Photosynthesis

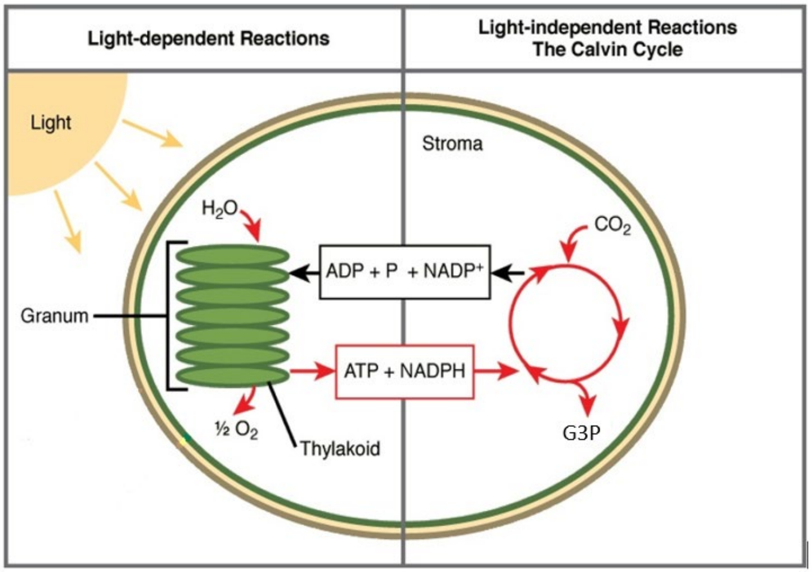
The vast majority of energy found within any ecosystem on Earth originates from the Sun itself and is transferred between organisms through complex food webs. Photosynthetic organisms such as plants and algae form the basis of these webs by converting sunlight, water, and carbon dioxide into usable energy. That energy can then be utilized by the photosynthetic organism, which itself may be consumed by other organisms for their own energy requirements. This handout will focus on explaining the steps involved in the most common version of photosynthesis, known as C_3 photosynthesis.

The purpose of the various anabolic redox reactions involved in photosynthesis is to generate a molecule of glyceraldehyde 3-phosphate (G3P), an important precursor to the carbohydrate glucose ($C_6H_{12}O_6$), a form of sugar, and other types of biomolecules. For every two G3P made, one molecule of glucose can be created.

The following equation and graphic provide a summary and general overview of the processes and reactants involved in photosynthesis:

Photosynthesis Equation			
Carbon dioxide +	Water $\xrightarrow{\text{SUNLIGHT}}$	Sugar +	Oxygen
$6CO_2$	$6H_2O$	$C_6H_{12}O_6$	$6O_2$

Source: OpenStax Biology. Download for free at http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.56



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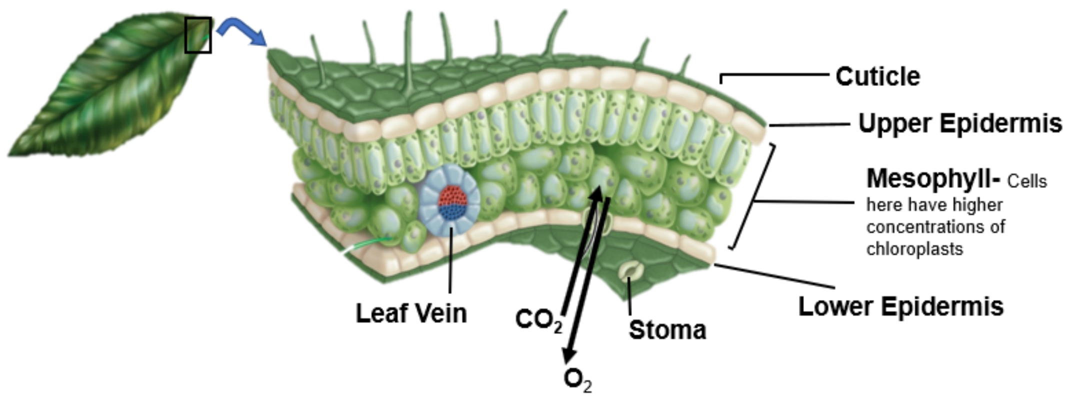
You can navigate to specific sections of this handout by clicking the links below.

Location of Photosynthesis

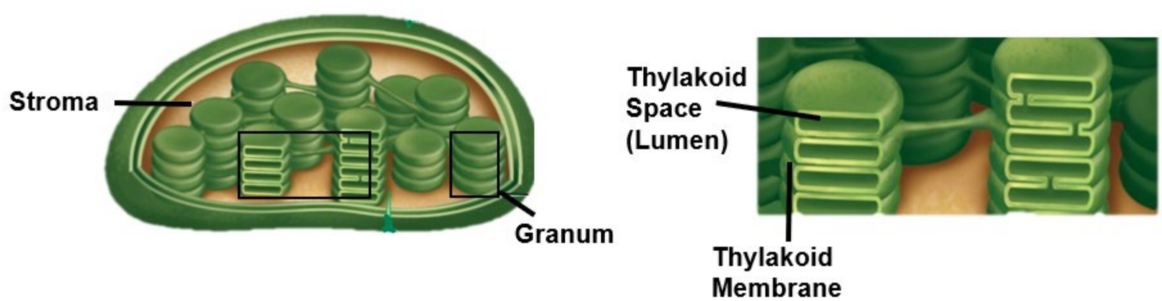
Photosynthesis occurs within specialized organelles called chloroplasts that are located in the cells of green plant tissues. As shown in the following graphic, chloroplasts are abundant within the mesophyll, a type of leaf tissue found in between layers of epidermis and a waxy cuticle that help to prevent the loss of water through evaporation. The stomata of each leaf allow for the diffusion of CO_2 and O_2 to and from chloroplasts through the protective epidermis and cuticle.



Source: Mader, S.S. & Windelspecht, M. (2016). Overview of photosynthesis. Biology (12th ed.). New York, NY: McGraw Hill Education.

Chloroplast Structure

Chloroplasts are membrane-bound organelles that are internally divided in a manner separating and facilitating the reactions required for photosynthesis. Inside each chloroplast, the light-dependent reactions take place in membrane-bound sacs called thylakoids. A stack of thylakoids may be referred to as a granum and multiple granum as grana. The internal space of each thylakoid is connected to adjacent thylakoids and may be referred to as either the thylakoid space or lumen. Surrounding the thylakoids is a fluid-filled space called the stroma, where light-independent reactions take place.

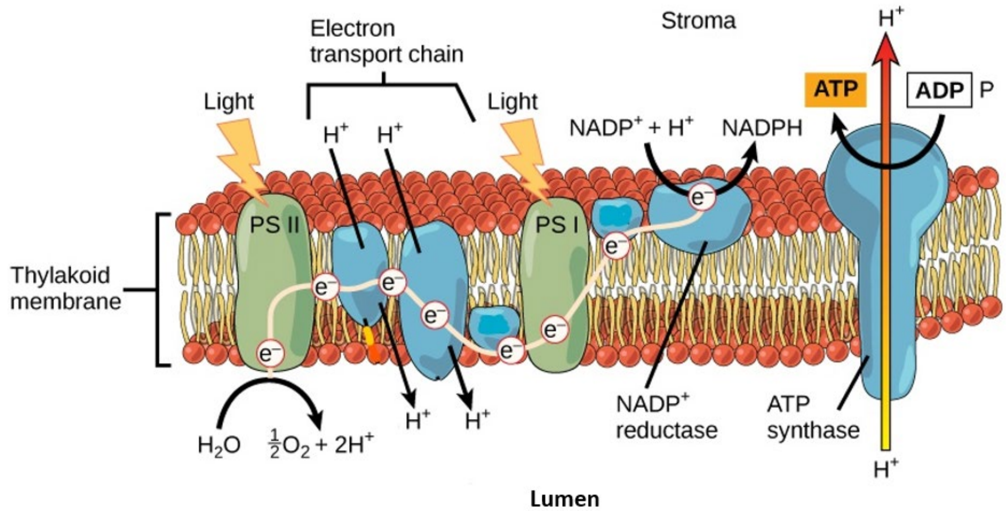


Source: Mader, S.S. & Windelspecht, M. (2016). Overview of photosynthesis. Biology (12th ed.). New York, NY: McGraw Hill Education.

Light-dependent Reactions

Reactions requiring the presence of light are known as photosystems and take place within the membrane of the thylakoids. This is where the various pigments that absorb energy from sunlight are located, usually some combination of chlorophylls and carotenoids. Photosystem II (PS II) is the initial phase of photosynthesis in which water molecules are broken down into hydrogen ions (H^+), electrons (e^-), and oxygen. The oxygen is released as a gas while the H^+ and e^- are retained. Then, e^- in Photosystem II enter a reaction center in the thylakoid membrane containing chlorophyll that captures energy from sunlight. The captured sunlight energy is absorbed by e^- in the reaction center, causing a jump to a high-energy state. This energy is then released in stages as the e^- travel through an ETC in the thylakoid membrane, causing H^+ from the stroma to be concentrated in the lumen as part of the process. As the e^- reaches the end of the ETC and moves on to be utilized in Photosystem I, the buildup of H^+ establishes a concentration gradient, thereby allowing chemiosmosis to take place through the enzyme ATP-synthase. As H^+ flow through the internal structure of the enzyme and back into the stroma, ADP is joined with phosphate, thus forming ATP. This ATP will be used later during the Calvin cycle.

The image below shows, from left to right, the paths taken by e^- and H^+ through both photosystems after being split from water.



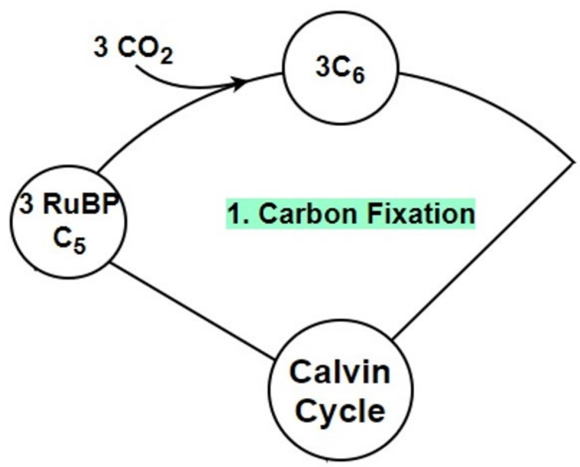
Source: OpenStax Biology. Download for free at http://cnx.org/contents/b3c1e1d2-839c-42b0-a314-e119a8aafbdd@8.56

Photosystem I (PS I) is the second phase of photosynthesis and begins with the e^- from Photosystem II entering another chlorophyll reaction center. The e^- are again energized by sunlight before moving from the reaction center to the enzyme NADP-reductase. There, the enzyme attaches the e^- from Photosystem I and H^+ from the stroma to the coenzyme $NADP^+$. With the addition of e^- and H^+, the $NADP^+$ is thereby reduced and becomes NADPH. With both photosystems now complete, the ATP and NADPH that were produced and positioned in the stroma are now ready to be used in the Calvin cycle.

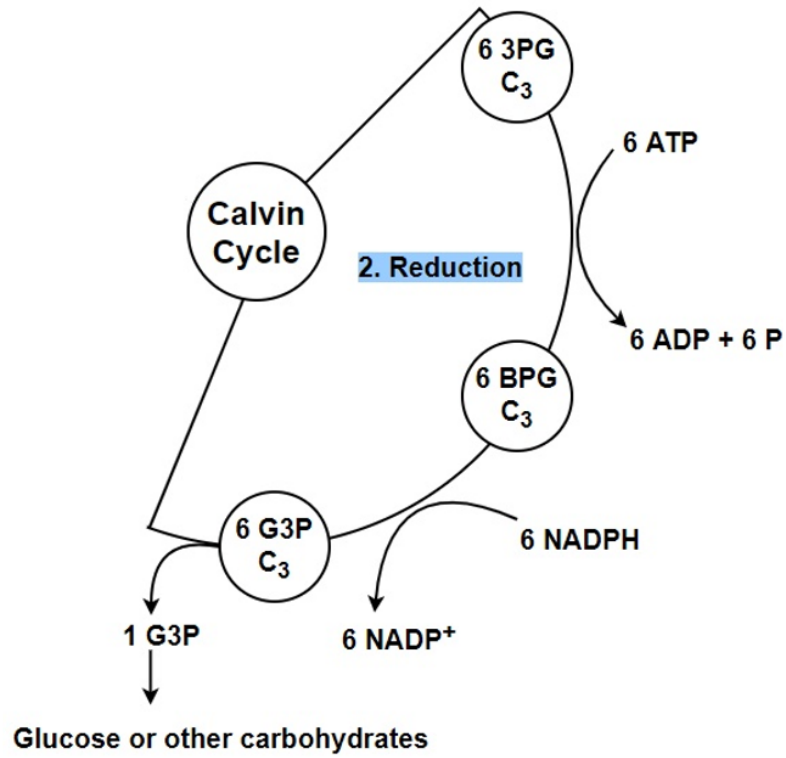
Light-independent Reactions (Calvin cycle)

The reactions of the Calvin cycle take place within the stroma and do not require sunlight. The Calvin cycle begins with the intake of atmospheric CO_2, to be combined with RuBP, forming the first in a series of metabolites that will eventually yield G3P. Each time the Calvin cycle is completed, one G3P molecule is retained for glucose production while the remaining five are converted into exactly enough RuBP to restart the cycle. The steps of the cycle may be broken down into the three phases listed below. Please note that C3, C5 and C6 refer to the number of carbon atoms present in each type of molecule during the Calvin cycle. For example, 3 RuBP C5 indicates that there are 3 RuBP molecules present, each containing 5 carbon atoms.

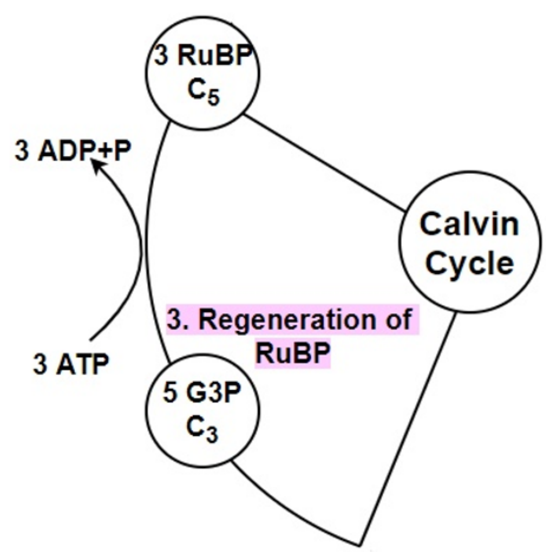
1. <u>Carbon Fixation</u>: As three molecules of CO_2 are brought into the stroma, three molecules of five-carbon RuBP are present. These will each be combined by the enzyme RubisCO. This results in three molecules of an unstable six-carbon intermediate metabolite that immediately break down into six three-carbon molecules of 3PG (3-PGA in some sources).

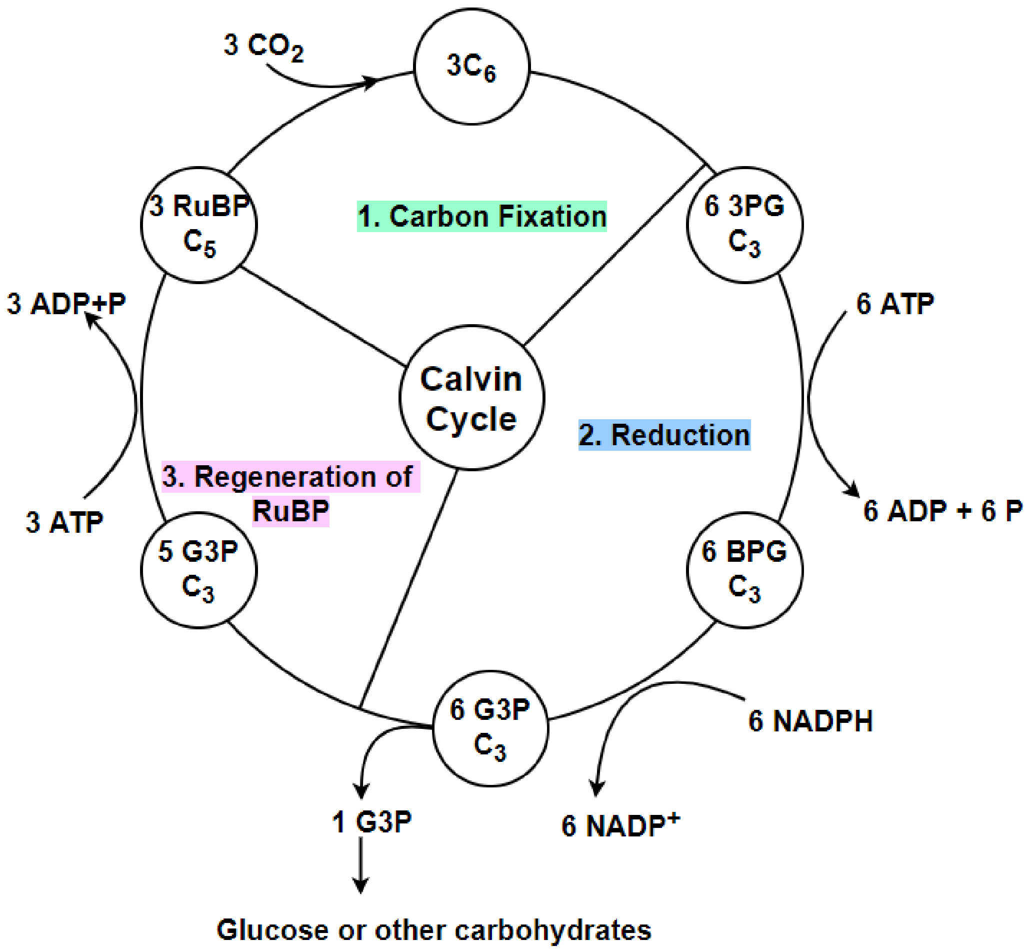


2. Reduction: Six molecules of ATP and NADPH, created earlier by the photosystems, are used to reduce the 3PG into six molecules of BPG, then into G3P. One molecule of G3P exits the cycle to be used in the production of glucose at the end of the reduction phase. The exit of this three-carbon molecule of G3P corresponds to the initial intake of the three carbon atoms contained within the three molecules of CO_2.



3. Regeneration: The remaining five molecules of G3P are converted back into RuBP by the application of three molecules of ATP. This results in exactly enough RuBP to restart the cycle.





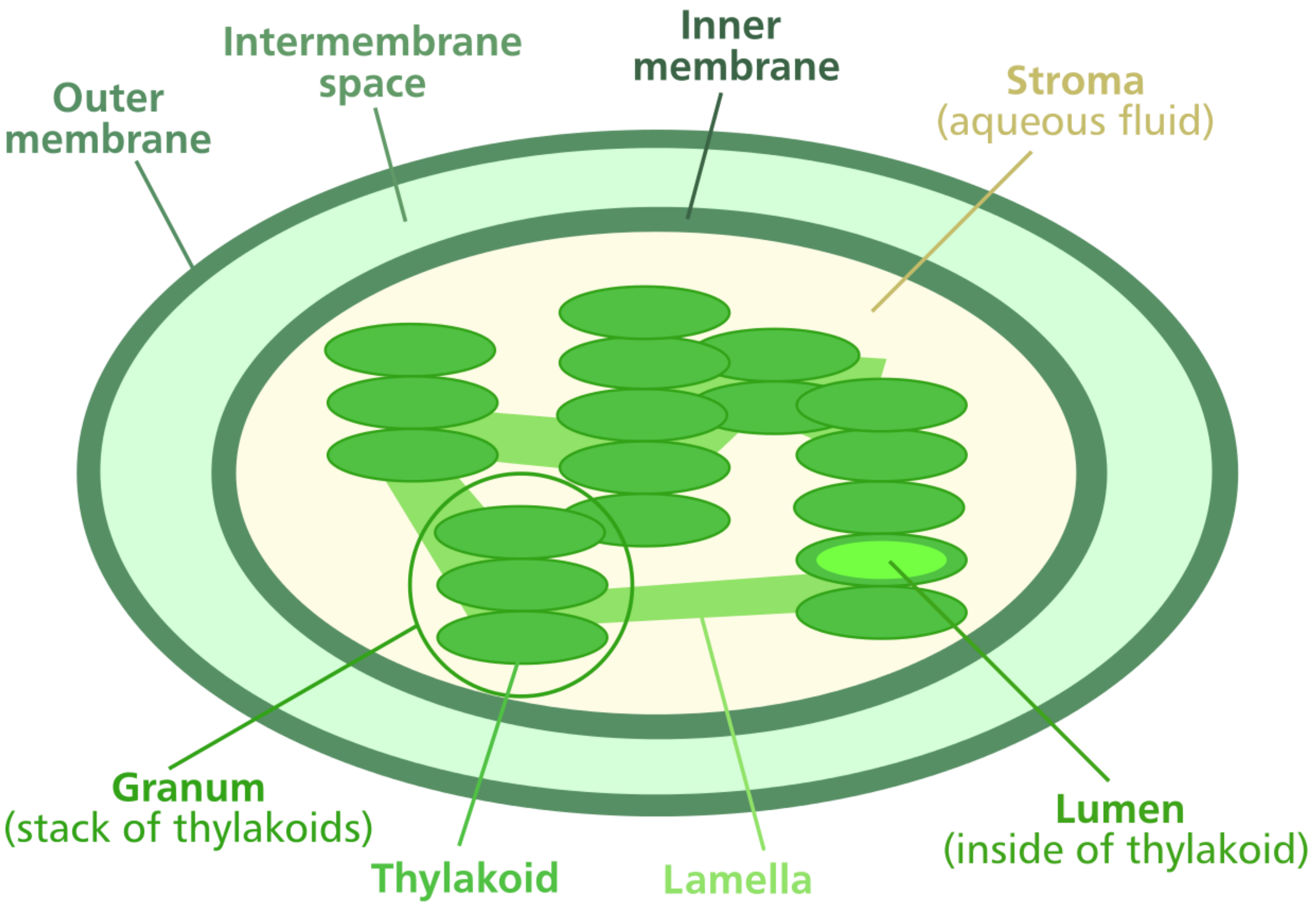
The Calvin cycle must be completed twice in order for enough G3P to be available to produce one molecule of the sugar glucose. Thus, this process satisfies the equation for photosynthesis stated at the beginning of this handout: $6CO_2 + 6H_2O + \text{Sunlight} = C_6H_{12}O_6 + 6O_2$.

Photosynthesis:

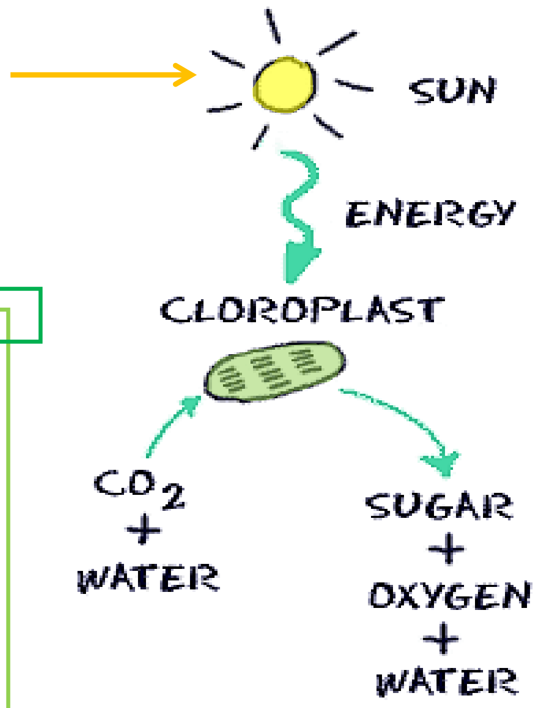
Photosynthesis is an autotrophic mode of nutrition by plants and some bacteria.

Photosynthesis is the physio-chemical process by which plants can convert light energy into chemical energy, in the form of carbohydrate from simple inorganic substances like atmospheric carbon dioxide and water

Structure of chloroplast



Photosynthesis is the process that converts solar energy into chemical energy that is used by biological systems (that means us).



Photosynthesis has 3 major events:

1. Sunlight is converted into chemical energy
2. Water (H_2O) is split into oxygen (O_2)
3. Carbon dioxide (CO_2) is fixed into sugars ($C_6H_{12}O_6$)

The photosynthesis reaction:

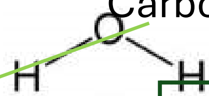
$6\ CO_2$ 6 Carbon dioxide molecules + **$12\ H_2O$** 12 Water molecules + **sunlight** → **$C_6H_{12}O_6$** 1 Sugar (glucose) molecule + **$6\ H_2O$** 6 Water molecules + **$6\ O_2$** 6 Oxygen molecules

Each atom's movement can be traced through the photosynthesis reaction.

A carbon dioxide molecule has 1 carbon and 2 oxygen atoms.

O=C=O

A water molecule has 2 hydrogen and 1 oxygen atoms



6 **C** 12.01	1 **H** 1.008	8 **O** 16.00
Carbon	Hydrogen	Oxygen

One molecule of glucose (sugar) has 6 carbon, 12 hydrogen and 6 oxygen atoms.

The sunlight provides the energy for the reaction.

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

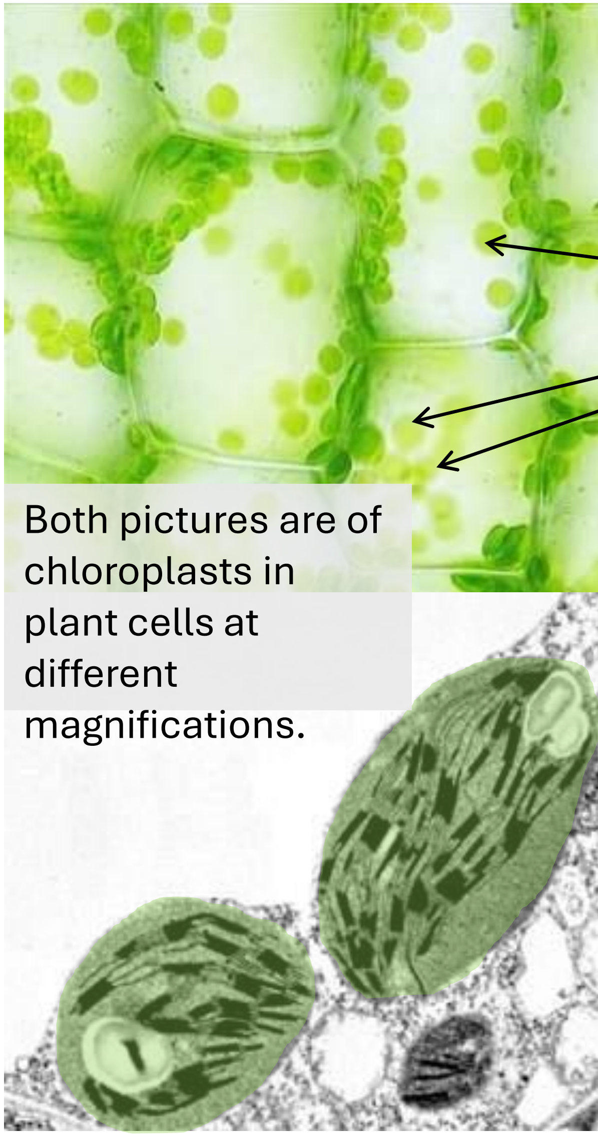
If 12 water molecules are used there are 24 hydrogen atoms (12 x 2 = 24) and 12 oxygen atoms total.

If 6 carbon dioxide molecules are used there are 6 carbon atoms and 12 oxygen atoms total (6 x 2 = 12).

Before		After
6 carbon atoms 12 oxygen atoms 24 hydrogen atoms 12 oxygen atoms		6 carbon atoms 12 hydrogen atoms 6 oxygen atoms 12 hydrogen atoms 6 oxygen atoms 12 oxygen atoms
6 oxygen atoms 24 oxygen atoms 24 hydrogen atoms	=	6 oxygen atoms 24 oxygen atoms 24 hydrogen atoms

If you count every atom before and after the reaction they are balanced.

Through evolution, plant cells, certain bacteria and some algae have acquired chloroplasts to help carry out the photosynthetic reaction.
Chloroplasts are a plastid or plant cell organelle.

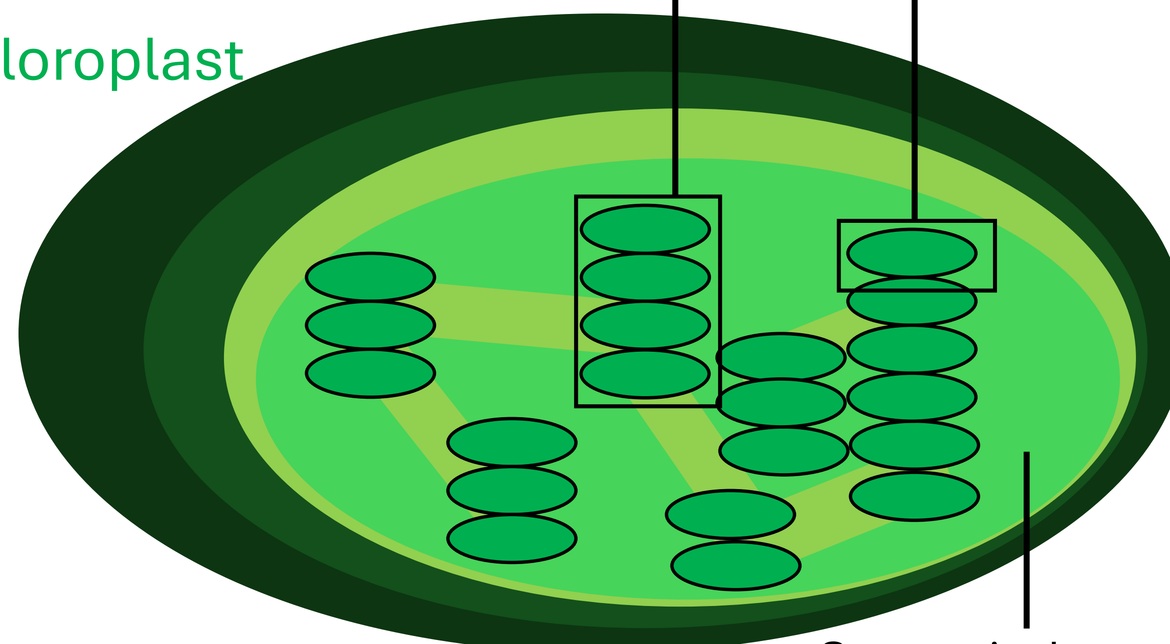


Both pictures are of chloroplasts in plant cells at different magnifications.

Chloroplasts are full of round flattened discs called **thylakoids**.

A stack of thylakoids is called a **granum**.

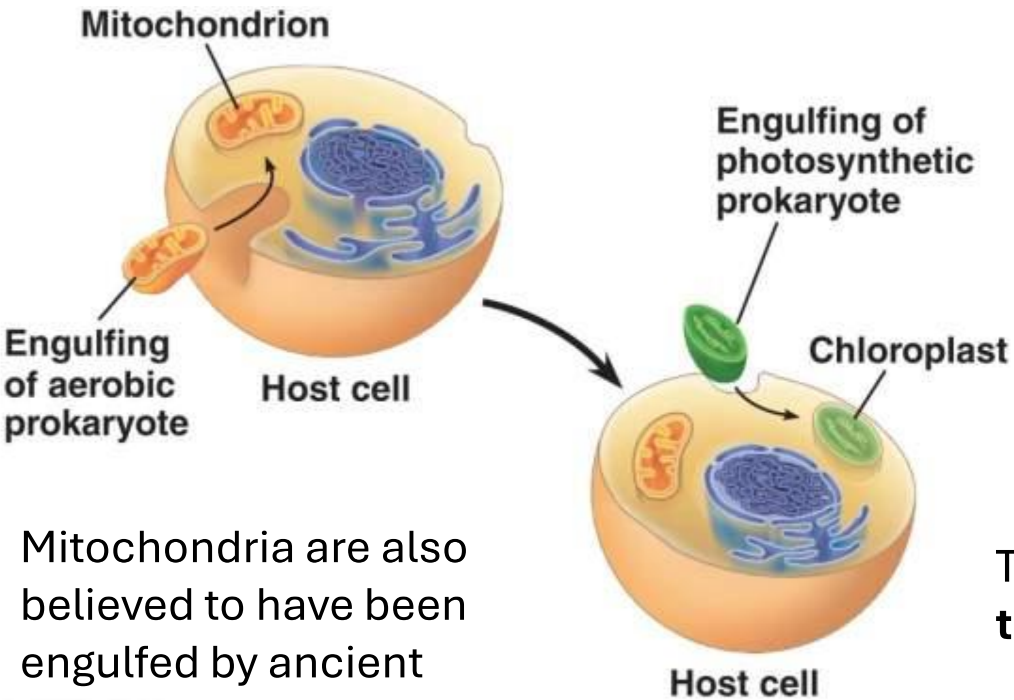
Chloroplast



Stroma is the space inside chloroplasts

Chloroplasts are where photosynthesis occurs.

Where did chloroplasts come from?

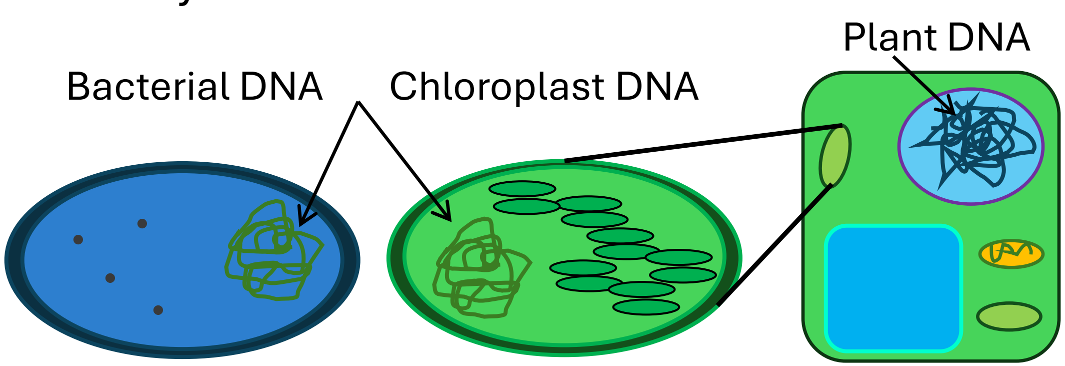


A very long time ago, plant cells were once ancient eukaryotic cells that had enveloped a cyanobacteria. Eventually, the cyanobacteria became a part of the cell and dependent upon it for life which in turn gave the cell the ability to photosynthesize.

Mitochondria are also believed to have been engulfed by ancient eukaryotic cells through endosymbiosis.

This is called the **endosymbiotic theory**.

(*endo* = inside)



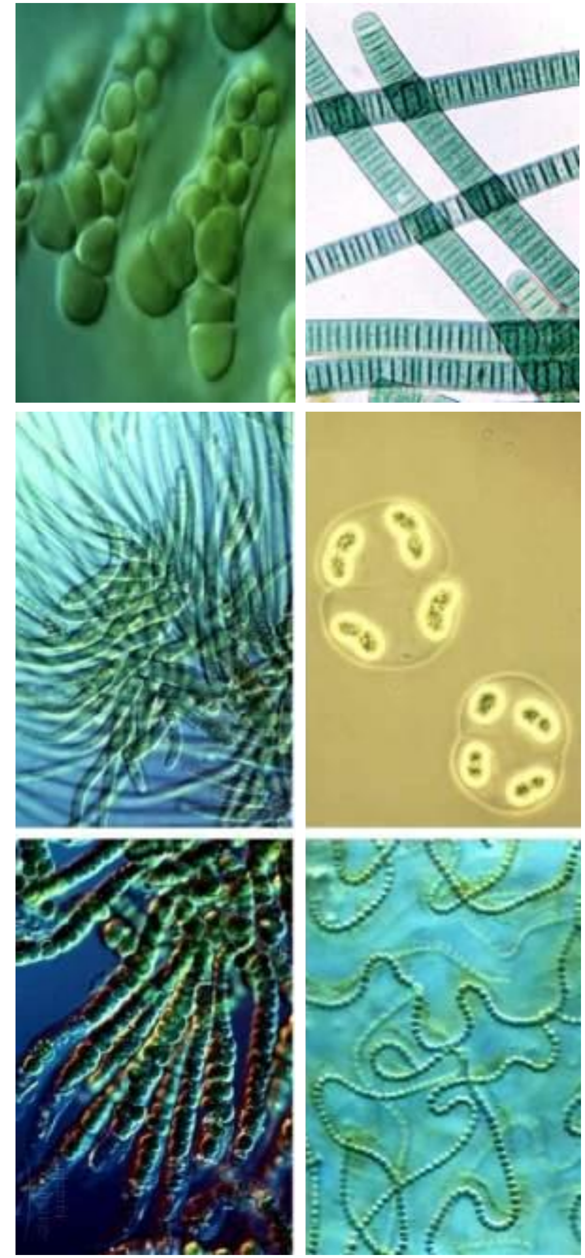
There are many reasons why scientists believe this theory. One is that chloroplasts have their own DNA that is different from plant DNA but similar to bacterial DNA.

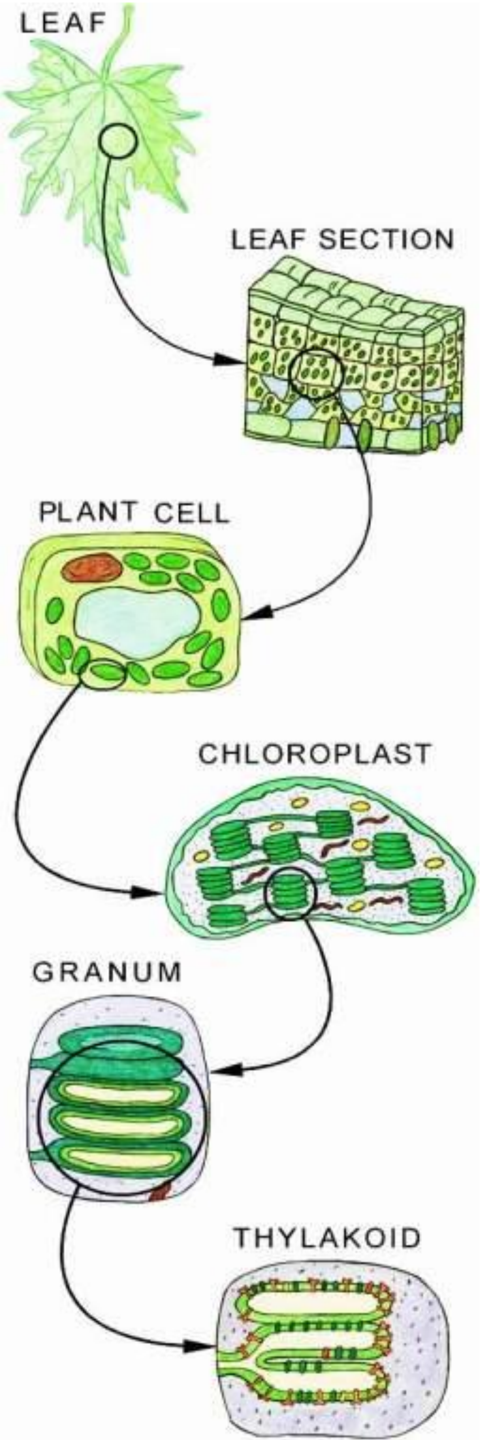
Cyanobacteria Today

Cyan comes from the Greek word *cyanin* which means aqua colored.

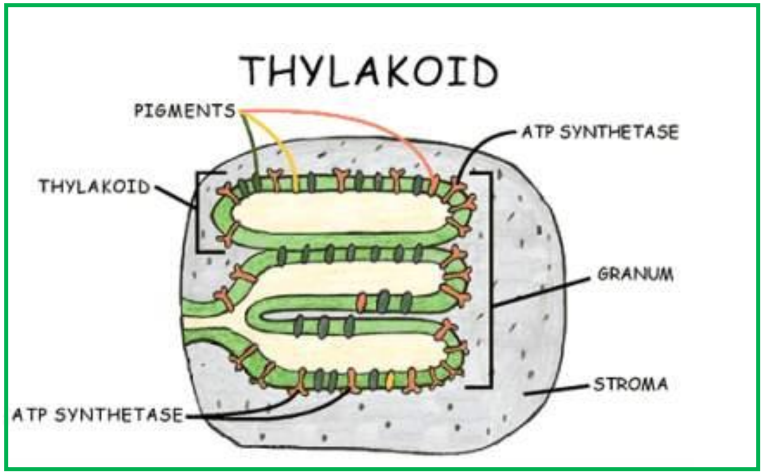
Not all bacteria that undergo photosynthesis are cyanobacteria, but all cyanobacteria are photosynthetic bacteria e.g. purple bacteria are not cyanobacteria but were the first bacteria discovered that can photosynthesize.

Cyanobacteria undergo photosynthesis in lakes, ponds, and oceans.





Photosynthesis in plants happens in the chloroplasts. Chloroplasts are full of **thylakoids** stacked in **granum**.

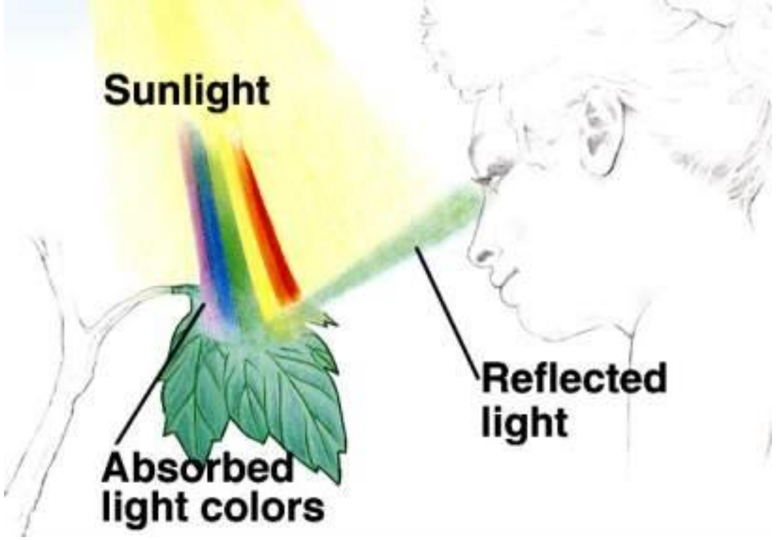


The thylakoid membranes are lined by pigments such as chlorophyll and cartenoids.

Chlorophyll is a green pigment and is the most abundant.

Chlorophyll absorbs all wavelength colors except green, which is reflected off giving plants their green appearance.

These pigments harvest light energy packets or **photons** when they absorb sunlight.



The Photosynthesis Reaction is divided into two parts:

Light Reactions

Light reactions or "light dependent reactions" capture light energy to power photosynthesis.
Light reactions occur during the day time.

They take place in the **thylakoids**.

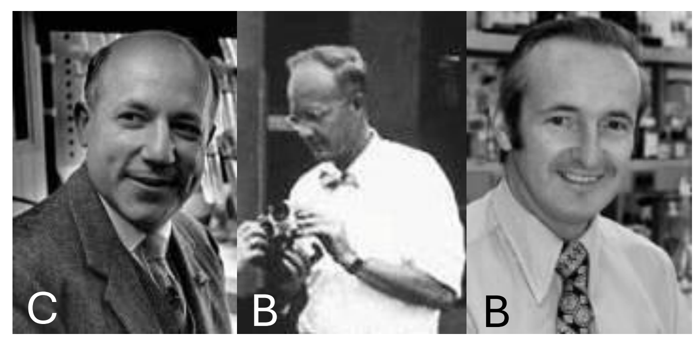
Pigments in the thylakoid membranes form protein complexes called **Photosystem I** and **Photosystem II**.

These photosystems harvest photons to charge up energy carrying molecules that will power the dark reactions.

Dark

Dark reactions or "light independent reactions" do not need light energy to power their reactions and can occur day or night.

Discovered by three scientists, the dark reactions are also called the Calvin-Bensen-Bassham cycle or just **Calvin Cycle**.



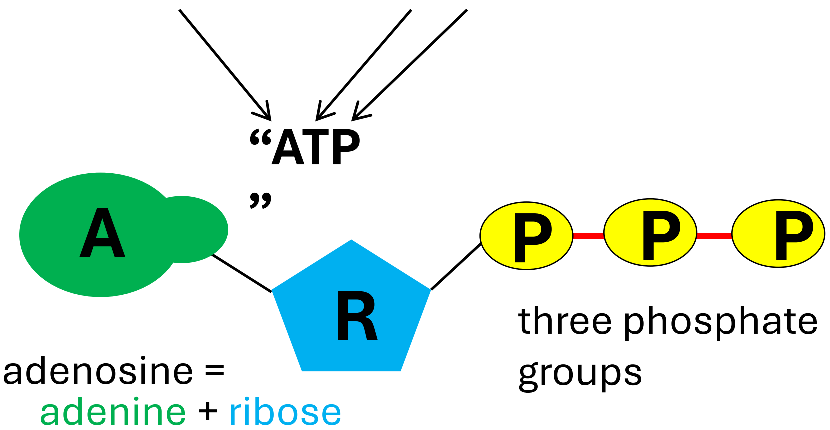
Dark reactions occur in the **stroma** of chloroplasts (the space that surrounds thylakoids) and fix carbon dioxide into glucose.

Energy Carrying Molecules: **ATP** & **NADP+**

Both are energy carrier molecules used in photosynthesis and cellular respiration.

NADP+ can hold excited electrons (e^-) charged from the light energy harvested by chlorophyll to become NADPH. Eventually, NADPH passes the electron it's holding to power the dark reactions and reverts back to NADP+.

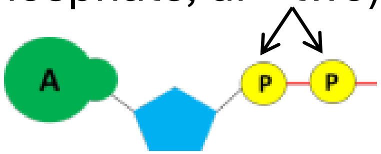
adenosine triphosphate



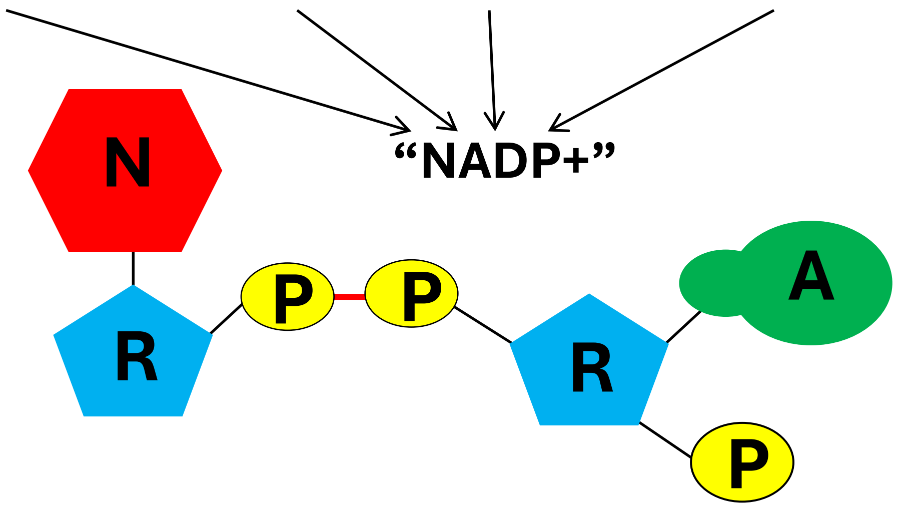
ATP is called the "cellular currency" because it is used to power all the reactions that take place in the cells of all living things.

When ATP's third phosphate is broken off it releases energy that the cell can use.

ATP is made when a third phosphate group is added to ADP (diphosphate, di = two).

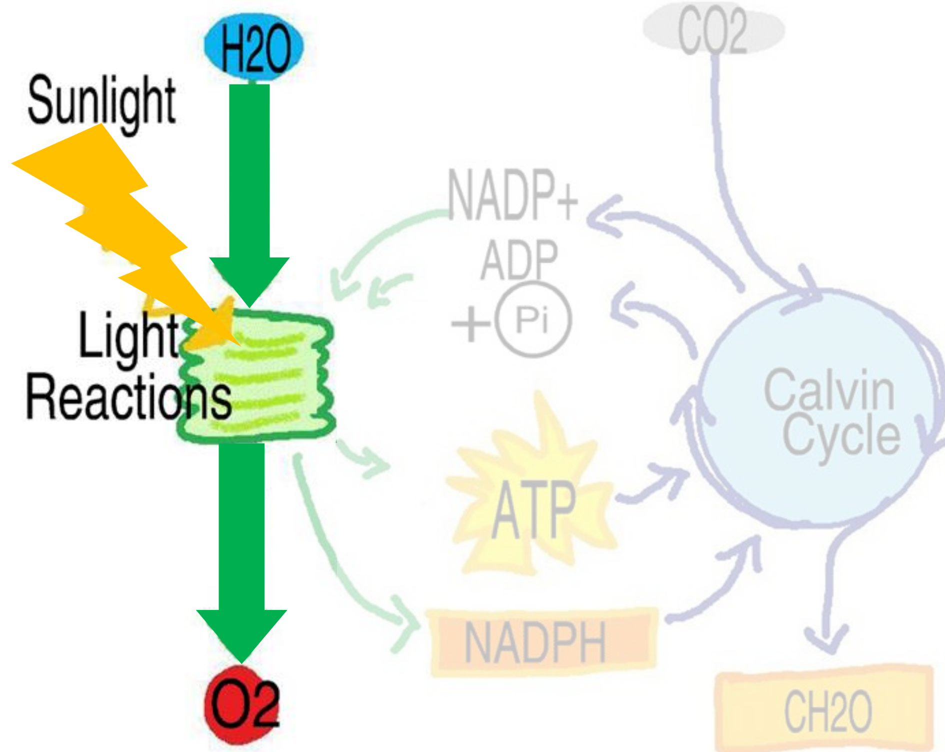


nicotinamide adenine dinucleotide phosphate



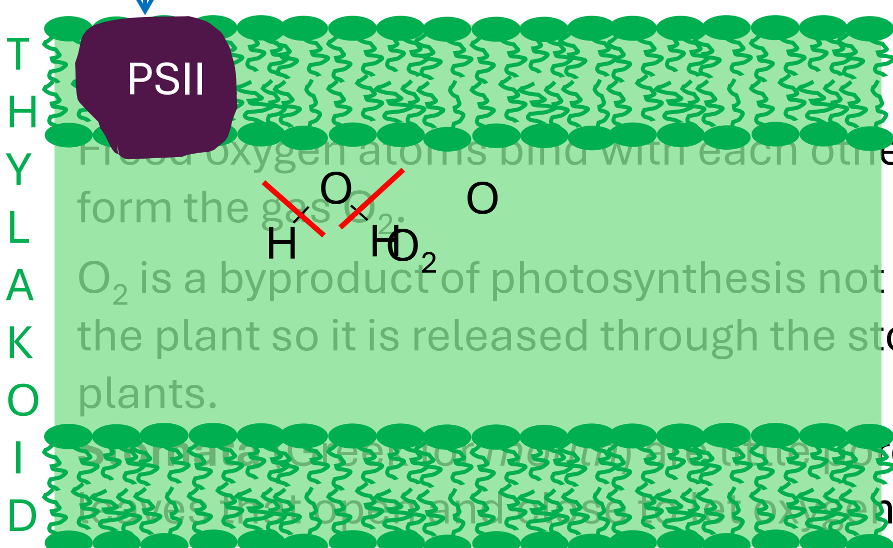
NADP is a very complex molecule, this is a simplification.

Light Reactions



The energy absorbed by the chlorophyll during the light reactions is used to power **photosystem II** that breaks the bonds of water absorbed through the plant's roots.

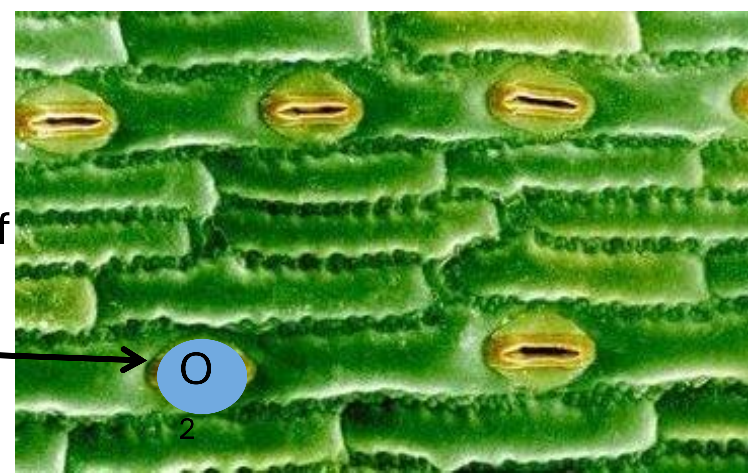
Photosystem II



Freed oxygen atoms bind with each other to form the gas O_2.

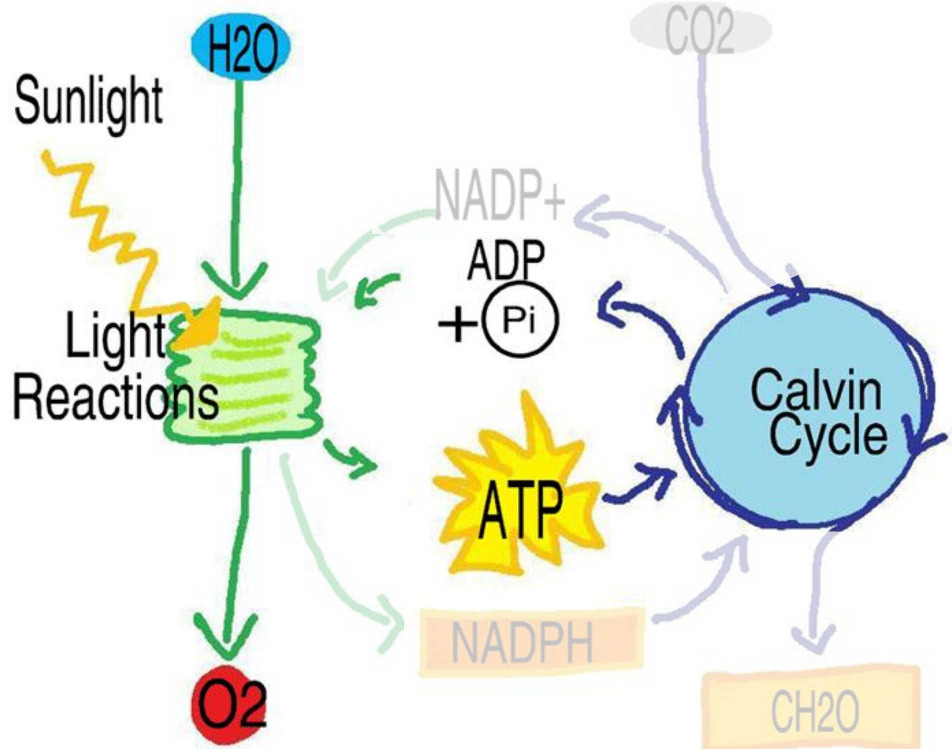
O_2 is a byproduct of photosynthesis not used by the plant so it is released through the stomata of plants.

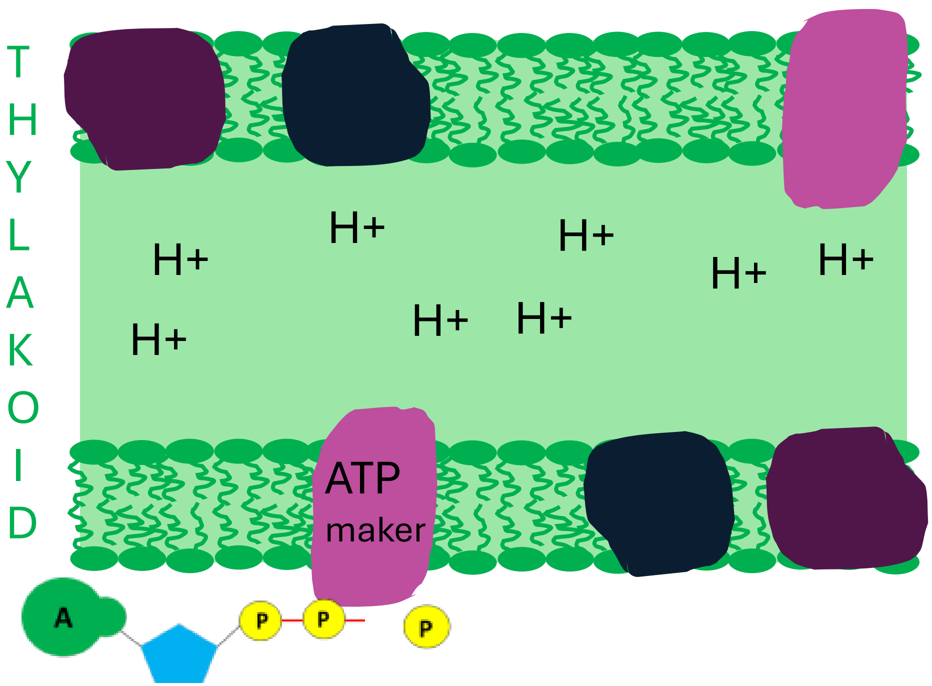
Stomata (Greek for *mouth*) are little pores in leaves that open and close to let oxygen out and carbon dioxide in.



Light Reactions

When water molecules break apart, the remaining two hydrogen atoms have a positive charge and are called **protons**. These protons are kept inside the thylakoid by the thylakoid membrane.





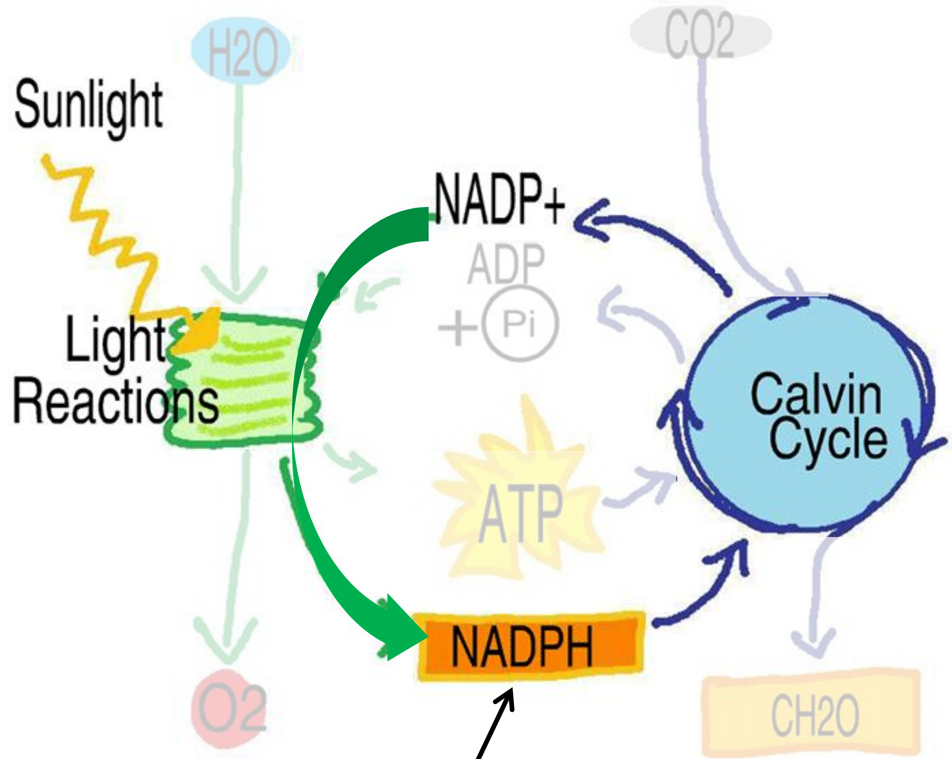
When there are more protons inside the thylakoid than in the stroma outside, protons want to leave the crowded thylakoid.

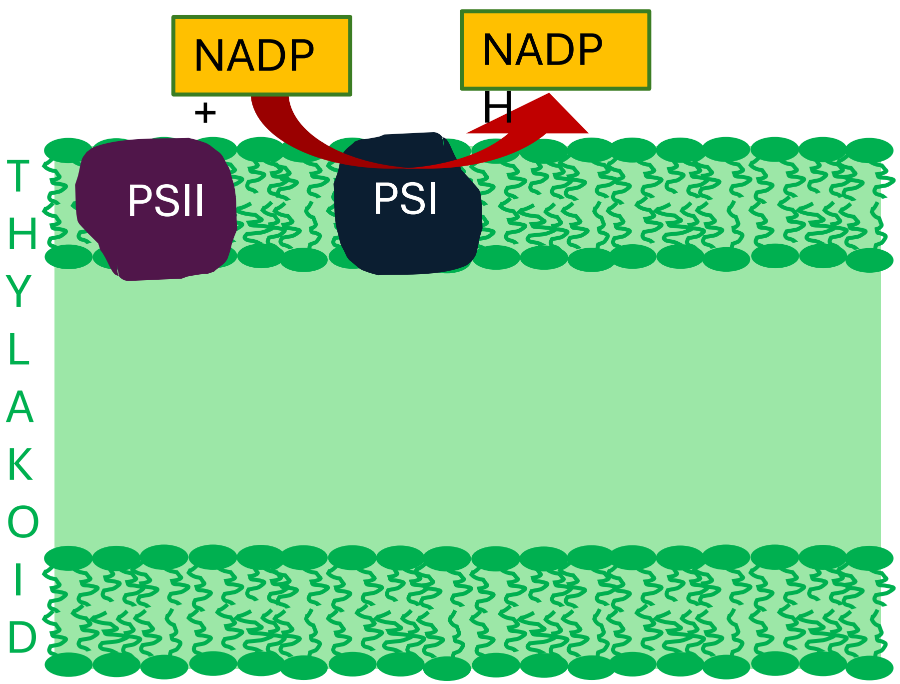
When the protons (H+) cross the membrane to leave, a protein uses their passage to power ATP production.

The protein **ATP synthase** attaches a phosphate group to ADP (D = *di* or two) making it ATP (T = *tri* or three).

Light Reactions

The light energy absorbed by chlorophyll also powers **photosystem I** that charges up the energy carrier molecule NADP+ into NADPH.





NADPH then carries its energy over to power the dark reactions or Calvin Cycle.

Light Reactions Summary

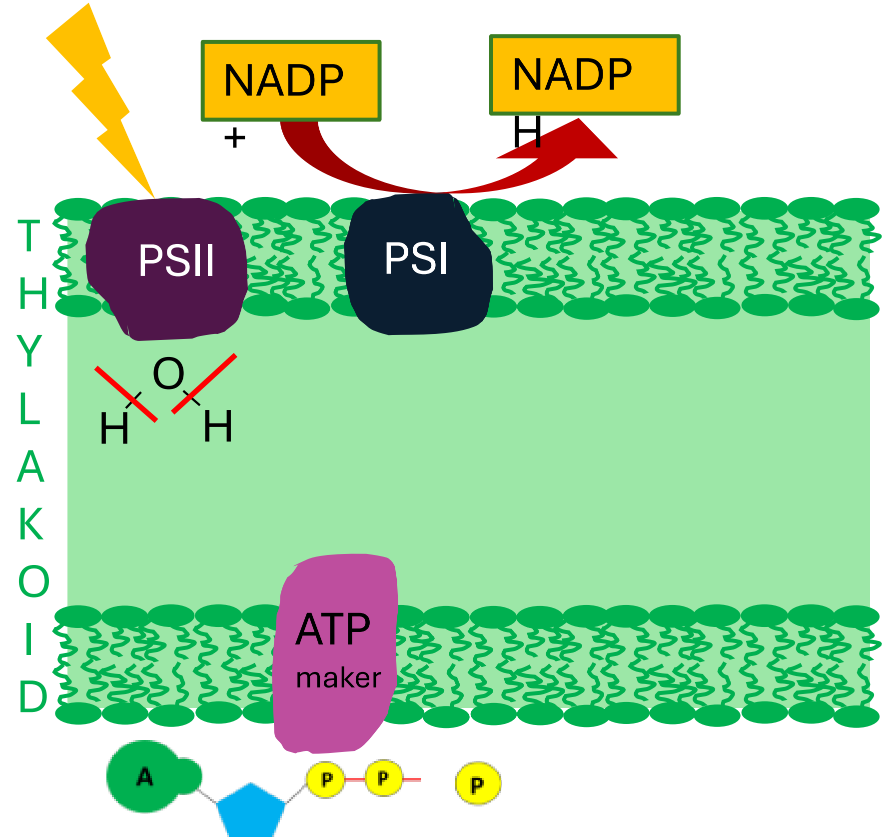
Photons are absorbed by the pigments to power photosystem I and photosystem II.

Photosystem II splits water molecules into two protons (H+) and oxygen atoms are expelled as O_2 gas through the stomata.

Protons cross the thylakoid membrane and power protein complex **ATP synthase** to make ATP.

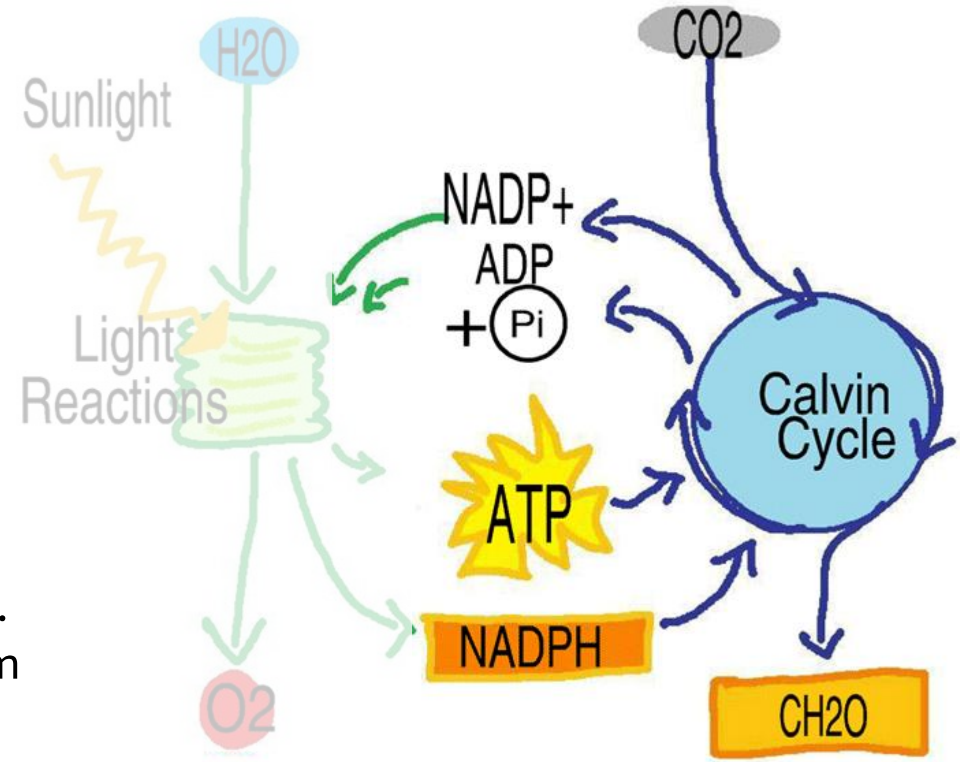
NADP+ is powered up by **photosystem I** to make NADPH to be used in the dark reactions.

Light dependent reactions finish with charged NADPH, ATP, and released O_2.

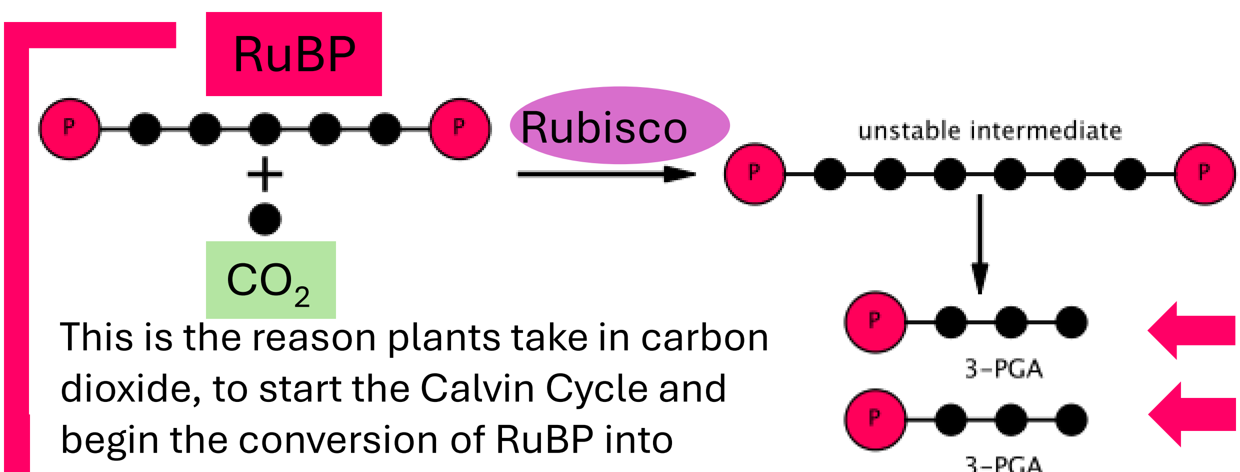


Dark Reaction

Also called the Calvin Cycle, the dark reactions start and end with the same products hence “cycle”.
All the dark reactions take place in the **stroma** of the chloroplast.



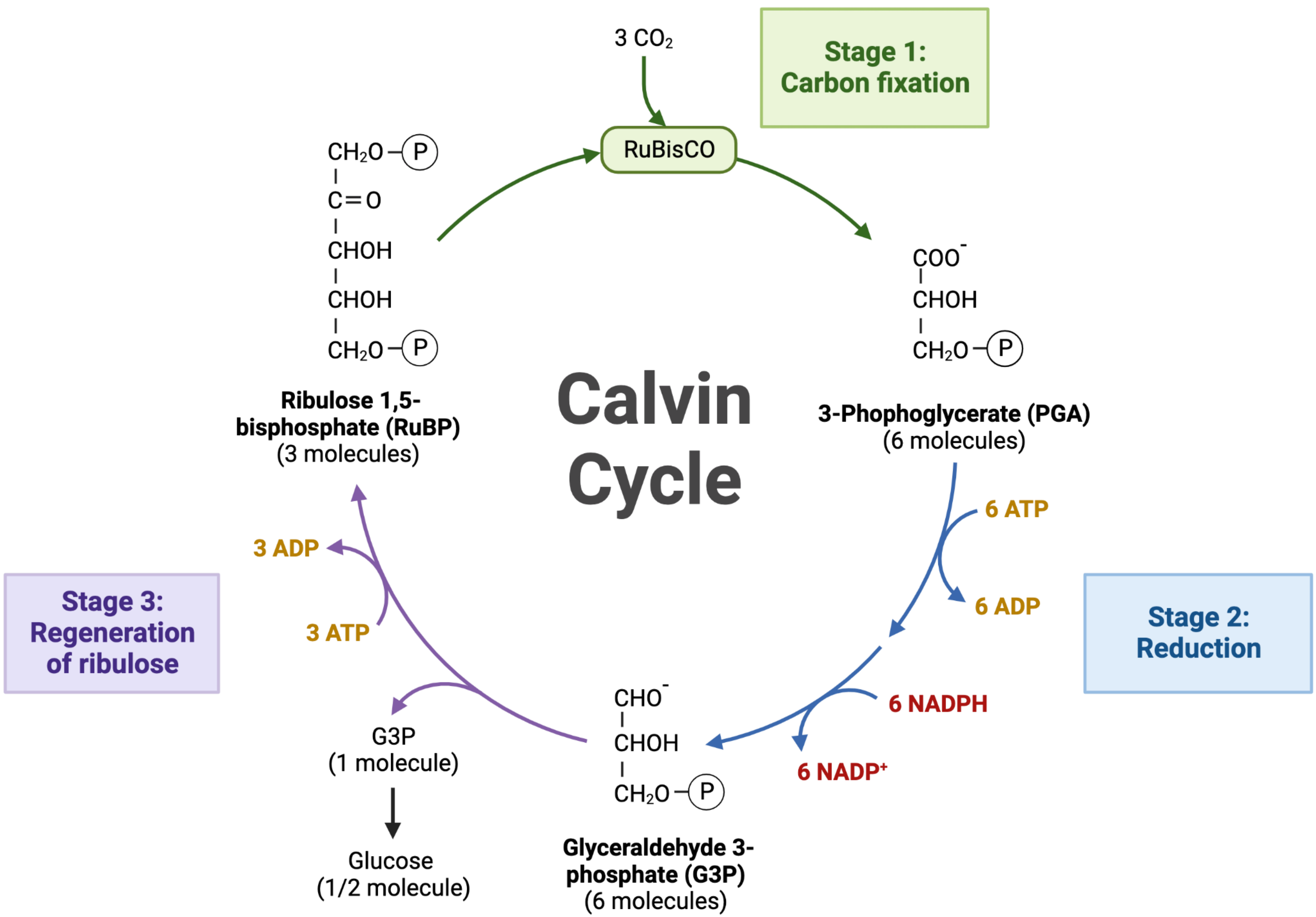
The Calvin Cycle starts with RuBP molecules and carbon dioxide molecules. An enzyme called Rubisco combines them into an unstable intermediate.



This is the reason plants take in carbon dioxide, to start the Calvin Cycle and begin the conversion of RuBP into glucose.

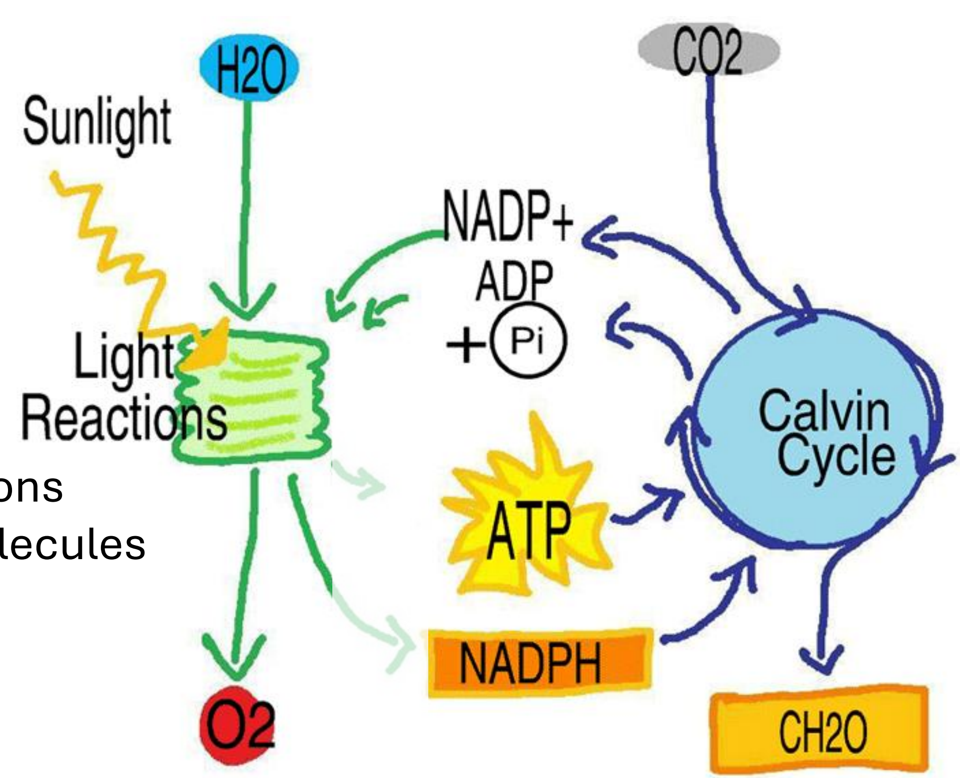
RuBP is the starting molecule and ending molecule of the Calvin Cycle. It will be remade at the end of the cycle so that the cycle can begin again.

Since the intermediate of combined RuBP and CO_2 is unstable it quickly splits in half and forms 2 molecules of 3-PGA which are stable.

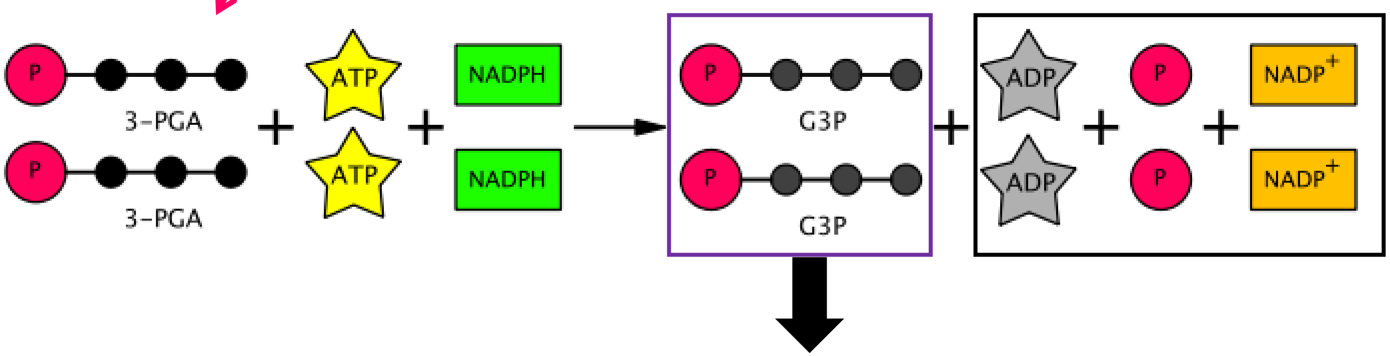


3 CO2
Stage 1:
Carbon fixation
RuBisCO
CH2O—P
C=O
CHOH
CHOH
CH2O—P
Ribulose 1,5-bisphosphate (RuBP)
(3 molecules)
Calvin Cycle
COO-
CHOH
CH2O—P
3-Phophoglycerate (PGA)
(6 molecules)
6 ATP
6 ADP
Stage 2:
Reduction
6 NADPH
6 NADP+
3 ADP
3 ATP
Stage 3:
Regeneration of ribulose
CHO-
CHOH
CH2O—P
Glyceraldehyde 3-phosphate (G3P)
(6 molecules)
G3P
(1 molecule)
Glucose
(1/2 molecule)

Dark Reactions

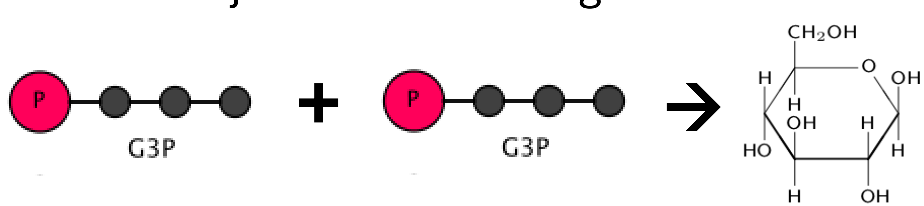


The ATP and NADPH from the light reactions provide the energy to convert the two molecules of 3-PGA into their final form.



The left overs are reused in the light reactions to remake ATP and NADPH.

2 G3P are joined to make a glucose molecule.

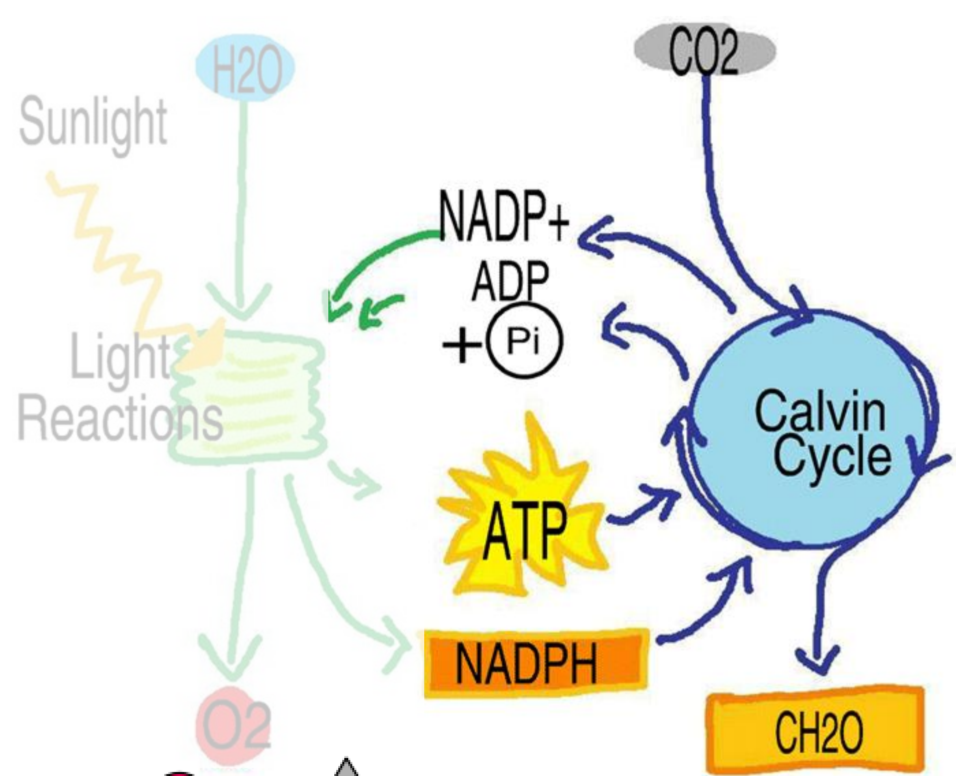


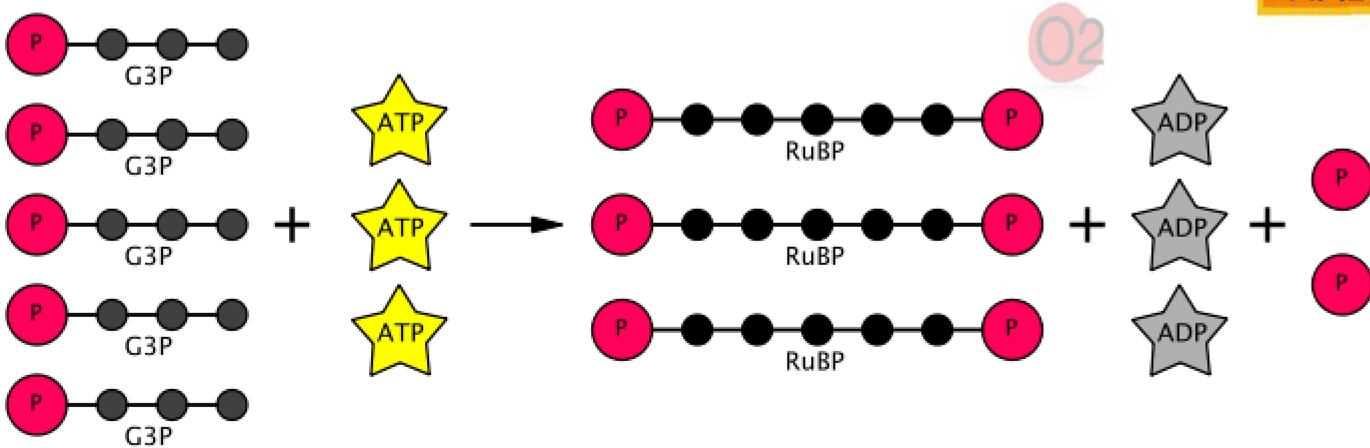
Dark Reactions

Not all G3P is made into glucose.

The Calvin Cycle occurs in every stroma in every chloroplast in every plant cell every second of every day.

That's a lot of reactions all happening simultaneously!





Most of the G3P made during the Calvin Cycle are made into RuBP, the starting molecule, with energy from ATP molecules.
Now the Calvin Cycle can begin again.

The spent ATP from the reaction leaves ADP and a phosphate group. These are reused in the light reactions to make more ATP.

Dark Reactions Summary

Chloropla
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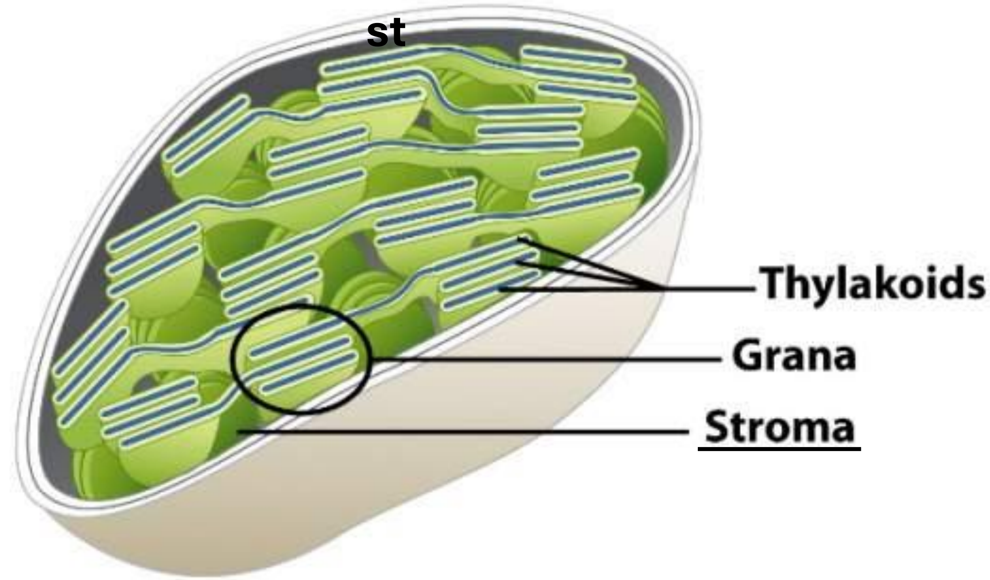

The Calvin Cycle converts the carbon from carbon dioxide into glucose in the stroma. This is called **carbon fixation** because carbon is fixed into another form.

Photosynthesis is carried out in two steps. First, in two light dependent photosystems. Second, in a light independent carbon fixation cycle called the Calvin Cycle. Through this process, the plant is able to convert sunlight, water, and CO_2 into glucose (or sugar) and ATP. As a byproduct of this process, O_2 is released.