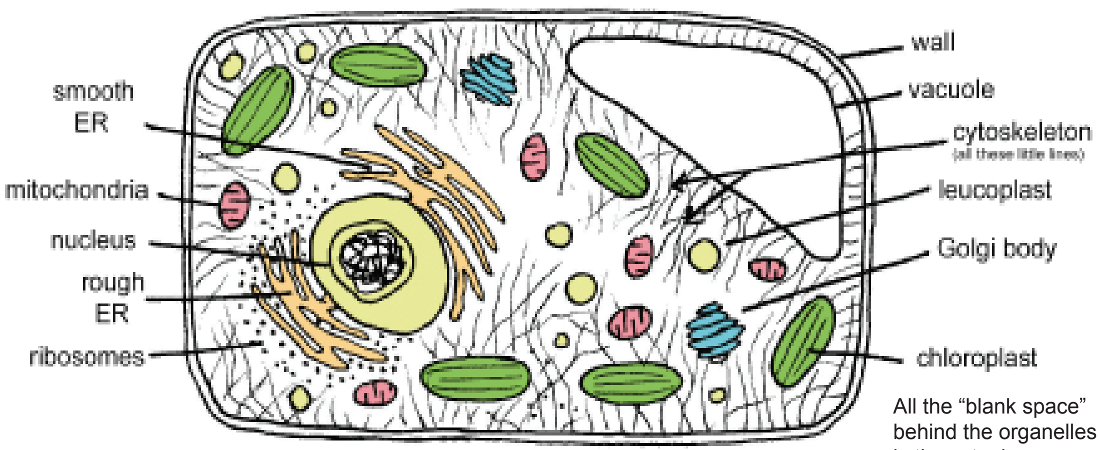
LEVEL TWO

A cell is sort of like a miniature factory. Real factories make products, store them in warehouses, and ship them out to customers. Cells make things like sugars, proteins and fats,and they store them and transport them. In this diagram, the plant cell looks flat. Remember that in real life plant cells are three-dimensional.



All the "blank space" behind the organelles is the cytoplasm.

Here is what each little organelle does:

Vacuole: This is like a water-filled bubble in the middle of the cell. Water from outside the cell constantly "leaks" into the vacuole, keeping it full. This water pressure inside the cell keeps the cell firm and healthy. If a plant can't get enough water to fill the vacuoles in its cells, the cells will shrink, causing the plant to wilt.

Cytoplasm: This is the jelly-like fluid inside the cell but outside the vacuole. It contains not only water, but proteins, fats, carbohydrates, and minerals. The cytoplasm circulates the chloroplasts around and around, making sure they all get an equal amount of light.

Chloroplasts: This is where photosynthesis occurs. Chloroplasts contain the chemical chlorophyll, which can use the energy in sunlight to turn carbon dioxide and water into sugar (making water and oxygen in the process).

***Cytoskeleton*:** This is a network of fibers that does two jobs: it helps the cell to maintain its shape, and it serves as a system of "roads" on which various things can travel across the cell.

Nucleus*:** This is sort of the "center" of the cell. It contains the instructions for how the cell operates. The instructions are in the form of a very long protein molecule called ***DNA. The DNA contains the "blueprints" for everything the cell makes.

Mitochondria: These are often called the "powerhouses" of the cell. Respiration takes place here. (Remember, respiration is how a cell gets energy out of glucose.) The mitochondria produce the energy the cell needs for its activities.

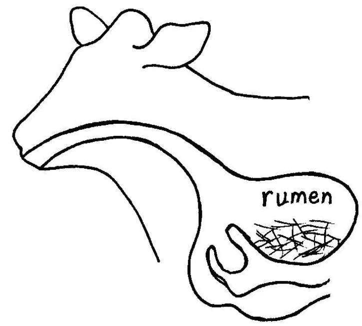
Leucoplasts: These are "storage tanks" for starches and lipids (fats). There are three different types of leucoplasts, the most common being the amyloplast. You will sometimes see the word "amyloplast" on a cell drawing instead of "leucoplast." ("Amylo" means "starch.")

Golgi bodies: These are often called the "post offices" of the cell. This is where proteins made by ribosomes are packaged and labeled for delivery to other areas of the cell, or to other cells.

Endoplasmic reticulum (ER): This seems to do several jobs. One type of ER manufactures protein molecules. Another type of ER makes lipids (fat) molecules. Both types of ER help the cell to maintain its shape by providing a bit of internal structure. ER also helps to transport things about the cell. Rough ER has ribosomes all around it; smooth ER does not.

Ribosomes: These little dots along the ER are a bit like the workers on an assembly line. They do the actual assembly of the plant's proteins.

Now for some info about the cell wall. It's not really an organelle, but it's still important. The outside wall of a plant cell is very tough. It is made of something called ***cellulose***, which animals cannot digest. Only microorganisms (such as bacteria) can tear it apart. That is why animals that live on nothing but plants (herbivores) need lots of "good" microorganisms in their digestive systems to help them digest the plants. For example, a cow can live on nothing but grass because of the microorganisms living in the first of its four stomachs—the rumen. The microorganisms can tear apart the outer wall of the grass cells so that the proteins, fats and sugars inside of them spill out and are then available for the cow's body to use.



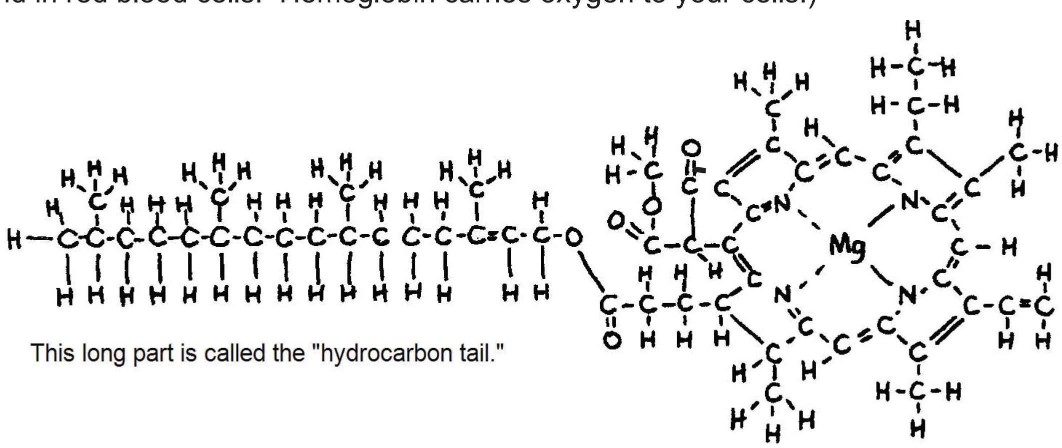
You don't have a rumen, so when you eat plant cells, most of them pass through your system undigested. This isn't bad for you, however. In fact, nutritionists call this plant material ***roughage*** or ***fiber***, and they recommend that you eat plenty of it. The plants in our diet help to keep our intestines healthy even though they provide only some nutrition. (Cooking can help to break down the cell walls, and very thorough chewing helps, too.)

Plant cells spilling open

Just inside the cell wall there is a ***cell membrane***. It is very thin and hard to see compared to the thick cell wall. Membranes are found in all types of cells, not just plant cells. They are fragile and come apart easily, but still have an important job. They control what comes into the cell, allowing nutrients and water to flow in but keeping harmful things out.

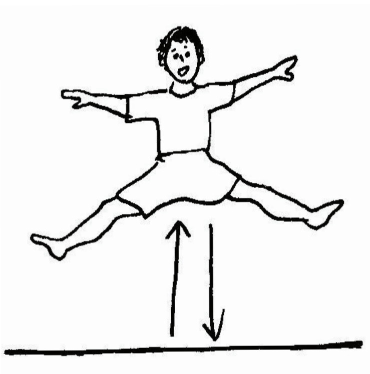
Let's discuss the process of photosynthesis again, this time taking a closer look at it. Just how does a chloroplast produce sugar?

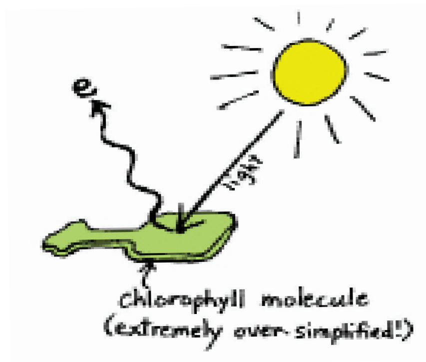
At the heart of photosynthesis is the chlorophyll molecule. (Interestingly enough, the ring of atoms around the magnesium atom can be found in other molecules, too. If you switch the magnesium atom for an iron atom, you get a "heme" molecule, an important part of the hemoglobin protein found in red blood cells. Hemoglobin carries oxygen to your cells.)



When a photon of light hits a chlorophyll molecule, it can super-charge an electron from one of these atoms, causing to become ***excited***. (It's hard to track down exactly which atom the electron belongs to.) The excited electron has so much energy that it is forced to leave the chlorophyll molecule and go elsewhere. A regular electron comes in and takes its place so the molecule doesn't fall apart.

When a person jumps up, gravity brings him back down again. An excited electron "jumps"

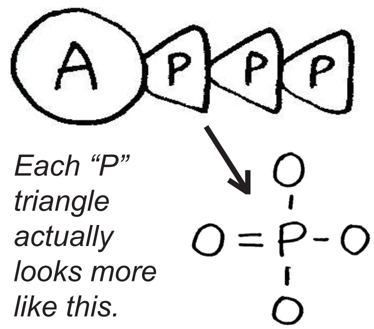




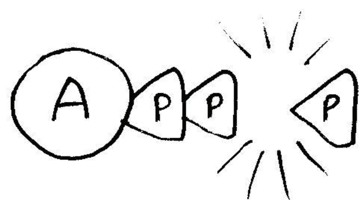
to a higher energy level, but it can't stay there any more than our jumper can stay in the air. The electron must come back down and return to its original energy level. On the way back down, though, the electron can pass its extra energy to other molecules, resulting in molecular "work" being done.

As it "falls," the high-energy electron passes through an assembly line made of tiny biological machines. The energy contained in the electron is used to power these machines. The goal of this assembly line is to re-charge the cell's biological batteries.

Floating around in the cell are millions of molecules called ATPs, which act like re-chargeable batteries. ATP is fairly simple, as far as biological molecules go. The A stands for ***adenine***, the same molecule found in the rungs of DNA. Then there is a little sugar called ***ribose***, which acts as a connector. The ribose holds on to three ***phosphates***. (A phosphate is nothing more than a phosphorus atom with a few oxygen atoms attached to it.) In this diagram, the ribose is not shown separately because when adenine and ribose are joined together they are called adenosine, which also starts with the letter A.

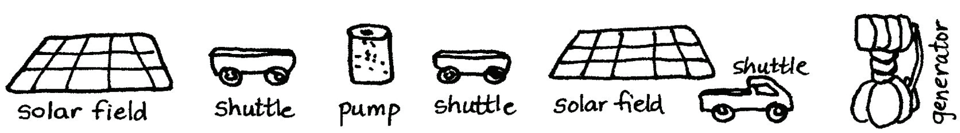


The way this battery works is to pop off the phosphate on the end. When that third phosphate comes off, energy is released. You could think of it as a nano-sized pop gun. To re-load the gun, you simply stick the phosphate back on again. A cell has a few ways it can do this, but all of them require energy. Ultimately, the sun will provide this energy.



There are two stages in the photosynthesis process. One stage uses the energy of sunlight and the other uses the energy stored in biological batteries. Sometimes these stages are called the "Light Phase" and the "Dark Phase." The Light Phase needs light, but the Dark Phase doesn't need darkness. The new-and-improved names for these phases are "Light Dependent" and "Light Independent." We'll look at the Light Dependent phase first, since it provides energy for the Light Independent phase. (We'll meet the Independent phase on page 13, disguised as a sugar factory.)

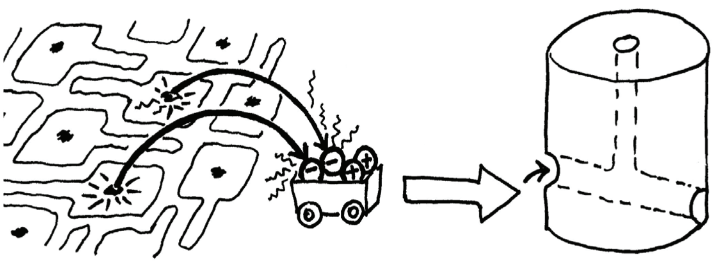
Each phase has its own little assembly line. A quick overview of the Light Dependent assembly line looks like this. →



We will look at each part separately and see how it works.

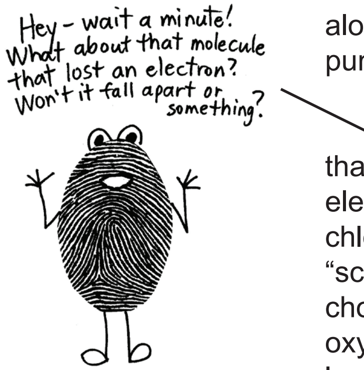
Have you ever seen fields full of solar panels? If not, go to Google, click "images," then type in "solar farms." You'll see huge, flat fields (usually in desert climates since they get a lot of sun) with hundreds of solar panels set up in neat lines. These solar panels collect energy from the sun and pass it along to a central collection area where the energy is then converted into electricity.

The plant cell's solar farms are embedded around the edges of the thylakoids (those pancake things in the chloroplasts). They are called ***photosystems***, instead of solar farms, and they have chlorophyll molecules instead of solar panels. Like solar farms, photosystems have a central collection point where the energy is harvested. These central points are called ***reaction centers***. Photons of light energy hit the chlorophyll molecule and energize them, causing them to vibrate. All the vibrations are passed along to the central chlorophyll molecule which then gets so energized

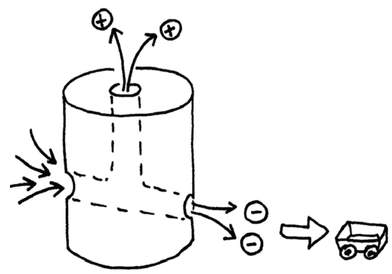


that an electron from its center goes flying off. While the electron is in this energized state, it can be used to do work. Quick! Get it to the pumping station! A little shuttle bus is waiting next to the photosystem, ready to pick up energized electrons and carry them over to the pumping station.

The shuttle bus has four seats and always picks up two electrons along with two protons. The protons also need to be transported to the pumping station, so the shuttle gives them both a ride. Off to the ion pump!



Good question! What is going to happen to the chlorophyll molecule that lost an electron? That electron was part of the molecule. Without the electron, the chlorophyll molecule will begin to collapse. Fortunately, the chloroplast has a way to deal with this emergency. It has little chemical "scissors" (made of atoms of manganese, calcium and chlorine) that can chop apart water molecules. Water is made of two hydrogen atoms and one oxygen atom. The chemical scissor cuts the bonds between the atoms. The lone oxygen atom goes off and finds another lone oxygen atom that has just been snipped, and the two form a bond and float off into the atmosphere together as a molecule of oxygen (O_2). The scissors then go to work on the hydrogen atoms. Since a hydrogen atom is nothing but one proton and one electron, only one snip is needed. The loose electron can go over and replace the missing electron in the chlorophyll molecule and the proton can go get on that shuttle bus.



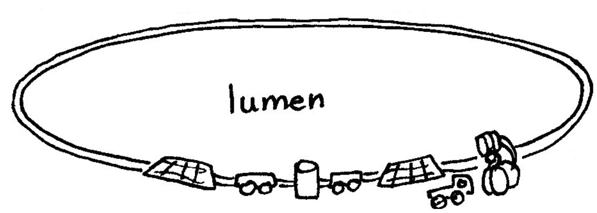
Now we are ready to go back and discuss the shuttle bus that was heading to the pumping station. Let's see what happens next.

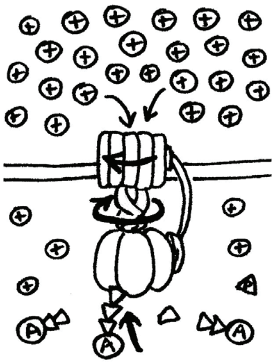
At the station, the electrons and protons are stuffed into the pump. The electrons provide a surge of energy to propel the protons up and out the top of the pump. When the electrons come out the other side they have given off a lot of their energy and are tired. They need to be re-charged to be of any further use. They get picked up by another shuttle bus. (We'll come back to the protons in just a minute.)

This next shuttle takes the tired electrons to another photosystem. The electrons get charged up again and then they are put into a fancy shuttle called NADPH. This letter group isn't very pronounceable. The closest word might be NAPA, an auto parts dealer in North America that has a fleet of blue and white pick-up trucks with big yellow hats on their roofs. So we've drawn the NADPH shuttle as a pick-up truck. The truck will take these energized electrons over to a sugar factory.

Now back to those protons that were pushed out the top of the pump. We need to zoom out for a second and look at where this assembly line is located. It lies right in the middle of the thylakoid membrane. The tops of all the little machines are on the inside (***lumen***) of the thylakoid, and the bottoms are outside of the thylakoid, in the fluid-filled space of the chloroplast (the ***stroma***).

The protons collect in the lumen of the thylakoid. The pumps keep pumping them in. Soon there are so many that they are looking for a way to escape. There is more "personal space" available out in the stroma, so that is where they want to go. This is where the generator comes in.





The correct name for the generator is ***ATP synthase***. "Synth" means "to make." This machine doesn't make ATP from scratch, though. It just pops the third phosphate back on. (ATP that is missing the third phosphate is called ADP, with the D being an abbreviation for "di," meaning "two.")

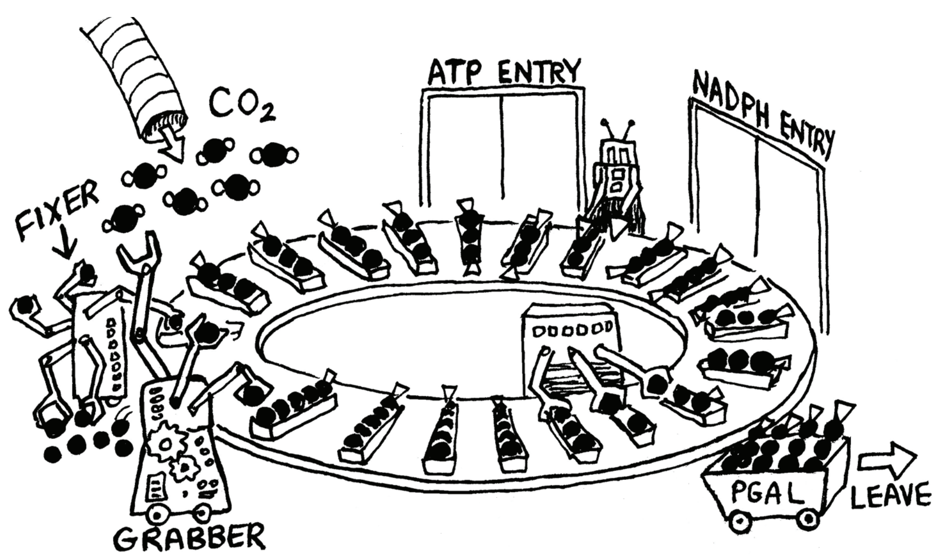
The protons upstairs in the lumen would like to get down where it is not so crowded and the only escape route is through this machine. The protons don't mind going through it, and on the way down their positive charge is used to turn the rotor of the machine. The bottom part of the rotor has spaces that were designed for ADP to be held in place while a phosphate is snapped back on. So all the ADPs in the area are re-charged back into ATPs.

This first part of photosynthesis has as its only goal the recharging of ATPs and the filling of NADPH shuttle buses with high-energy electrons. The next part of the process is the formation of sugar molecules. This process does not need light because it is powered by these little bio-batteries. (But since the batteries need light to be re-charged, even this Light Independent process is still ultimately dependent on light.)

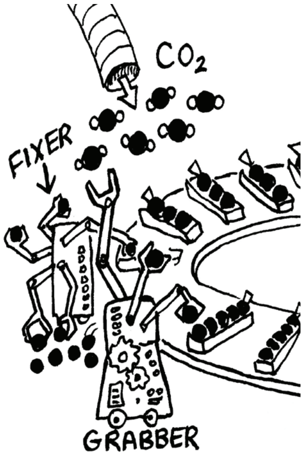
Let's imagine our little NADPH shuttle buses and ATP molecules pulling into the parking lot of a sugar factory. (We were tempted to call it a candy factory, since candy is made from sugar, but then you would have been disappointed when the man who came out to greet you was not Willy Wonka.) The sign above the door says, "Welcome to the Calvin Cycle." The manager comes to the door to greet us and introduces himself as Professor Melvin Calvin. (Okay, he's not as cool as Willy Wonka, but he did receive a Nobel Prize in 1961, so try to be impressed.) When asked if he invented or built this factory that bears his name, he humbly admits that he simply discovered it. It was already built and in operation when he arrived. He just figured out how it worked. However, his friends were so impressed with his discoveries that they decided to name the factory after him.

Professor Calvin invites us inside to watch the factory in operation. The assembly line is a large circle. Fastened to the conveyor belt are compartments with black balls inside them. We learn that these black balls are carbon atoms. The Professor laughs as he comments how strange it is that sugar is made of carbon atoms—the same kind of carbon atoms that are found in the gasoline we put into our cars. He thinks of this factory as a fuel factory more than a sugar factory.

There is an air hose hanging from the ceiling in one place. The professor explains that the hose brings in a constant supply of air from the outside. The air contains something very necessary for this sugar-making process: carbon dioxide molecules. The compartments right below the air hose contain 5 carbon atoms. We notice that one of the carbons in each 5-carbon chain has a phosphate attached to it. Apparently,



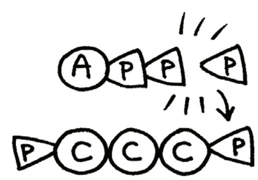
phosphates show up others places, too, not just on ATP. Professor Calvin says that phosphates are very common in the world of biological chemistry.

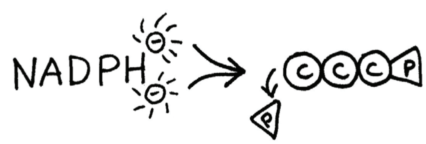


As we watch, a little robotic machine reaches up and grabs a carbon dioxide molecule. It snips off the two oxygens and then tries to stuff the carbon into a compartment that already has five carbons in it.

"This is what I can't understand," says the Professor. "The compartments can only hold five carbons, but the robot is programmed to try to add a sixth carbon. It never works. As soon as the circle begins to rotate, the six carbons fall out of the compartment! Luckily, the next robot down the line picks them all up and then puts sets of three carbons into compartments. I've thought about fixing that first robot so it doesn't keep trying to overload the compartments, but even without repairs, the assembly line manages to crank out an amazing number of sugar units, so I decided not to mess with it. Since the second robot fixes the first one's mistake, I call this part of the operation 'carbon fixing.'"

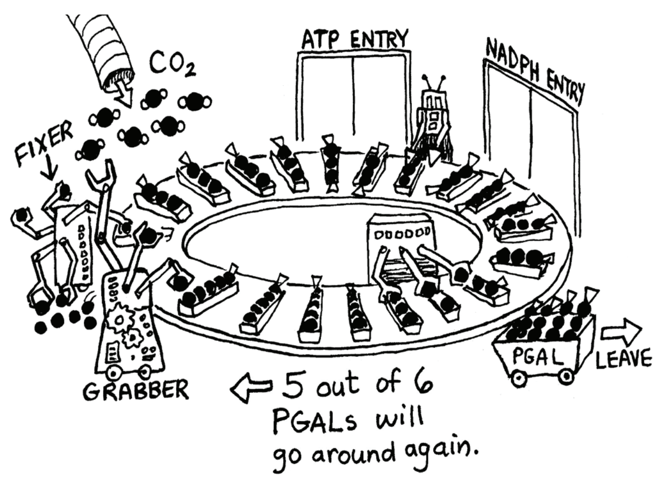
The 3-carbon arrangement works out very well, and as we watch the circular conveyor rotate, the carbons stay in groups of three for the rest of the ride. After the carbons leave the "fixer" robot, one carbon in each group of three has a phosphate attached to it. Professor Calvin then warns us that the next two steps won't make a lot of sense to us. At the next station, some ATPs are waiting and ready. They pop off their third phosphate and give it to a 3-carbon group. Now the group has two phosphates—one at each end. At the next station, we see some NADPH trucks ready to unload their passengers of high-energy electrons. Oddly enough, after being given a high-energy electron, the carbon groups then lose the phosphate they just gained! What was the point of receiving a phosphate if you are just going to get rid of it right away? The Professor tells us that there is more to this process than meets the eye. The end result of this cycle is that the 3-carbon groups are energized and ready to become part of a 6-carbon sugar molecule. These ready-to-go, 3-carbon molecules are called PGALs. (You can say "pea-gals" if you want to. That makes it easier to remember, too.)





This is the end of the cycle, but we notice that some of these 3-carbon groups stay on the belt, ready to go around the loop again. We are confused.

"It's simple math," says the Professor. "This process always begins with 5-carbon groups. The lowest number of 3-carbon groups that can be turned into 5-carbon groups without any left over is five groups. 5 x 3 = 3 x 5. Five of these PGALs must be recycled around again, to form three more 5-carbon units. One out of every six PGALs is taken off the conveyor belt. Seems very inefficient to me, but I've decided not to tamper with the system."

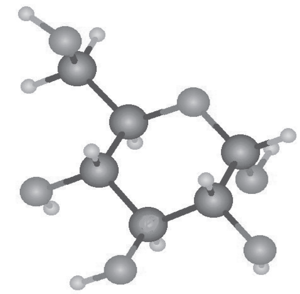


We ask if the factory runs 24 hours a day or whether it shuts down at night.

"We can only operate if we have an adequate supply of ATPs and NADPH electrons. They come from the solar farm down the street. On sunny days there's plenty of energy. At night the solar farm can't operate. After the sun goes down, we eventually run out of ATPs and NADPH electrons and have to shut down. We do have some emergency back-up systems, though. If it gets really hot and dry and our plant has to close its air vents (to prevent water loss) we can store some of the incoming carbon dioxide by mixing it with chemical preservatives. But we'd much rather have a steady supply of carbon dioxide coming in through our air hose."

We have one last question for the Professor. We wonder what happens to those PGALs that leave the conveyor belt.

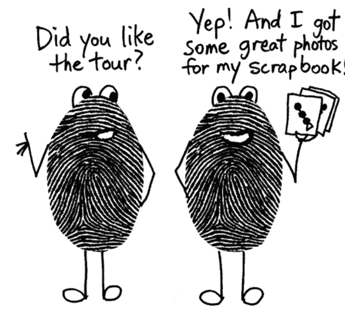
"Those are like half-sugars. This factory doesn't have to worry about final assembly. The PGALs get dumped out into the stroma where floating robots pick them up. The robots are programmed to take two PGALs and put them together to form a 6-carbon molecule called ***glucose***. Glucose is a type of sugar. I guess calling this a sugar factory is a tiny bit inaccurate, since we don't do the final assembly. But all the hard work gets done here. The final assembly is such a 'snap' that this hard-working factory gets credit for the sugar-building process."



GLUCCOSE: $C_6H_{12}O_6$

We thank the professor for the tour. What a strange but fascinating place! As we are leaving, he adds one last comment.

"I forgot to warn you — not everyone calls our products PGALs. If you hear someone talking about G3Ps, don't get confused. They're talking about PGALs."



We promise to remember his warning and not get upset about molecules having more than one name. We know someone who gets called "Robert" by his parents, "Bob" by his classmates, and "Blinky" by his best friend. (We're too polite to ask the best friend where the nickname "Blinky" came from.)

ONE FINAL NOTE: We have greatly simplified the Calvin Cycle. We've focused on just the carbon atoms, since they form the "backbone" of the glucose molecule. Glucose also has oxygen and hydrogen atoms attached to it. In the picture above, the darkest atoms are the carbons, the tiny ones are the hydrogens and the medium gray ones are the oxygens. The carbons almost form a ring, but not quite. One oxygen completes the ring, with one carbon stuck off to the side.

ACTIVITY 1: WATCH ANIMATIONS OF ATP SYNTHASE

Go to YouTube.com/TheBasementWorkshop and click on the Botany playlist. You will find some awesome computer animations showing the ATP synthase machine in action. There are also a few other photosynthesis-related videos. (Watch any other videos listed for this chapter that you have not already watched.)

ACTIVITY 2: MATCHING

Match the cell part on the left with its function on the right.

1) nucleus __	A) makes energy
2) endoplasmic reticulum ___	B) does packaging and shipping
3) Golgi bodies ___	C) jelly-like fluid
4) leucoplasts ___	D) an empty area
5) chloroplasts ___	E) network of fibers
6) vacuole ___	F) stores starches and fats
7) mitochondria ___	G) uses light, water and CO_2 to make sugar
8) ribosomes ___	H) assembles proteins
9) cytoplasm ___	I) assembles, transports, gives shape
10) cytoskeleton ___	J) contains DNA instructions