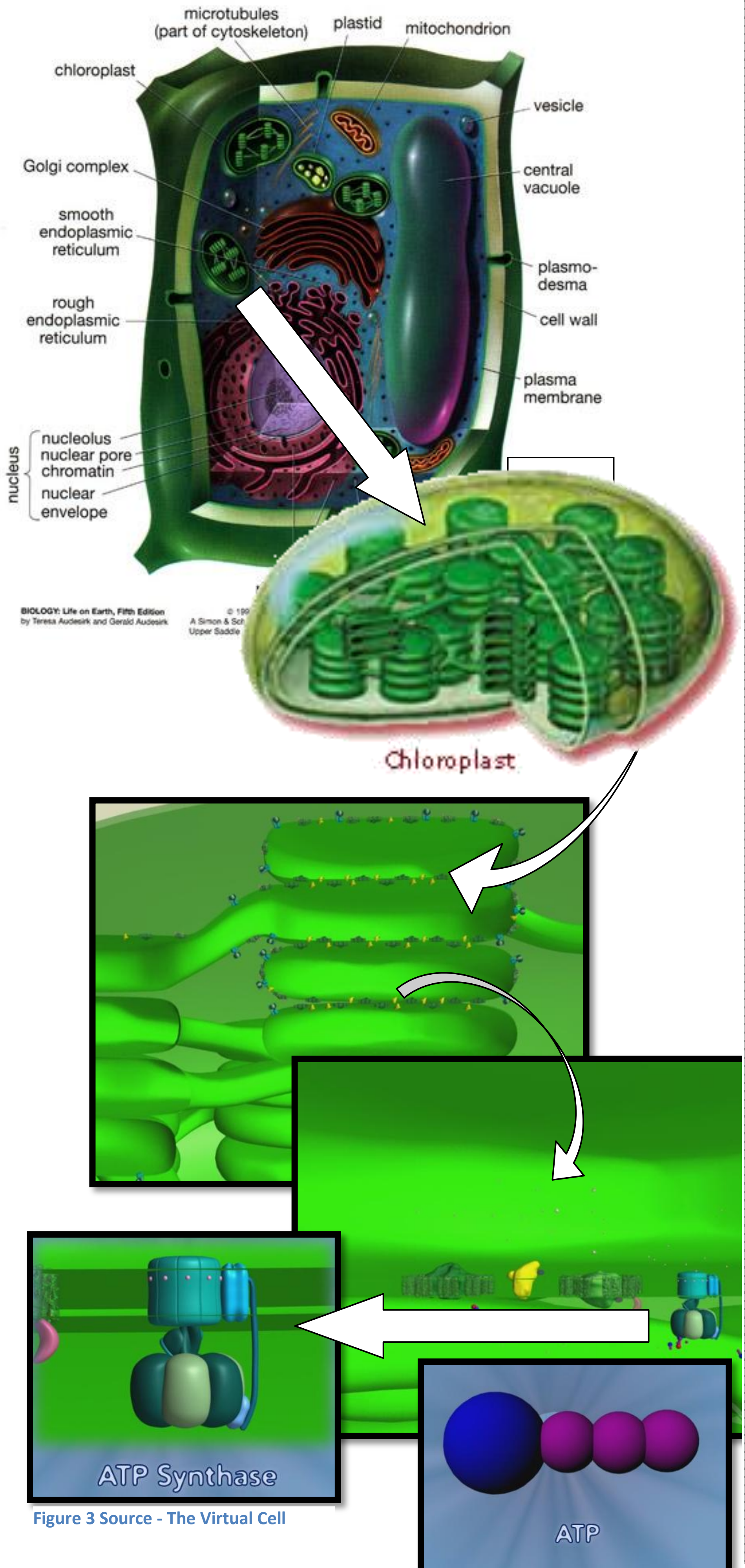


Figure 3 Source - The Virtual Cell

Production of ATP in Chloroplasts

If we could shrink in size and open up a plant cell, we would see something similar to the top picture on the left. Inside of the plant cell is a cellular structure called a chloroplast; this is the site of photosynthesis and some ATP production.

Inside of the chloroplast are structures that look like stacks of pancakes. These "stacks" are called grana, and each "pancake" is called a thylakoid.

Like the mitochondria, the thylakoid is stuffed with H+ atoms (also called protons). Like relatives in a car on a long road trip, they want to get out, but the only way out of the thylakoid is through a special opening called the ATP Synthase.

Drs. John Walker and Paul Boyer received the 1997 Nobel Prize for Chemistry for discovering ATP synthase. They discovered that the energy released when cells break down molecules of fat and carbohydrates is used to create an excess of H^+ atoms on one side of a membrane. H^+ atoms flow through ATP synthase embedded in the membrane and power the production of ATP.

The ATP created by the thylakoids in the chloroplasts is used to create glucose from carbon dioxide and water. It is NOT used to power the cell. The ATP used by the chloroplasts is "repaid" when glucose is used to create much larger supplies of ATP in the mitochondria.