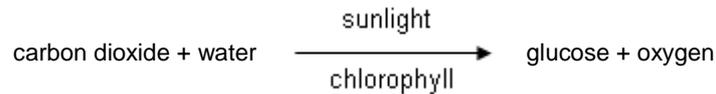


# Photosynthesis

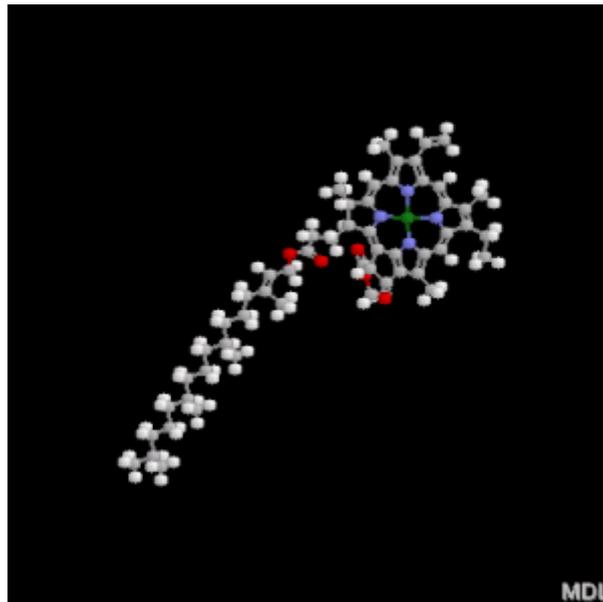
**Photosynthesis** is the process by which plants, some bacteria and some protists use the energy from sunlight to produce glucose from carbon dioxide and water. This glucose can be converted into pyruvate which releases adenosine triphosphate (ATP) by cellular respiration. Oxygen is also formed.

Photosynthesis may be summarised by the word equation:



The conversion of usable sunlight energy into chemical energy is associated with the action of the green pigment chlorophyll.

Chlorophyll is a complex molecule. Several modifications of chlorophyll occur among plants and other photosynthetic organisms. All photosynthetic organisms have chlorophyll a. Accessory pigments absorb energy that chlorophyll a does not absorb. Accessory pigments include chlorophyll b (also c, d, and e in algae and protists), xanthophylls, and carotenoids (such as beta-carotene). Chlorophyll a absorbs its energy from the violet-blue and reddish orange-red wavelengths, and little from the intermediate (green-yellow-orange) wavelengths.



*Chlorophyll*

All chlorophylls have:

- a lipid-soluble hydrocarbon tail ( $C_{20}H_{39}$  -)
- a flat hydrophilic head with a magnesium ion at its centre; different chlorophylls have different side-groups on the head

The tail and head are linked by an ester bond.

## Leaves and leaf structure

Plants are the only photosynthetic organisms to have leaves (and not all plants have leaves). A leaf may be viewed as a solar collector crammed full of photosynthetic cells.

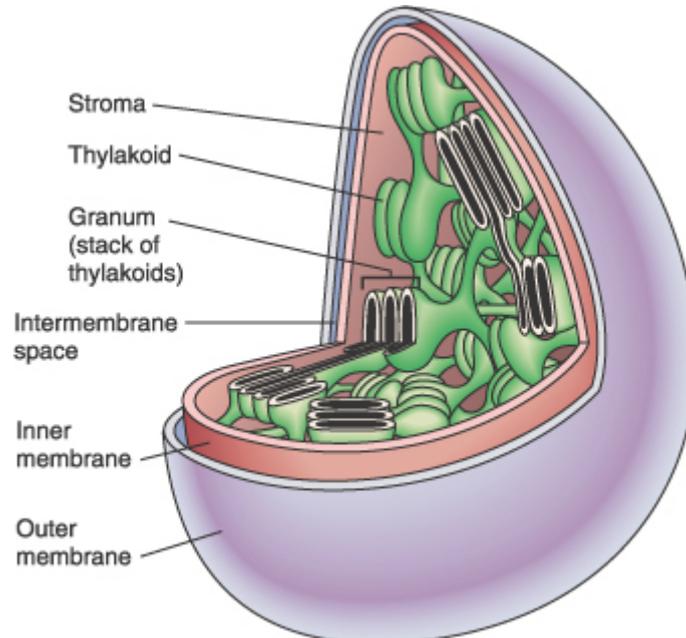
The raw materials of photosynthesis, water and carbon dioxide, enter the cells of the leaf, and the products of photosynthesis, sugar and oxygen, leave the leaf.

Water enters the root and is transported up to the leaves through specialized plant cells known as xylem vessels. Land plants must guard against drying out and so have evolved specialized structures known as **stomata** to allow gas to enter and leave the leaf. Carbon dioxide cannot pass through the protective waxy layer covering the leaf (**cuticle**), but it can enter the leaf through the **stoma** (the singular of stomata), flanked by two guard cells. Likewise, oxygen produced during photosynthesis can only pass out of the leaf through the opened stomata. Unfortunately for the plant, while these gases are moving between the inside and outside of the leaf, a great deal of water is also lost. Cottonwood trees, for example, will lose 100 gallons (about 450 dm<sup>3</sup>) of water per hour during hot desert days.

## The structure of the chloroplast and photosynthetic membranes

The thylakoid is the structural unit of photosynthesis. Both photosynthetic prokaryotes and eukaryotes have these flattened sacs/vesicles containing photosynthetic chemicals. Only eukaryotes have chloroplasts with a surrounding membrane.

Thylakoids are stacked like pancakes in stacks known collectively as grana. The areas between grana are referred to as stroma. While the mitochondrion has two membrane systems, the chloroplast has three, forming three compartments.



*Structure of a chloroplast*

## Stages of photosynthesis

When chlorophyll a absorbs light energy, an electron gains energy and is 'excited'. The excited electron is transferred to another molecule (called a primary electron acceptor). The chlorophyll molecule is oxidized (loss of electron) and has a positive charge. Photoactivation of chlorophyll a results in the splitting of water molecules and the transfer of energy to ATP and reduced nicotinamide adenine dinucleotide phosphate (NADP).

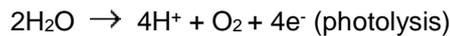
The chemical reactions involved include:

- condensation reactions - responsible for water molecules splitting out, including phosphorylation (the addition of a phosphate group to an organic compound)
- oxidation/reduction (redox) reactions involving electron transfer

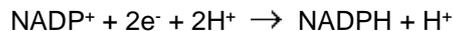
Photosynthesis is a two stage process.

The **light dependent reactions**, a light-dependent series of reactions which occur in the **grana**, and require the direct energy of light to make energy-carrier molecules that are used in the second process:

- light energy is trapped by chlorophyll to make ATP (photophosphorylation)
- at the same time water is split into oxygen, hydrogen ions and free electrons:



- the electrons then react with a carrier molecule nicotinamide adenine dinucleotide phosphate (NADP), changing it from its oxidised state (NADP<sup>+</sup>) to its reduced state (NADPH):



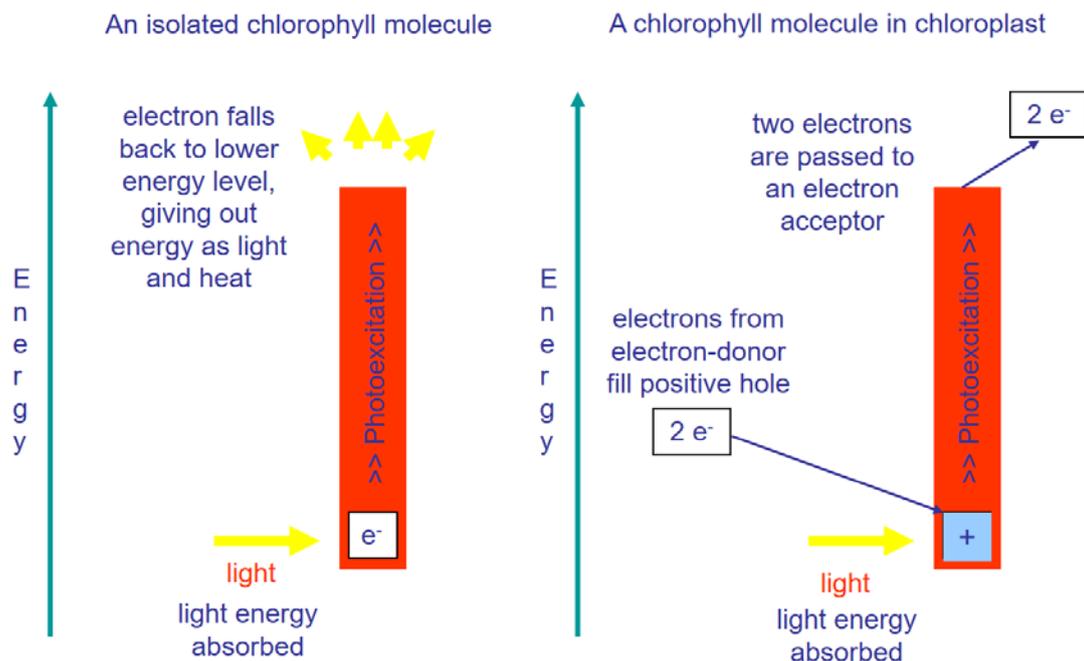
The **light-independent reactions**, a light-independent series of reactions which occur in the stroma of the chloroplasts, when the products of the light reaction, ATP and NADPH, are used to make carbohydrates from carbon dioxide (reduction); initially glyceraldehyde 3-phosphate (a 3-carbon atom molecule) is formed.

## The light-dependent reactions

When light energy is absorbed by a chlorophyll molecule its electrons gain energy and move to higher energy levels in the molecule (photoexcitation). Sufficient energy ionises the molecule, with the electron being 'freed' leaving a positively charged chlorophyll ion. This is called photoionisation.

In whole chloroplasts each chlorophyll molecule is associated with an **electron acceptor** and an **electron donor**. These three molecules make up the core of a **photosystem**. Two electrons from a photoionised chlorophyll molecule are transferred to the electron acceptor. The positively charged chlorophyll ion then takes a pair of electrons from a neighbouring electron donor such as water.

### The effect of light on chlorophyll



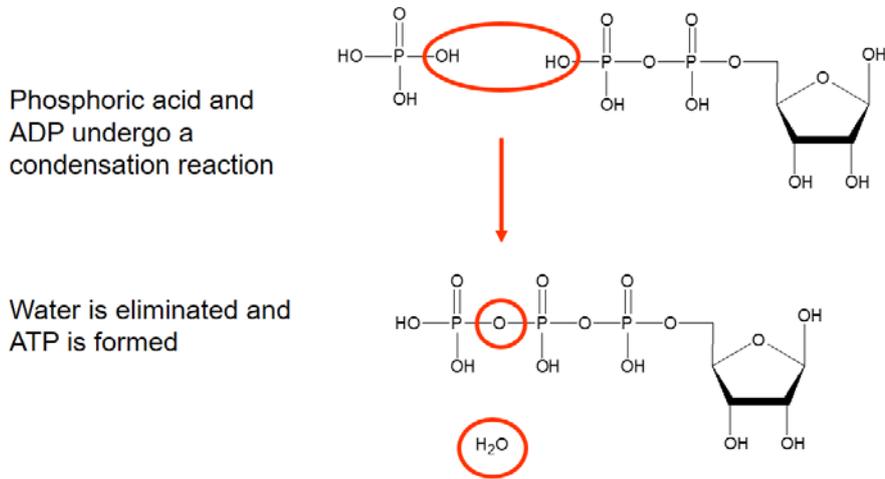
An electron transfer system (a series of chemical reactions) carries the two electrons to and fro across the thylakoid membrane. The energy to drive these processes comes from two photosystems:

- Photosystem II (PSII) (P680)
- Photosystem I (PSI) (P700)

It may seem confusing, but PSII occurs *before* PSI. It is named because it was the second to be discovered and hence named second.

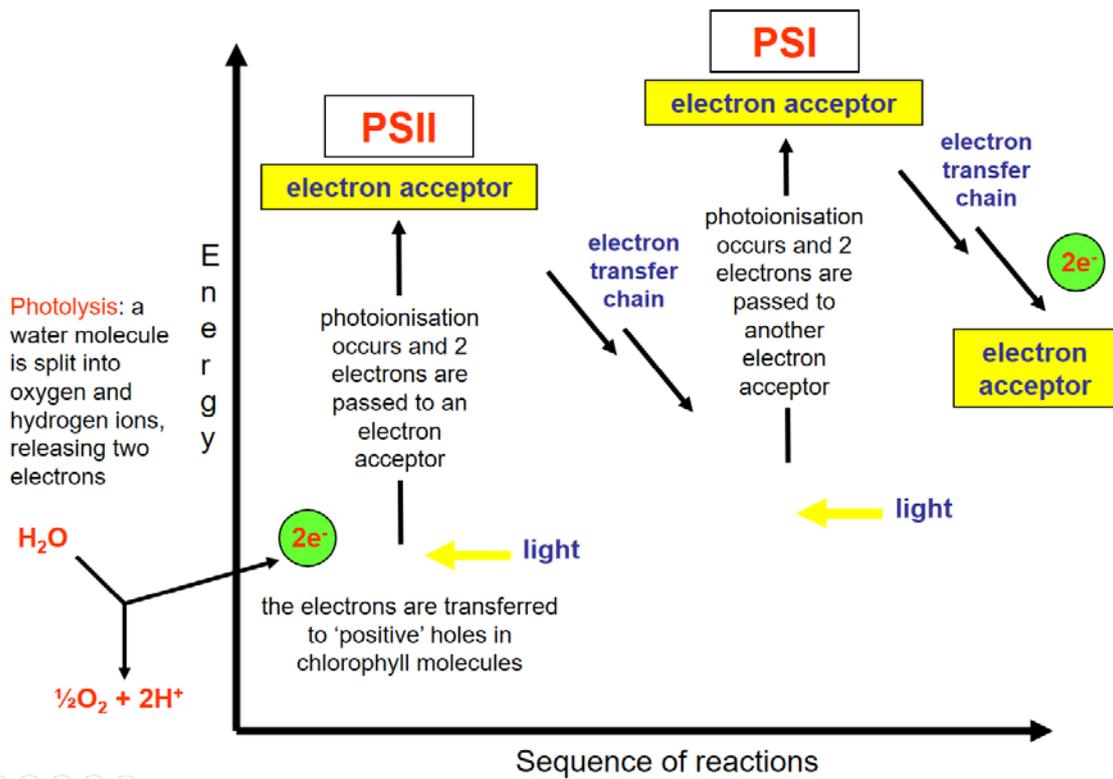
The energy changes accompanying the two sets of changes make a Z shape when drawn out. This is why the electron transfer process is sometimes called the Z scheme. Key to the scheme is that sufficient energy is released during electron transfer to enable ATP to be made from ADP and phosphate.

## Synthesis of ATP from ADP



A condensation reaction has led to phosphorylation.

## PSII and PSI: the Z scheme

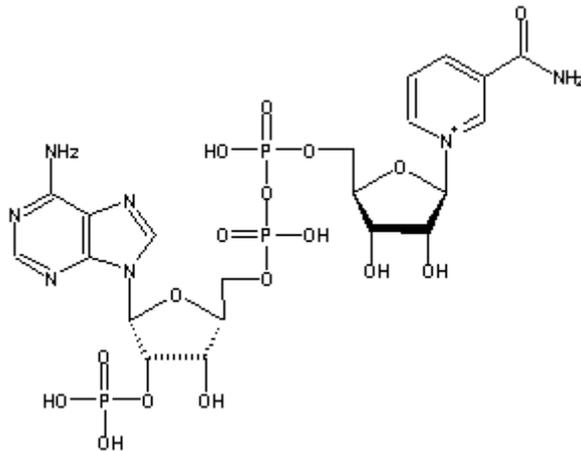


## Non-cyclic phosphorylation (the Z scheme)

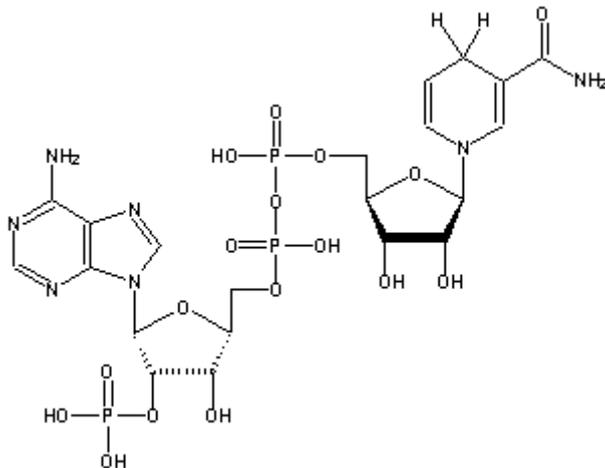
Both adenosine triphosphate (ATP) and NADPH are produced.

In the first photosystem (Photosystem II, PSII):

- photoionisation of chlorophyll transfers excited electrons to an electron acceptor
- photolysis of water (an electron donor) produces oxygen molecules, hydrogen ions and electrons, and the latter are transferred to the positively-charged chlorophyll
- the electron acceptor passes the electrons to the electron transport chain; the final acceptor is photosystem PSI
- further absorbed light energy increases the energy of the electrons, sufficient for the reduction of  $\text{NADP}^+$  to NADPH



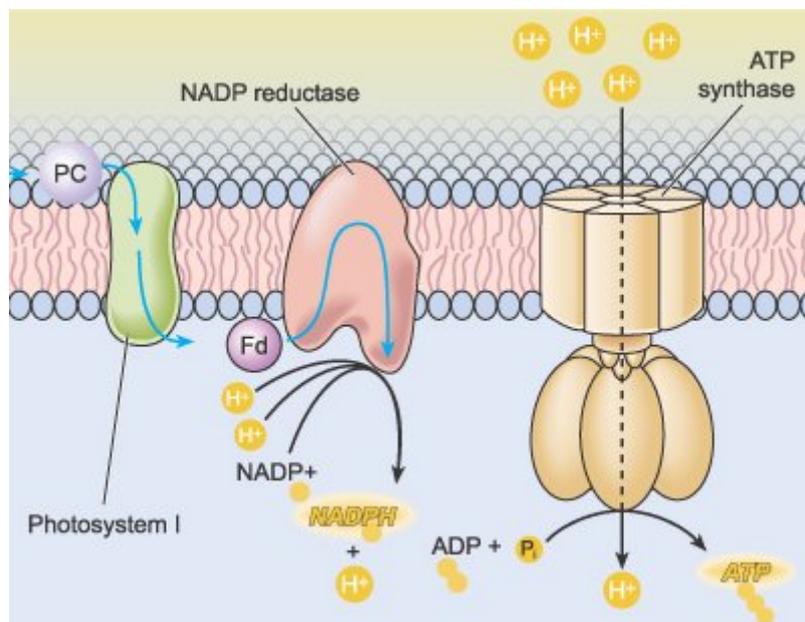
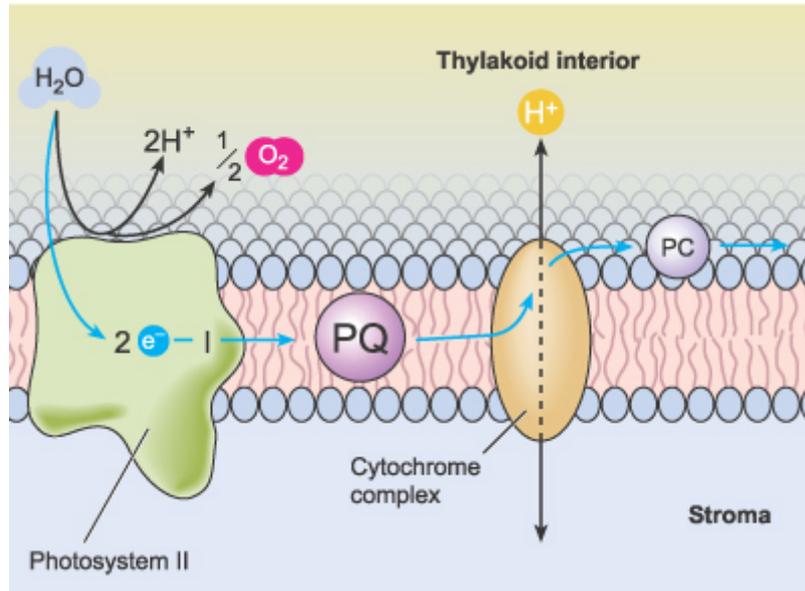
*The oxidised form of nicotinamide adenine dinucleotide phosphate ( $\text{NADP}^+$ )*



*The reduced form of nicotinamide adenine dinucleotide phosphate (NADPH)*

## Chemiosmosis and ATP synthesis

The components of non-cyclic phosphorylation are found in the thylakoid membranes of the chloroplast. Electrons passing through the transport chain provide energy to pump  $H^+$  ions from the stroma, across the thylakoid membrane into the thylakoid compartment.  $H^+$  ions are more concentrated in the thylakoid compartment than in the stroma. We say there is an electrochemical gradient.  $H^+$  ions diffuse from the high to the low regions of concentration. This drives the production of ATP.



*Chemiosmosis as it operates in photophosphorylation within a chloroplast*

## Cyclic phosphorylation

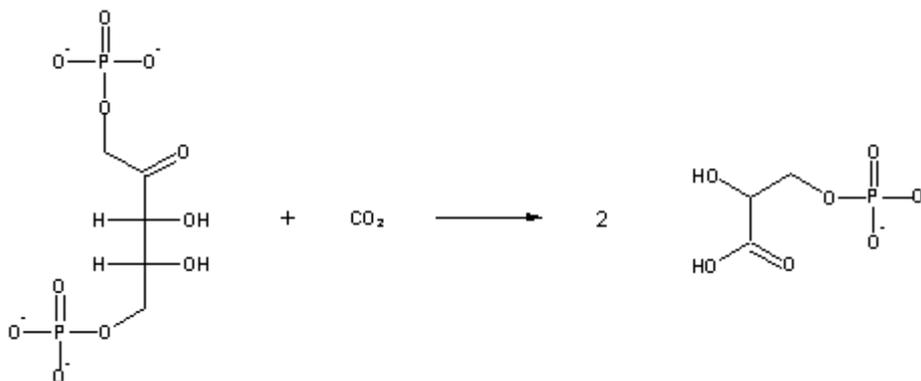
The net effect of non-cyclic phosphorylation is to pass electrons from water to NADP. Energy released enables the production of ATP. But much more ATP is needed to drive the light-independent reactions.

This extra energy is obtained from cyclic phosphorylation. This involves only Photosystem I which generates excited electrons. These are transferred to the electron transport chain between PSII and PSI, rather than to NADP<sup>+</sup> and so no NADPH is formed. The cycle is completed by electrons being transported back to PSI by the electron transport system.

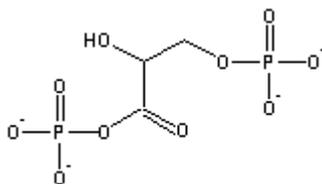
## The light-independent reactions

In the Light-Independent Process (the Dark reaction) carbon dioxide from the atmosphere (or water for aquatic/marine organisms) is captured and modified by the addition of hydrogen to form carbohydrates. The incorporation of carbon dioxide into organic compounds is known as **carbon fixation**. The energy for this comes from the first phase of the photosynthetic process. Living systems cannot directly utilize light energy, but can, through a complicated series of reactions, convert it into C-C bond energy that can be released by glycolysis and other metabolic processes.

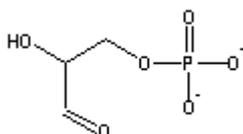
Carbon dioxide combines with a five-carbon sugar, ribulose 1,5-biphosphate (RuBP). A six-carbon sugar forms but is unstable. Each molecule breaks down to form two glycerate 3-phosphate (GP) molecules.



These glycerate 3-phosphate (GP) molecules are phosphorylated by ATP into glycerate diphosphate molecules.

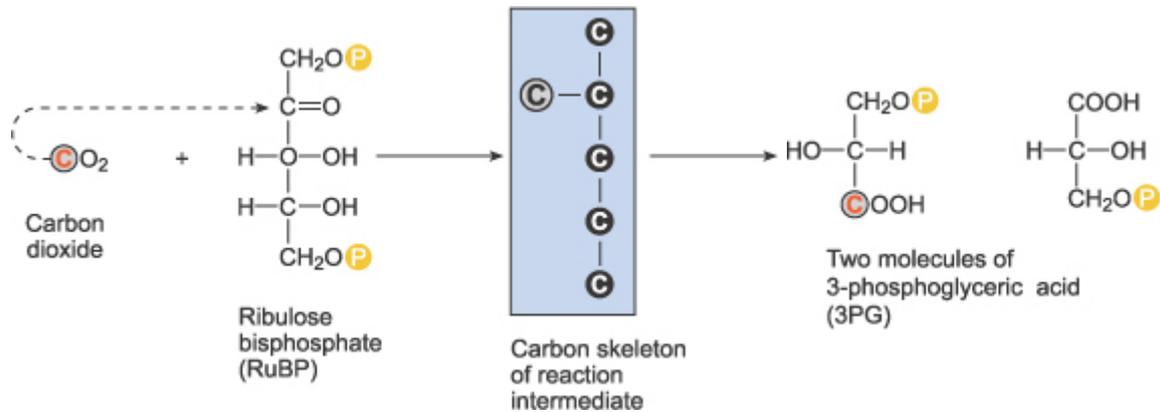


These are reduced by NADPH to two molecules of glyceraldehyde 3-phosphate (GALP).



Of each pair of GALP molecules produced:

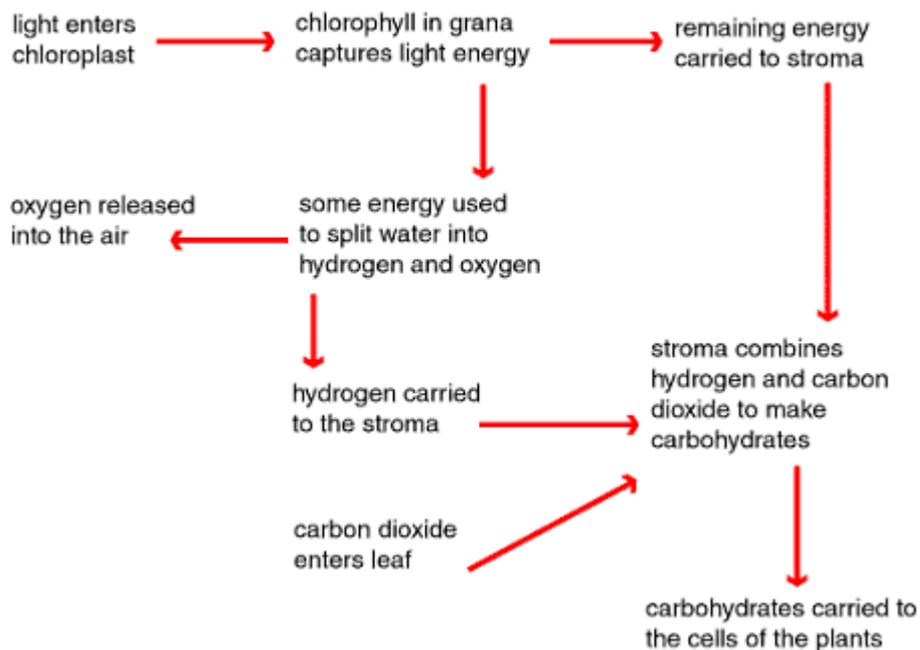
- one molecule is the initial end product of photosynthesis; it is quickly converted to glucose and other carbohydrates, lipids or amino acids
- one molecule forms RuBP through a series of chemical reactions



*The first steps in the Calvin cycle*

The first stable product of the Calvin Cycle is phosphoglycerate (PGA), a 3-C chemical. The energy from ATP and NADPH energy carriers generated by the photosystems is used to phosphorylate the PGA. Eventually there are 12 molecules of glyceraldehyde phosphate (also known as phosphoglyceraldehyde or PGAL, a 3-C), two of which are removed from the cycle to make a glucose. The remaining PGAL molecules are converted by ATP energy to reform six RuBP molecules, and thus start the cycle again.

## Summary of stages of photosynthesis



## Factors affecting the rate of photosynthesis

The main factors are light intensity, carbon dioxide concentration and temperature, known as limiting factors.

As light intensity increases, the rate of the light-dependent reaction, and therefore photosynthesis generally, increases proportionately. As light intensity is increased however, the rate of photosynthesis is eventually limited by some other factor. Chlorophyll a is used in both photosystems. The wavelength of light is also important. PSI absorbs energy most efficiently at 700 nm and PSII at 680 nm. Light with a high proportion of energy concentrated in these wavelengths will produce a high rate of photosynthesis.

An increase in the carbon dioxide concentration increases the rate at which carbon is incorporated into carbohydrate in the light-independent reaction and so the rate of photosynthesis generally increases until limited by another factor.

Photosynthesis is dependent on temperature. It is a reaction catalysed by enzymes. As the enzymes approach their optimum temperatures the overall rate increases. Above the optimum temperature the rate begins to decrease until it stops.

## Test your knowledge

[Take quiz on \*Photosynthesis\*](#)