Chapter 8

The storage form of glucose in plants is *starch*. Starch is a polysaccharide. The leaves of a plant make sugar during the process of photosynthesis. Photosynthesis occurs in light (photo=light), such as when the sun is shining. The energy from the sunlight is used to make energy for the plant. So, when plants are making sugar (for fuel, energy) on a sunny day, they store some of it as starch. When the simple sugars need to be retrieved for use, the starch is broken down into its smaller components. They literally save some energy for a rainy day.

Respiration is a key function to survival. The process of respiration is key to how plants create their fuel and how animals get oxygen into their systems. Respiration contains some of the most important metabolic reactions that occur in organisms.

Plants do not have digestive systems like animals do. But they do break down (digest) fuel to create useable energy like animals do. Why, you ask? Well, to grow, plants need to make more cells. Energy is needed to do that. Energy also is needed for the most basic metabolic processes in a plant, such as to continually run the reactions of photosynthesis, which ironically, convert more energy. Fuel is found not only in sugars such as glucose, fructose, sucrose, and starch, which are used throughout the life of the plant, but also in the fats in seeds, which are used to help the plant get started.

You know how animals not only take in food and water but also oxygen to survive? In animals, the process of taking in oxygen and giving off CO_2 and H_2O is called *respiration*. Plants undergo respiration too, except that they take in carbon dioxide and give off oxygen and H_2O.

The entire process of *photosynthesis* (including both light and dark reactions) is summed up like this:

$$\text{Energy (light)} + 6\,H_2O + 6\,CO_2 \rightarrow C_6H_{12}O6 + 6\,O_2$$

The entire process of *respiration* can be summed up like this:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$$

Notice anything? Notice how respiration is the reverse of photosynthesis? In plants, the creation of glucose and the breaking down of glucose happen continuously, and both major processes happen in each and every cell. There are no organ systems in plants, so the breaking down of fuel is not separated from where it us used. This design eliminates the need for a circulatory system, per se, as well as the need for a circulatory pump like a heart. And it eliminates the need for an excretory system. Because plants are so efficiently designed, they really do not create much waste. Their "waste" consists of oxygen and H_2O, which they give off as products of this entire process of respiration.

In plants, the steps of respiration are fairly similar to respiration in animals. The steps include glycolysis, the Krebs cycle (or citric acid cycle) and the respiratory chain.

Remember glycolysis is the process of breaking down glucose. This process happens in the cytoplasm of the cell. In plants, glycolysis occurs through the glycolytic pathway (most often) or the oxidative pentose phosphate pathway. The glycolytic pathway is important because along the pathway, the substances that are produced (called *intermediates* because they are between the original substance being degraded – glucose – and the final product, which is pyruvic acid) are then used to form other important structural substances in the plant.

Once pyruvic acid is produced, it crosses into the mitochondria of the plant and starts the Krebs cycle. The rest of the process of respiration occurs in the mitochondria as well. After the Krebs cycle is completed and high-energy molecules are created, the energy is passed through a chain of events call the respiratory chain. At the end of the chain, oxygen and H_2O are released.

Refer to information provided in Chapter 7 for glycolysis, Krebs cycle and respiratory chain. Remember in glucose synthesis, CO_2 is the carbon source, and NADPH is the source for hydrogen, and ATP supplies the energy that drives the process.

Photosynthesis (Overview):

Photosynthesis is the process by which plants convert energy from the sun. It is the process that allows plants to create organic molecules that they use as fuel (remember that plants are autotrophic, meaning "self-feeders". Here is how it works.

The molecules of chlorophyll contained in the *chloroplasts* (which are scattered throughout each cell and the organelle eukaryotes use for photosynthesis) absorb energy in the form of light from the sun. Some plants need more sunlight than others, but all need at least a little.

Instead of taking in oxygen and breathing out CO_2 like animals do, plants take in CO_2 (which is the carbon source for photosynthetic plants) from the atmosphere. Plants absorb water from the ground up through their roots. During photosynthesis, the energy from the sun splits the H_2O molecule into H and O. The O molecules are given off by the plant and emitted into the atmosphere, so that you and I can breathe and create energy. Molecules of ATP are created within the plant cell. These reactions are called *photochemical* or *light reactions* because they require light to occur.

Enzymes within the plant then catalyze the combination of H and CO_2 to create a *carbon compound that is called an *intermediate*. An intermediate is a compound used to continue a process to create a different compound. In plants, the intermediate is called phosphoglyceraldehyde (PGAL). PGAL goes on in the process to produce glucose, which the plant uses *as fuel to survive. These reactions are called carbon-fixation reactions (*or dark reactions) because atoms of carbon are "fixed"; that is, they are put into stable compounds that can be used purposefully instead of just floating around the cell aimlessly.

When the plant has created more glucose that it needs to sustain life, it combines glucose molecules into larger carbohydrates molecules called starch. The starch molecules are stored within the large vacuoles in the plant cells. When necessary, the plant can break the starch molecules down to retrieve glucose for energy or to create other compounds, such as proteins (plants use proteins to carry electrons used in photosynthesis), nucleic acids (to create DNA), or fats.

Base on the above, another way to define photosynthesis is the process by which autotrophs capture the sun's energy and store it in the form of chemical bonds in carbohydrate molecules.

Some examples of photosynthetic organisms:

Prokaryotic cyanobacteria
Eukaryotic algae
Land plants
Fungi are NOT photosynthetic organisms

Limiting Factors:

1. Tempereature
2. Light
3. CO_2 concentration
4. Amt of end products produced

- *Carbon-fixation*: the enzyme ribulose biphsophate carboxylase attaches CO_2 to ribulose biphosphate (RuBP) forming a 6 carbon compound that hydrolyzes to 2, 3 carbon molecules of phosphoglycerate (PGA), which is reduced to glyceraldehydes 3-phosphate (PGAL) using energy from ATP and hydrogen from NADPH. Some of the PGAL are converted to new molecules of the 5 carbon starting material RuBP. The whole process is a cycle called the C_3 cycle or Calvin-Benson cycle.

Light Reactions: Overview:

First phase of photosynthesis involves trapping light energy. Light travels from its source as waves of energy and different wavelengths carry different amounts of energy. Short wavelengths carry more energy than long wavelengths.

Sunlight is a mixture of many colors, and color is determined by wavelength. If sunlight passes through a glass prism, the light is separated into the visible spectrum of colors. The basic unit of energy in the electromagnetic spectrum is the *photon* (it takes 4 photons of light to split 2 H_2O molecules). The colors of the visible spectrum from longest to shortest wavelength are red, orange, yellow, green, blue and violet. Which colors carry the most energy?

When sunlight strikes a plant leaf*, (which is the primary photosynthetic structure of the plant) the energy of certain wavelengths is absorbed by special photosynthetic pigments. A pigment is a substance that absorbs light. Different pigments absorb different wavelengths. Wavelengths that are not absorbed are reflected. Each pigment has a characteristic color determined by the light it reflects. (A graph that shows how much light from each wavelength of visible light is absorbed by pigment is called the *absorption spectrum*).

- *When I say a leaf absorbs energy in the form of light from the sun, what I really mean is that the energy is absorbed by the electrons in the atoms of the chlorophyll molecule. These tine little electrons are so excited to be part of the plant that they just bounce all over the place.
- While doing the happy dance, the electrons give off energy and then bounce into another pigment molecule, where they are incorporated and thrilled again to the point where they give off more energy. This cycle is called the electron transport chain, and it continues until the electrons bump into the "bouncers": chlorophyll a P_{680} and P_{700}. These "bouncers" don't like rowdy little electrons at this dance club, so they restrain them: that is, chlorophyll P_{700} absorbs electrons into photosystem I; chlorophyll P_{680} absorbs electrons into photosystem II.

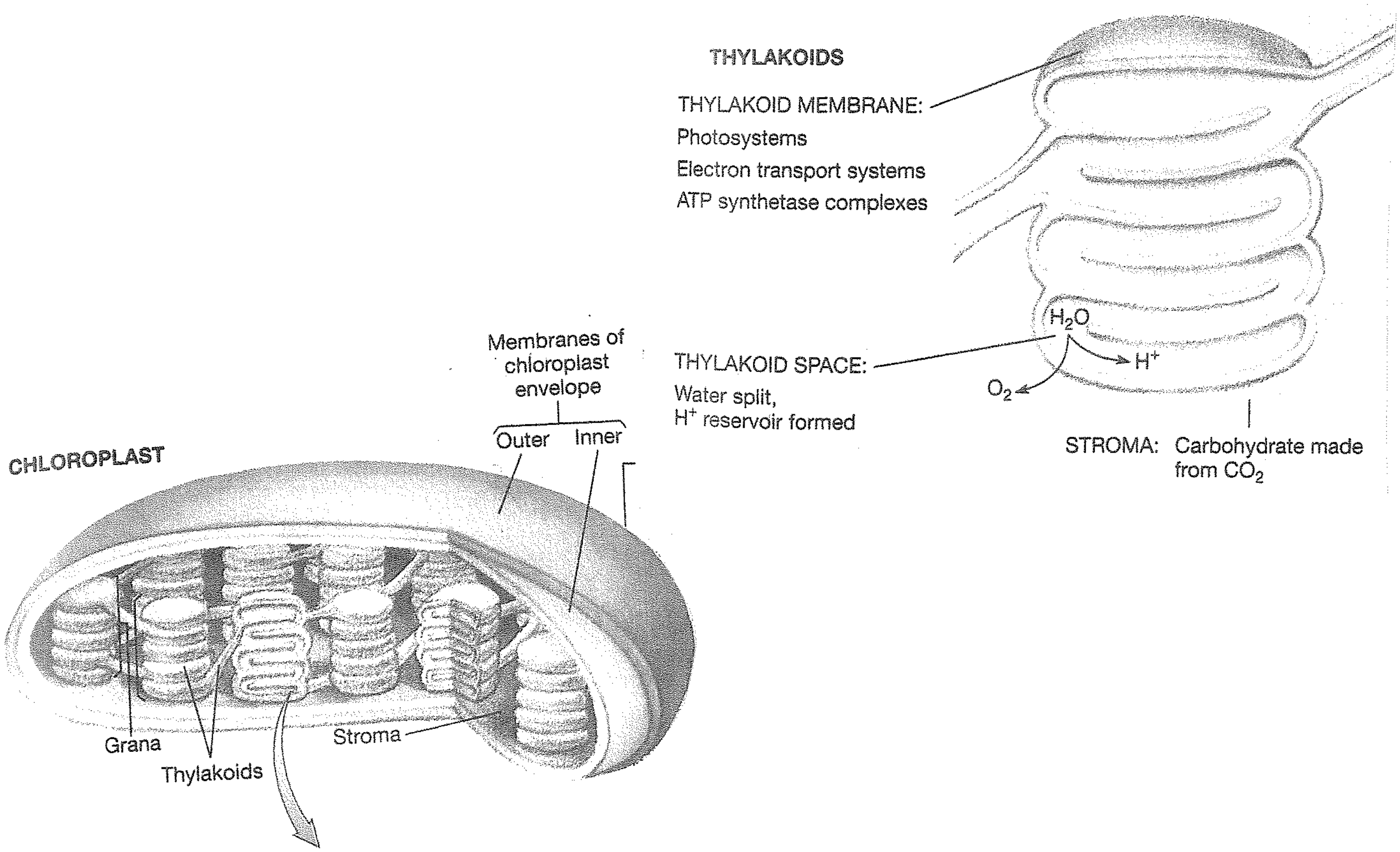
Chlorophyll is the major photosynthetic pigment. Chlorophyll *a* absorbs large amounts of red, orange, blue, and violet light, but very little yellow and green light. Because it reflects green and yellow light, chlorophyll *a* appears green. (Chlorophyll *b* absorbs light at every wavelength except red, orange, and yellow.) In addition to chlorophyll, autotrophs contain other pigments which absorb some of the other wavelengths of light. These pigments are responsible for the yellow, red and orange colors of some tree leaves in autumn. If pigments are essential for photosynthesis, where in the plant does photosynthesis occur? What about parts of the plant that are underground?

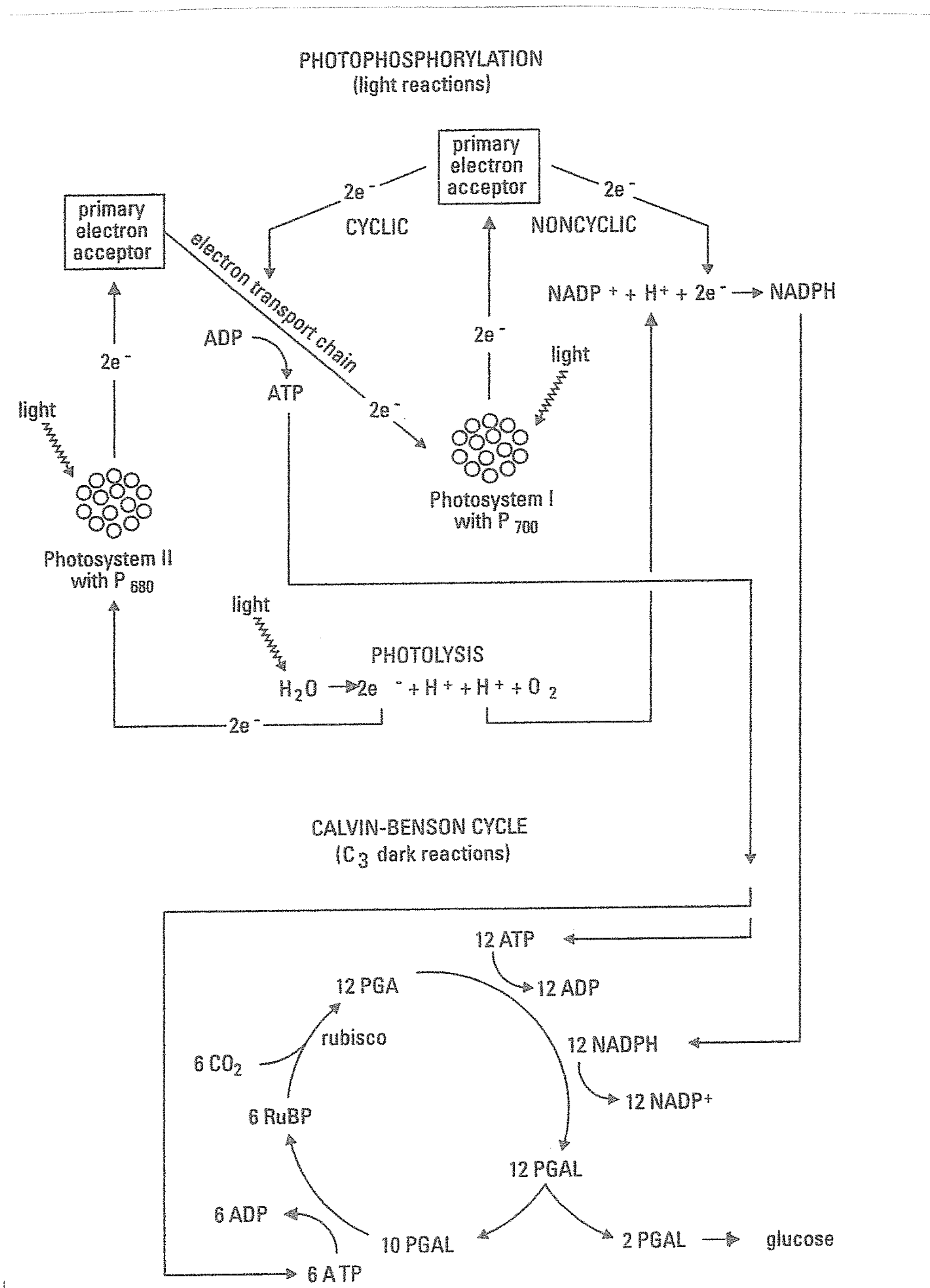
Carotenoids are a group of accessory pigments (absorb protons and transfer their energy to chlorophyll *a*) found in all green plants. They absorb blue and green wavelengths, imparting yellow or orange hues to the plant. They also protect the chlorophyll and may absorb energy and pass it onto the chlorophyll. (Phycobilins, anthocyanin, and chlorophyll *b* and *c* are also considered to be accessory pigments.)

Photosynthetic pigments are located in chloroplasts. Like mitochondria, chloroplasts have an inner and an outer membrane. The inner chloroplast membrane folds to form stacks of disk-like structures called *thylakoids* (where the light-energy capturing reactions of photosynthesis take place)*. Each thylakoid contains from 200-400 molecules of chlorophyll. Some of the thylakoids occur in stacks called *grana*. Surrounding the thylakoids is a fluid called the *stroma*. The stroma contains enzymes that make carbohydrates, as well as the chloroplast's DNA, RNA and ribosomes.

- Non-cyclic electron transport: hydrogen ion gradient across the *thylakoid membrane where the thylakoid space serves as a reservoir whose function is to accumulate H^+ ions (hydrogen atoms from splitting of H_2O) to supply energy for the **chemiosmotic synthesis of ATP using a hydrogen ion gradient (Chapter 7) is called photosynthetic phosphorylation.
- So, where do these H+ ions come from? If you said the splitting of the H_2O molecule and NADPH (later used in carbon fixation), you were right. And the thylakoid membrane is associated with Photosystem I and II, the electron transport systems and ATP synthetase molecules.
- Cyclic electron transport: $chlorophyll_{700}$ (in Photosystem I) serves both as an electron donor and final electron acceptor and results in the formation of ATP.

** photosynthetic ATP synthesis:
- requires a hydrogen ion gradient
- requires the presence of ATP synthetase molecules.
- Occurs due to either non-cyclic electron flow or cyclic electron flow.
- Occurs in photosystem II.





PHOTOPHOSPHORYLATION
(light reactions)
primary electron acceptor
2e⁻
CYCLIC
NONCYCLIC
primary electron acceptor
electron transport chain
$NADP^+ + H^+ + 2e^- \rightarrow NADPH$
ADP
ATP
light
Photosystem I with P_{700}
Photosystem II with P_{680}
PHOTOLYSIS
$H_2O \rightarrow 2e^- + H^+ + H^+ + O_2$
CALVIN-BENSON CYCLE
(C_3 dark reactions)
12 ATP
12 ADP
12 PGA
rubisco
$6\ CO_2$
6 RuBP
12 NADPH
$12\ NADP^+$
12 PGAL
10 PGAL
2 PGAL
glucose
6 ADP
6 ATP

Figure 1

Calvin-Benson cycle: dark reactions

The Calvin-Benson cycle (also known as C_3 photosynthesis), is a series of reactions that occur during photosynthesis by are not initiated by light. These reactions use the energy created during photolysis and photophosphorylation. After this cycle is performed six times, one molecule of glucose is created. Here is how it happens. Refer to **Figure 1**.

The cycle is broken down into the following types of reactions:

- Carboxylation
- Reduction
- Regeneration
- Carbohydrate synthesis

Overall the entire Calvin-Benson cycle can be put into an equation:

$$6CO_2 + 18\ ATP + 12NADPH + H^+ \rightarrow 18\ ADP + 18P_i + 12\ NADP^+ + 2\ glucose$$

Carboxylation:

A carboxylation reaction is one that takes CO_2, which is an unreactive inorganic molecule, and uses it to create an organic molecule that is involved in metabolic reactions.

In plant, CO_2 is taken from the air and, through the series of reactions in the Calvin-Benson cycle, used to create glucose. Specifically, one molecule of CO_2 enters chloroplast and combines with 1molecule of ribulose bisphosphate (a sugar-phosphate molecule abbreviated RuBP). CO_2 attaches to RuBP via an enzyme called ribulose phosphate carboxylase (rubisco). RuBP which is found in the stroma to creates 2 molecules of phosphoglycerate (PGA), which is a molecule containing 3 carbon atoms. The fact that a 3-carbon molecule is created explains why the Calvin-Benson cycle is also called C_3 photosynthesis: C_3 stands for 3 carbons. Because this entire process needs to occur six times, the overall equation is:

$$6\ CO_2 + 6\ RuBP \quad 12\ PGA$$

Reduction:

Remember the ATP and the NADPH molecules that were created during photophosphorylation? Well, this part of the cycle is where they come in during photosynthesis. This step also explains why these are the "dark" reactions. ATP and NADPH bring the energy into these reactions of photosynthesis; energy from light is not used directly here – it was already converted to the ATP and NADPH molecules.

At this point in photosynthesis (after 6 turns of the Calvin-Benson cycle), the 12 PGA molecules from the caraboxylation reaction combine with 12 ATP molecules (from 12 photophophorylations) and 12 NADPH molecules (from 12 photolysis and photophosphorylation reactions). These molecules create phosphoglyceraldehyde (PGAL). Three turns of the cycle will produce 6 molecules of PGAL. Only one PGAL molecule can be used by the plant to form carbohydrate.

The energy to create PGAL is taken from the molecules of ATP and NADPH. Remember that ATP is formed from ADP and P_i; NADPH is formed from $NADP^+$ and H^+. So, when the ATP and NADPH are broken apart to release energy, they also release ADP, P_i, and $NADP^+$. But do not worry – Mother Nature would not let energy go to waste. The ADP_i, P_i, and $NADP^+$ are recycle back through the steps of photohosphorylation.

Regeneration:

Back in the carboxylation reaction of the Calvin-Benson cycle, RuBP is used to create PGA. Then, in the reduction reaction, PGAL is formed. In this regeneration reaction, then PGAL is converted to RuBP so that the entire process of photosynthesis can keep occurring. I told you Mother Nature would not let energy go to waste. You cannot get much more efficient than the organism creating its own food, as well as the products from which it forms fuel. Can you imagine how efficient your car's engine would be if it used not only gas but could also use the products created when gas is broken down to re-form gas? You would never have to pull up to the pumps (and price increases would not be such an issue)!

For this regeneration reaction to occur, more energy in the form of ATP is used. The overall equation is:

$$10\ \text{PGAL} + 6\ \text{ATP} \rightarrow 6\ \text{RuBP}$$

May be your are asking yourself what happened to the other 2 PGAL molecules.

Carbohydrate synthesis:

If you were following along closely and keeping tabs on numbers, you would see that in the reduction reaction a total of 12 PGAL molecules were created (after six Calvin-Benson cycles, of course). Then, in the regeneration reaction, only 10 PGAL molecules were used to create RuBP. What happened to the other 2 PGAL molecules?

Look at **Figure 1**. See the point in the circle where 12 PGAL is labeled? An arrow splits off the circle labeled 2 PGAL, and that has an arrow pointing toward glucose. That means that this is the point in photosynthesis where the glucose is made!

The Calvin-Benson cycle is also called C3 photosynthesis because a molecule containing 3 carbon atoms is created. (it is called PGA.) Well, eventually PGAL is created, but that also contains only 3 carbon atoms. And, of you put two of those 3-carbon molecules together, you create a 6-carbon molecule, right? And glucose is a 6-carbon molecule.

In plants, other 6-carbon monosaccharides like fructose also can be formed in this step. Then, the monosaccharides can be combined to form disaccharides such as sucrose or polysaccharides such as starch and cellulose.

Photosynthesis in the Leaf - Xylem and Phleom:

Plants undergo photosynthesis to produce energy for themselves (and ultimately humans). Light and H_2O are needed to perform this process. But how do the plants get the water and light into their cells?

Tissues called the xylem and the phloem usually are found together in what are called vascular bundles. Both types of tissue conduct substances up through the root and stem of a plant. The xylem conducts H_2O and minerals from the soil; the phloem "flows" sugar molecules.

All plant cells have a cell wall, but cells in the xylem have an additional cell wall to give them extra strength (helps to avoid a blowout of H_2O through the stem). Vessel elements are specialized cells in the xylem that form column called vessels. Water passes through holes at the ends of each vessel element, and continues up through the entire vessel column.

Phloem tissue contains cells called sieve-tube elements, which connect in column called sieve tubes. Each sieve-tube element has a pore on the end of it, through which the cytoplasm from one sieve-tube element can "touch" the cytoplasm of the next sieve-tube element. This structure allows the fuel that the plant makes in the leaves to pass through and nourish the rest of the plant.

Recall that chloroplasts require water, CO_2, and light energy in order to carry on photosynthesis. Glucose and oxygen gas are produced. The plant uses the glucose and the oxygen diffuses into the atmosphere. The oxygen in the air you breathe comes almost entirely from the process of photosynthesis.

Water also travels to the mesophyll through the vascular bundles. Since the branching of the xylem is so fine, no mesophyll cell is more than a short distance from the water supply. Water can easily diffuse through the distance of a few cells.

Phloem, like xylem, branches out in the leaf so that no mesophyll cell is far from phloem. Glucose produced during photosynthesis is quickly loaded into the phloem. Some of the glucose is converted to starch, which may be stored in the mesophyll cells. Additional glucose is used by the leaf to make ATP for it own needs. Still more glucose is carried by the phloem to the stems and roots where it us used for storage, growth, and metabolism.

Since roots are below the ground, they are not exposed to light and cannot photosynthesize. This means they get their glucose from mesophyll cells in the leaves. It is interesting to observe that if the leaves of plant dies, the roots and stems will eventually die also. The Irish potato famines of the 1850's were caused by a fungus which destroyed the leaves of the potato plant. Since the leaves could not photosynthesize, there was no glucose for the potato plants.

Gas Exchange

The *guard cells* and the *stomata* regulate the exchange of gases between the leaf and the atmosphere. Special adaptations of the guard cells allow them to control the rate at which water vapor leaves the leaf.

Because the guard cells contain chloroplasts, they are able to carry out photosynthesis. During photosynthesis, the guard cells become swollen with water, or *turgid.*

The walls of the guard cells next to the stomata are thick and relatively inflexible. The outer walls of the guard cells, the ones next to the epidermis, are thinner and more elastic. As the guard cells become turgid, the thinner, outer walls of the cells push outward into the epidermal cells. This change in shape pulls the thicker inner walls away from each other, opening the stomata.

On sunny days when photosynthesis is proceeding rapidly, the cells in the leaf require CO_2. At that time, the stomata are usually open. When it is dark, of course, photosynthesis cannot occur. Then the guard cells lose water. The loss of water causes the guard cells to become limp, closing the stomata. When the stomata are closed, CO_2 does not enter the leaf, and water vapor does not leave. Since photosynthesis does not occur at night, there is not need for CO_2. The closed stomata conserve water. *Note: Once in the leaf, some of the water is used for photosynthesis. Some is used in other metabolic processes. Most of the water evaporates through the stomata into the atmosphere. The evaporation of water from leaves is called transpiration.*

Many people wonder if the tissues of the leaf carry out cellular respiration as well as photosynthesis. They do. In respiration, sugars are broken down to provide energy (ATP) for the processes occurring in the plant. Leaves use the food they produce during photosynthesis for respiration. The cells of the leaf use some of the oxygen produced for respiration. Photosynthesis occurs only while it is light, while respiration continues around the clock.