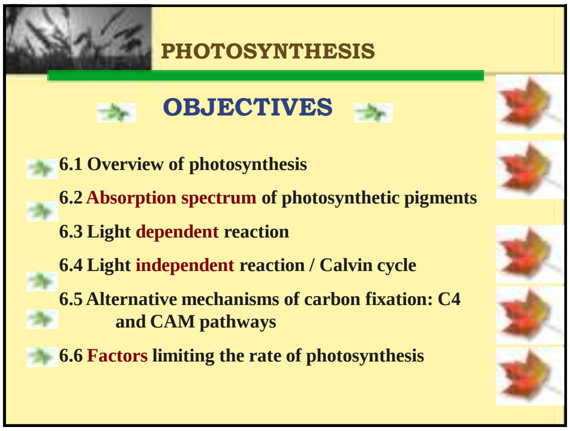


PHOTOSYNTHESIS

OBJECTIVES

- 6.1 Overview of photosynthesis
- 6.2 Absorption spectrum of photosynthetic pigments
- 6.3 Light dependent reaction
- 6.4 Light independent reaction / Calvin cycle
- 6.5 Alternative mechanisms of carbon fixation: C4 and CAM pathways
- 6.6 Factors limiting the rate of photosynthesis

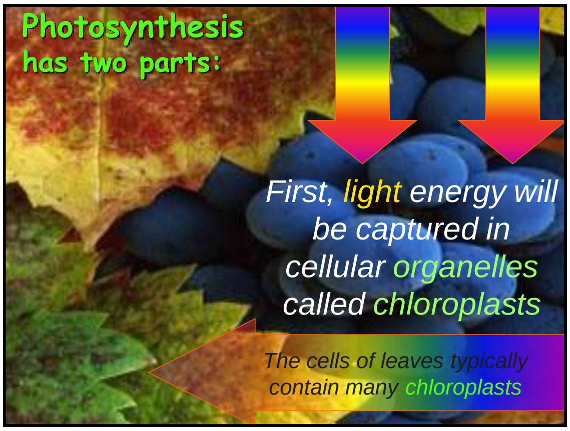
WHAT IS PHOTOSYNTHESIS

? ? ?

Photosynthesis:

- *is the manufacture of sugars with solar energy*
- *comes from the Greek, "photos" (light) and "syntithenai" (putting together)*
- *means, literally:*

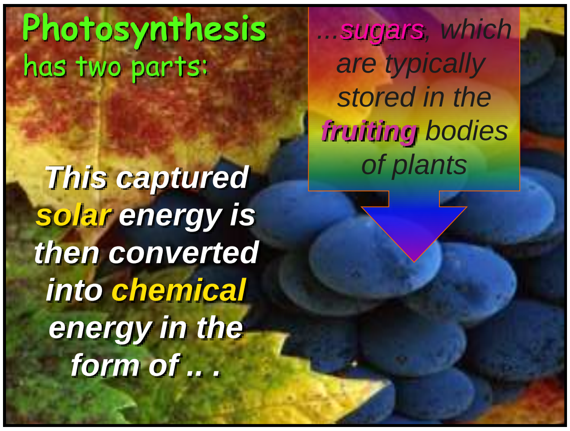
"light-putting-together"



Photosynthesis has two parts:

First, light energy will be captured in cellular organelles called chloroplasts

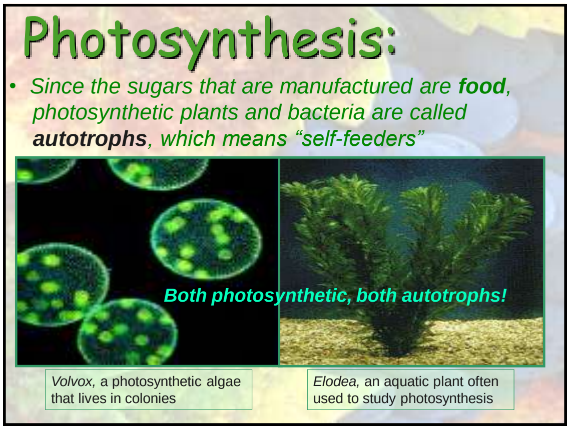
The cells of leaves typically contain many chloroplasts



Photosynthesis has two parts:

This captured solar energy is then converted into chemical energy in the form of .. .

...sugars, which are typically stored in the fruiting bodies of plants



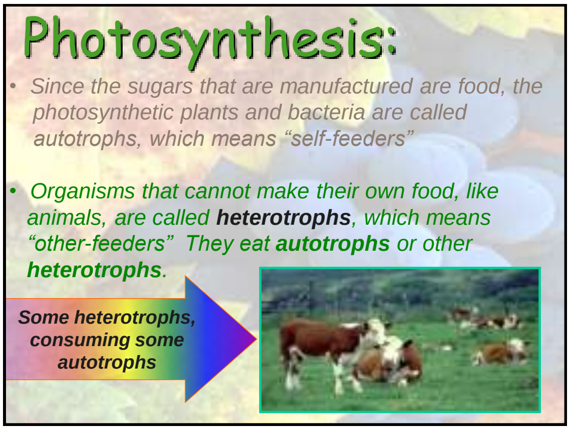
Photosynthesis:

- *Since the sugars that are manufactured are* ***food****, photosynthetic plants and bacteria are called* ***autotrophs****, which means "self-feeders"*

Both photosynthetic, both autotrophs!

Volvox, a photosynthetic algae that lives in colonies

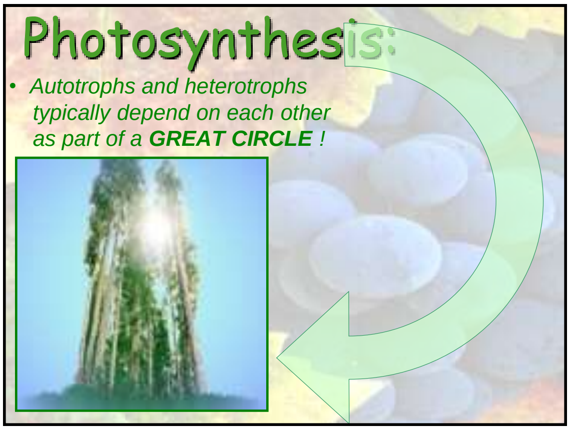
Elodea, an aquatic plant often used to study photosynthesis



Photosynthesis:

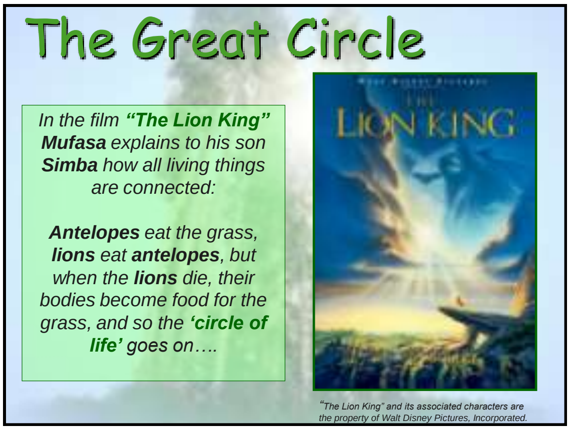
- *Since the sugars that are manufactured are food, the photosynthetic plants and bacteria are called autotrophs, which means "self-feeders"*
- *Organisms that cannot make their own food, like animals, are called* ***heterotrophs****, which means "other-feeders" They eat* ***autotrophs*** *or other* ***heterotrophs****.*

Some heterotrophs, consuming some autotrophs



Photosynthesis:

- *Autotrophs and heterotrophs typically depend on each other as part of a* ***GREAT CIRCLE*** *!*



The Great Circle

In the film ***"The Lion King"*** ***Mufasa*** *explains to his son* ***Simba*** *how all living things are connected:*

Antelopes *eat the grass,* ***lions*** *eat* ***antelopes****, but when the* ***lions*** *die, their bodies become food for the grass, and so the* ***'circle of life'*** *goes on….*

"The Lion King" and its associated characters are the property of Walt Disney Pictures, Incorporated.

The Great Circle

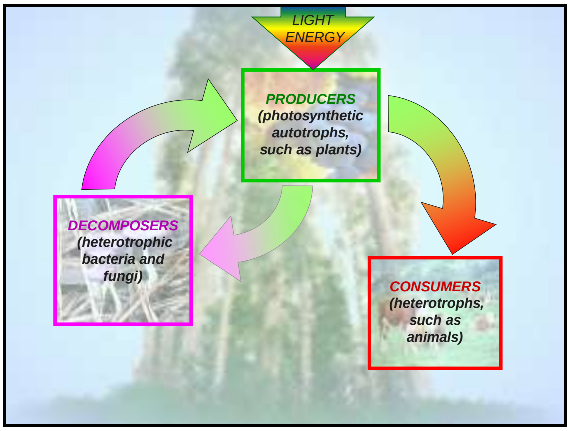
"The Lion King" *is fiction, of course, and not meant to be taken as literally true:* ***lions,*** *in real life, don't have other animals as* ***friends.***

"The Lion King" and its associated characters are the property of Walt Disney Pictures, Incorporated.

The Great Circle

But a great story, even if fictional, can sometimes carry great truths, and the basic idea that all living things participate in a great circle is, in fact, TRUE.

"The Lion King" and its associated characters are the property of Walt Disney Pictures, Incorporated.

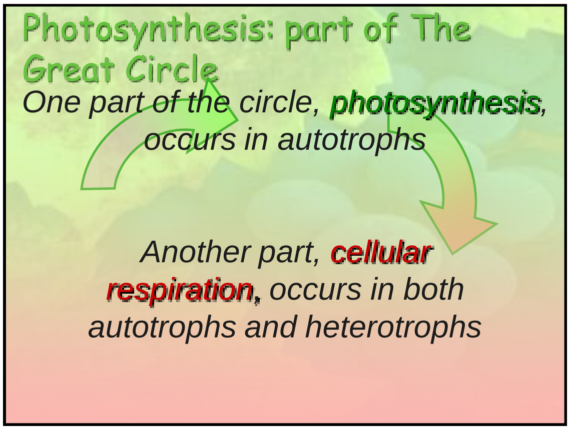


LIGHT ENERGY

PRODUCERS *(photosynthetic autotrophs, such as plants)*

DECOMPOSERS *(heterotrophic bacteria and fungi)*

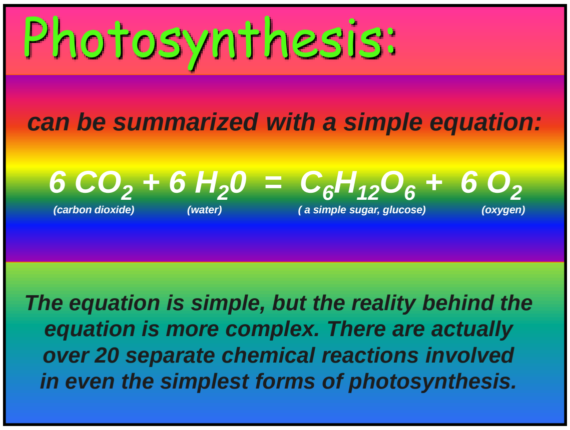
CONSUMERS *(heterotrophs, such as animals)*



Photosynthesis: part of The Great Circle

*One part of the circle, **photosynthesis**, occurs in autotrophs*

*Another part, **cellular respiration**, occurs in both autotrophs and heterotrophs*



Photosynthesis:

can be summarized with a simple equation:

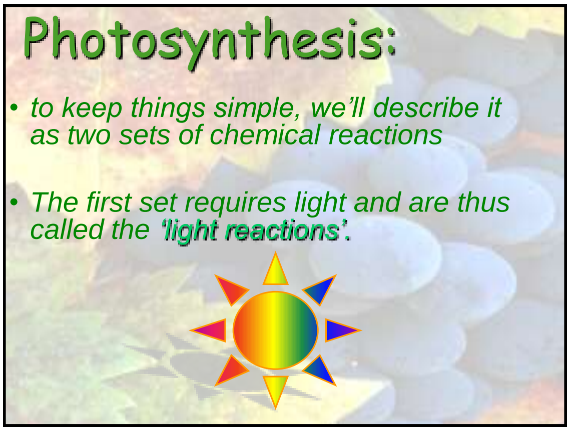
$$6\ CO_2 + 6\ H_20\ =\ C_6H_{12}O_6 +\ 6\ O_2$$

(carbon dioxide) (water) (a simple sugar, glucose) (oxygen)

The equation is simple, but the reality behind the equation is more complex. There are actually over 20 separate chemical reactions involved in even the simplest forms of photosynthesis.

Photosynthesis:

- *to keep things simple, we'll describe it as two sets of chemical reactions*

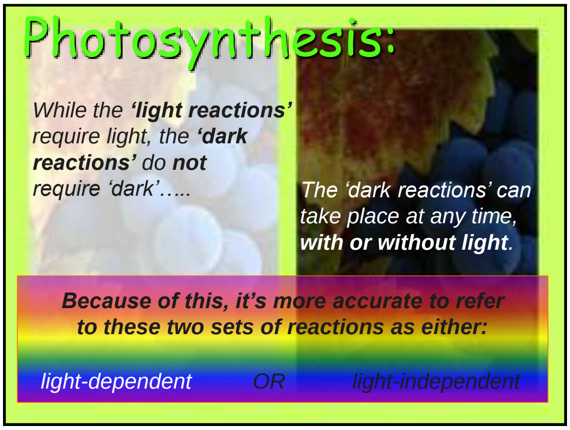


Photosynthesis:

- *to keep things simple, we'll describe it as two sets of chemical reactions*
- *The first set requires light and are thus called the 'light reactions'.*

Photosynthesis:

- *to keep things simple, we'll describe it as two sets of chemical reactions*
- *The first set requires light and are thus called the 'light reactions'.*
- *The second set don't require light and are often misleadingly referred to as the 'dark reactions.'*



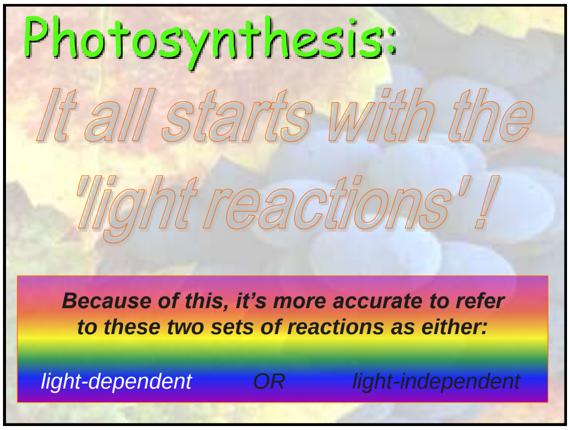
Photosynthesis:

While the **'light reactions'** require light, the **'dark reactions'** do **not** require 'dark'…..

The 'dark reactions' can take place at any time, **with or without light**.

Because of this, it's more accurate to refer to these two sets of reactions as either:

light-dependent *OR* *light-independent*



Photosynthesis:

It all starts with the 'light reactions' !

Because of this, it's more accurate to refer to these two sets of reactions as either:

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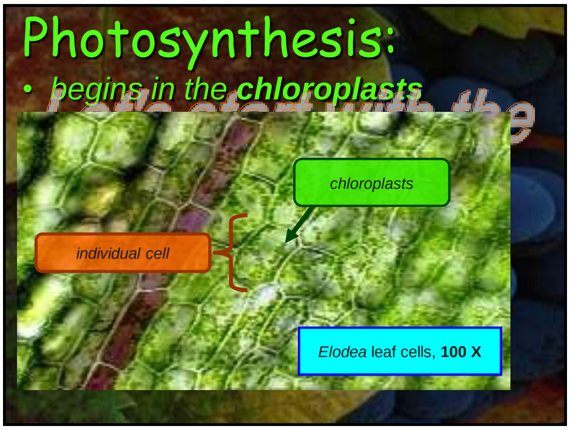
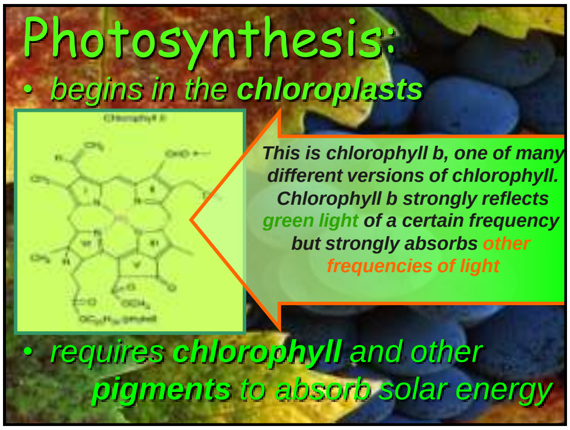


Photosynthesis:

- *begins in the **chloroplasts***

Let's start with the

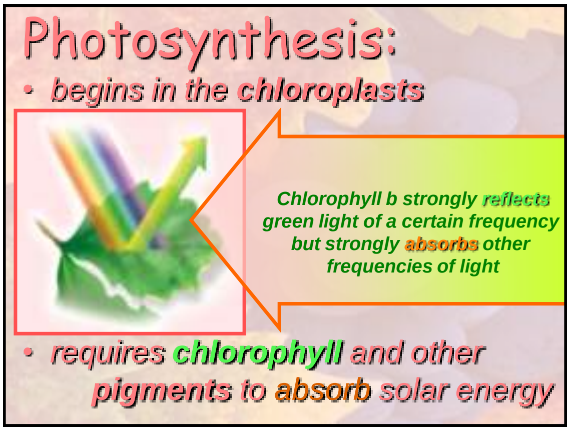


Photosynthesis:

- *begins in the **chloroplasts***

This is chlorophyll b, one of many different versions of chlorophyll. Chlorophyll b strongly reflects green light of a certain frequency but strongly absorbs other frequencies of light

- *requires **chlorophyll** and other **pigments** to absorb solar energy*



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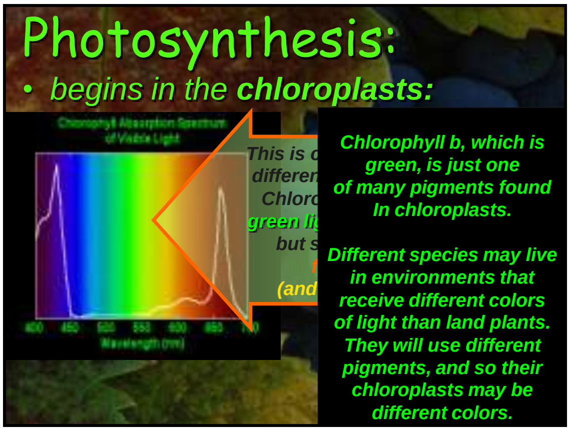
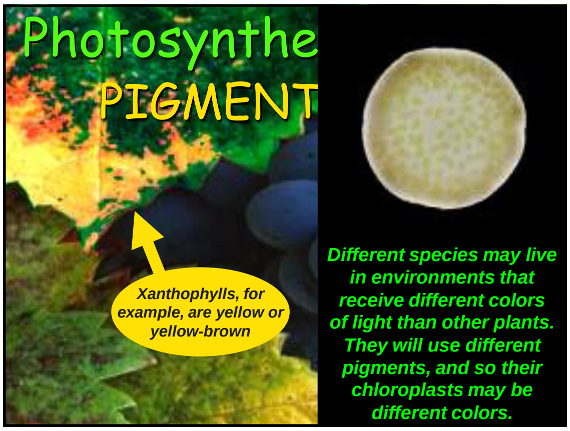


Photosynthesis:

- *begins in the **chloroplasts:***

Chlorophyll b, which is green, is just one of many pigments found In chloroplasts.

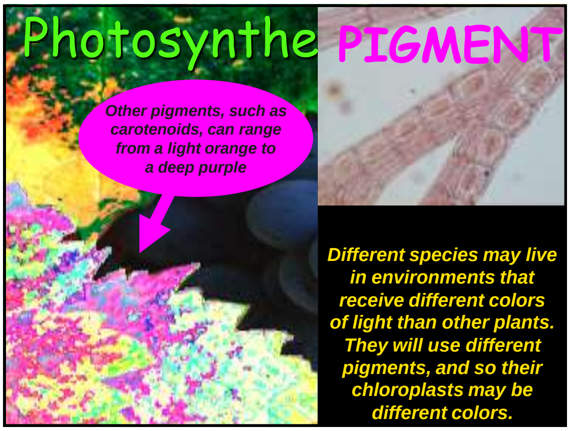
Different species may live in environments that receive different colors of light than land plants. They will use different pigments, and so their chloroplasts may be different colors.



Photosynthe PIGMENT

Xanthophylls, for example, are yellow or yellow-brown

Different species may live in environments that receive different colors of light than other plants. They will use different pigments, and so their chloroplasts may be different colors.



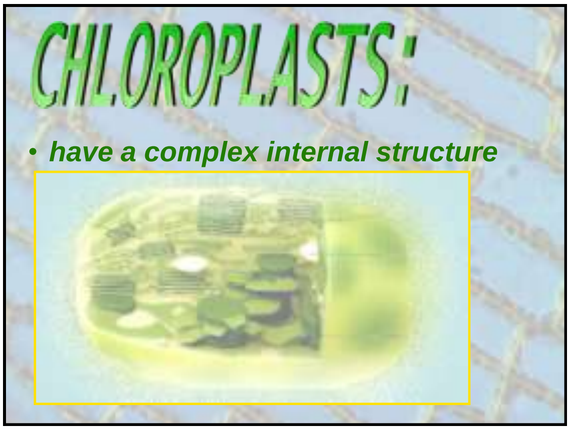
Photosynthe PIGMENT

Other pigments, such as carotenoids, can range from a light orange to a deep purple

Different species may live in environments that receive different colors of light than other plants. They will use different pigments, and so their chloroplasts may be different colors.

CHLOROPLASTS:

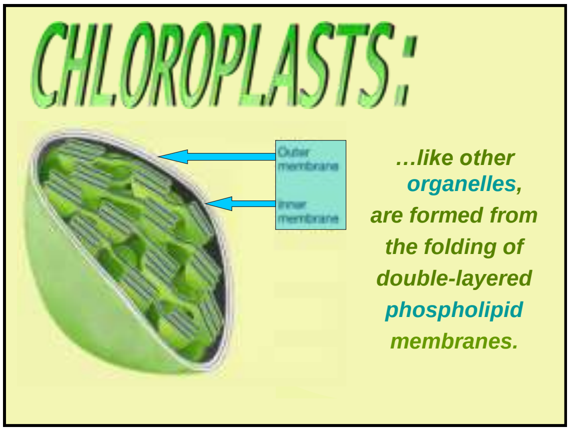
- *have a complex internal structure*



CHLOROPLASTS:

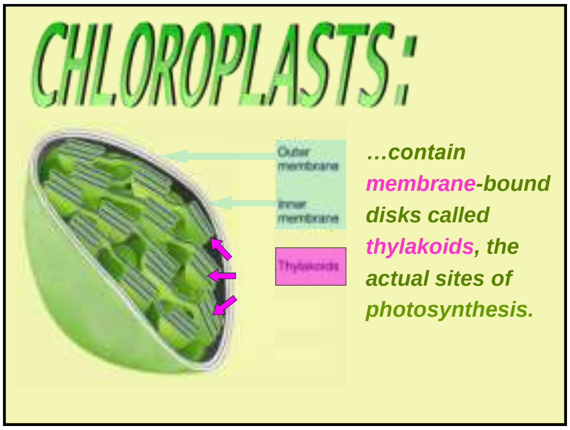
- *have a complex internal structure*

CHLOROPLASTS:



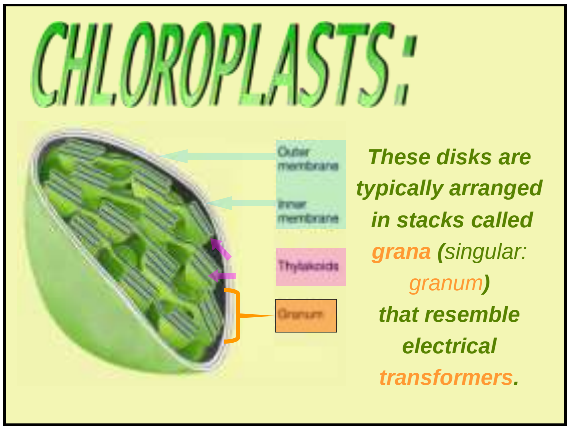
CHLOROPLASTS:

…like other organelles, are formed from the folding of double-layered phospholipid membranes.



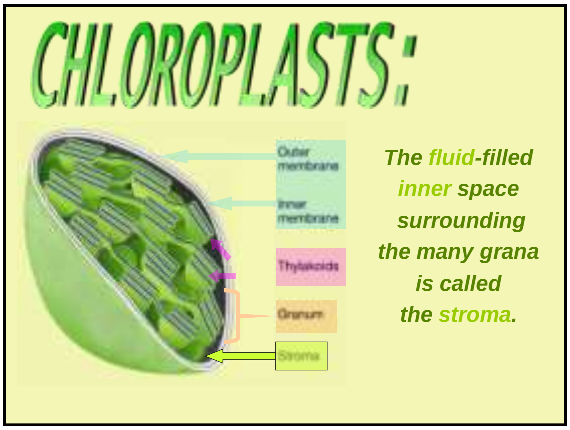
CHLOROPLASTS:

…contain **membrane**-bound disks called **thylakoids**, the actual sites of photosynthesis.



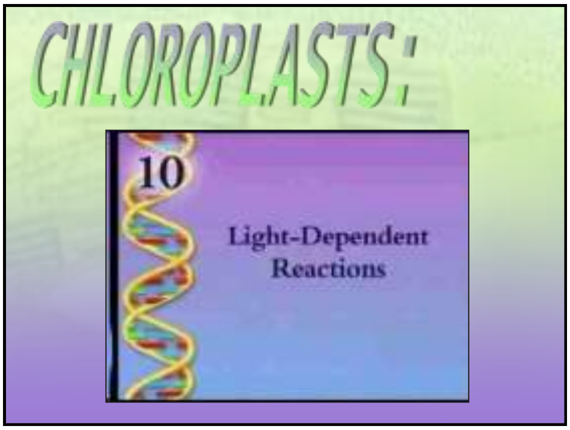
CHLOROPLASTS:

These disks are typically arranged in stacks called **grana** (singular: granum) that resemble electrical **transformers**.

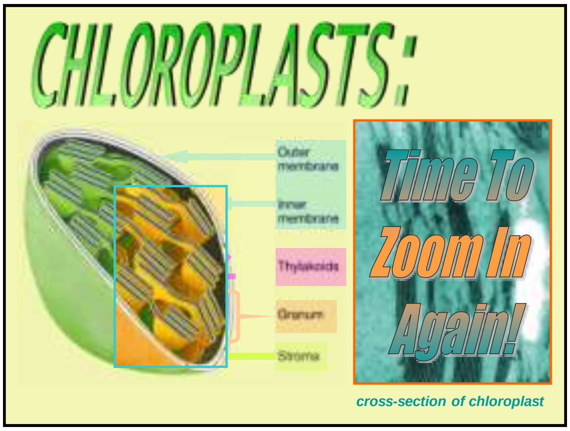


CHLOROPLASTS:

The **fluid**-filled **inner** space surrounding the many grana is called the **stroma**.

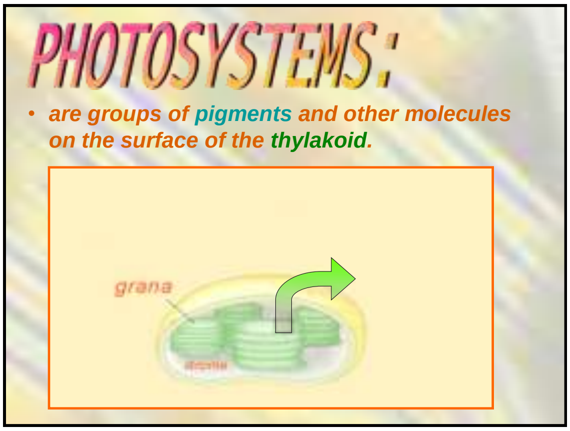


CHLOROPLASTS:



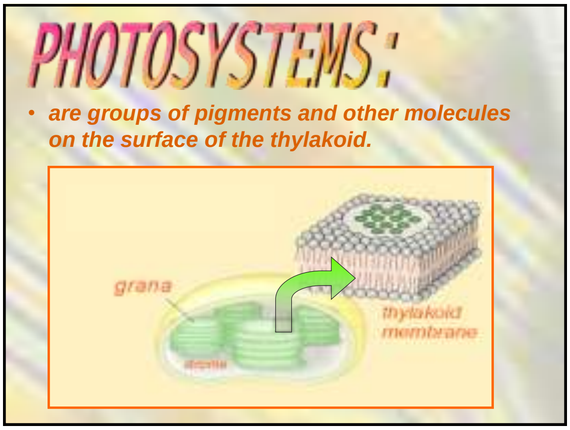
CHLOROPLASTS:

cross-section of chloroplast



PHOTOSYSTEMS:

- are groups of **pigments** and other molecules on the surface of the **thylakoid**.



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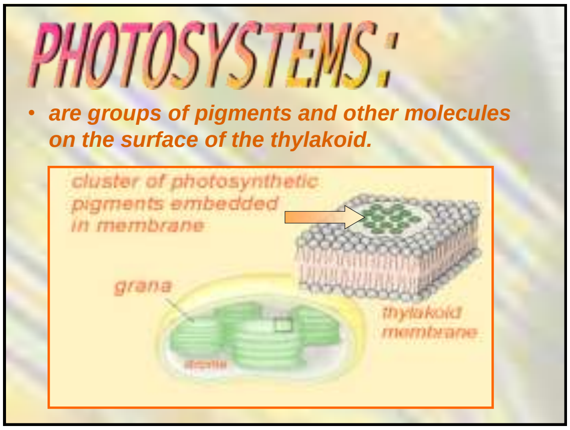

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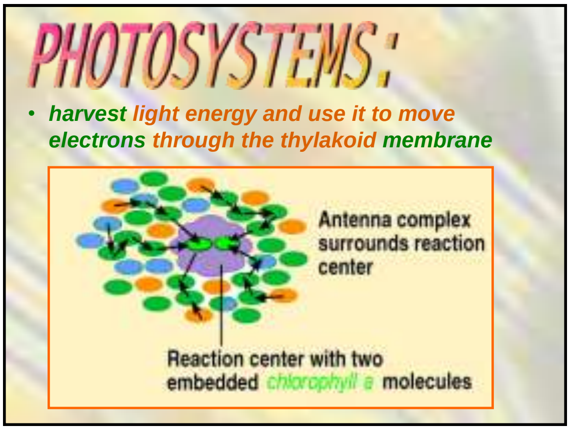
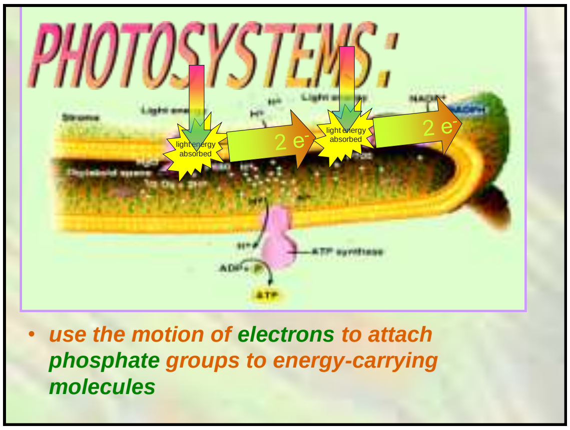


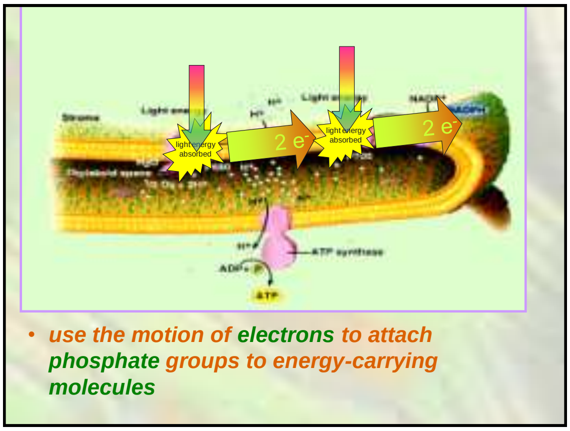
PHOTOSYSTEMS:

- harvest light energy and use it to move electrons through the thylakoid membrane



PHOTOSYSTEMS:

- use the motion of electrons to attach phosphate groups to energy-carrying molecules



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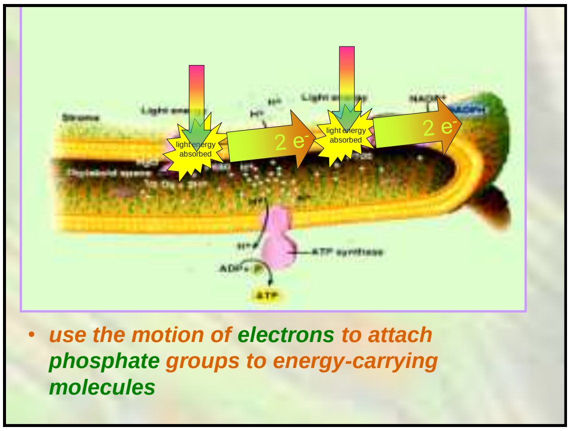

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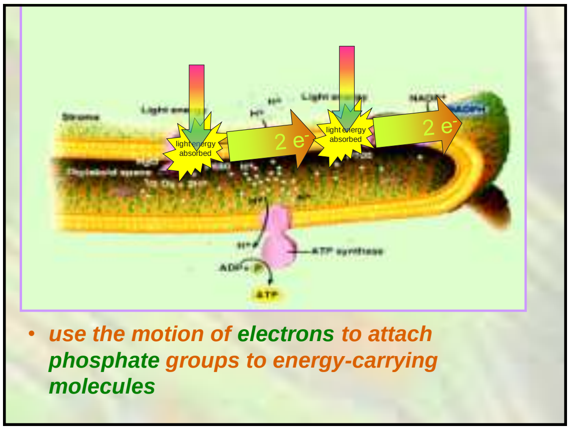
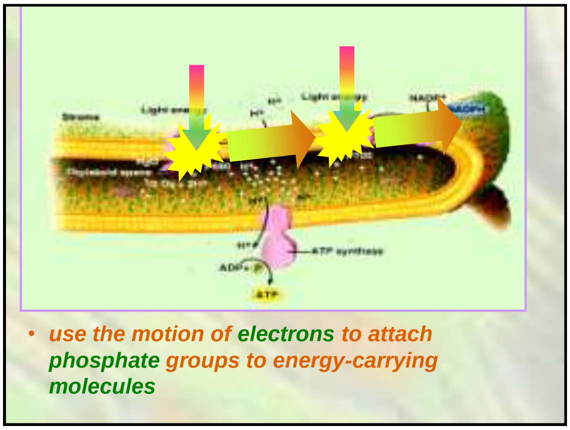


- *use the motion of **electrons** to attach **phosphate** groups to energy-carrying **molecules***



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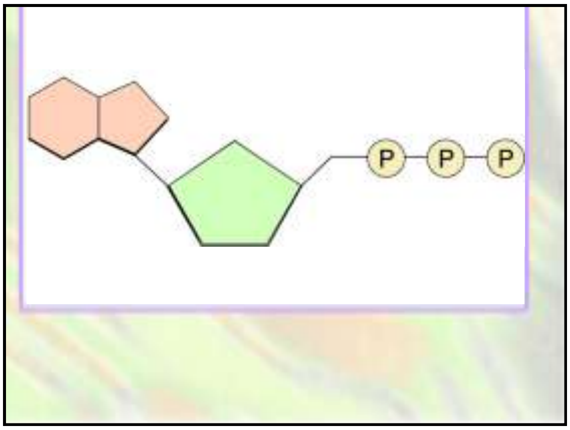
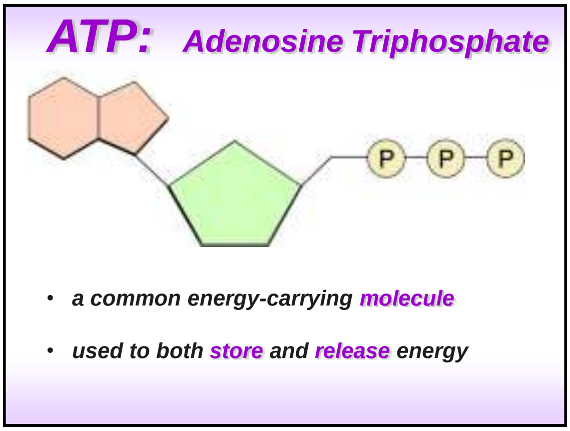
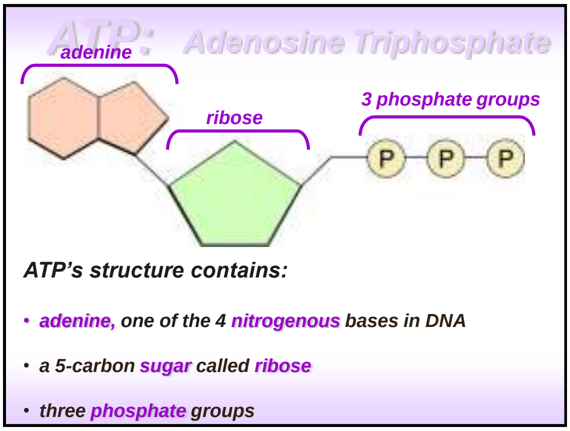




ATP: *Adenosine Triphosphate*

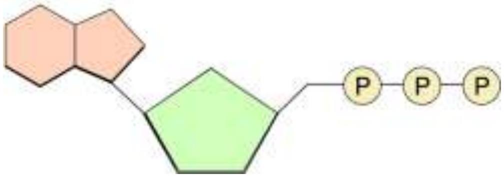
- *a common energy-carrying **molecule***
- *used to both **store** and **release** energy*



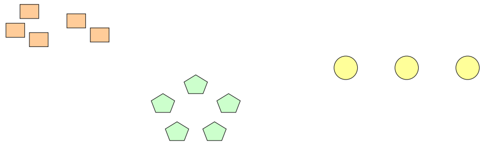
ATP: *Adenosine Triphosphate*

ATP's structure contains:

- ***adenine,** one of the 4 **nitrogenous** bases in DNA*
- *a 5-carbon **sugar** called **ribose***
- *three **phosphate** groups*



*ATP is made of molecular ‘**building blocks**’ that are already present in large numbers in the cell!*



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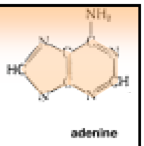

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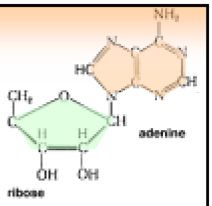

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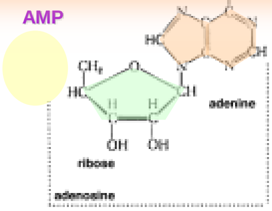

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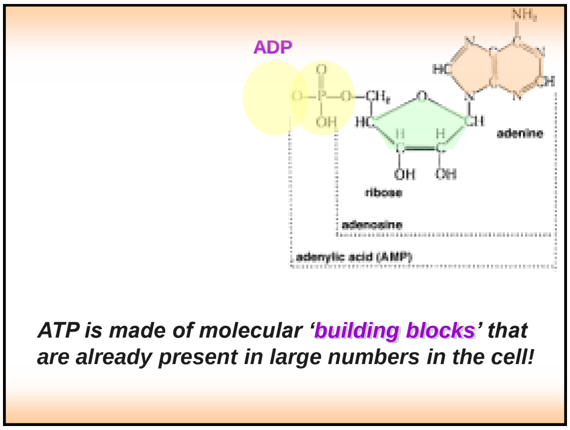

ADP

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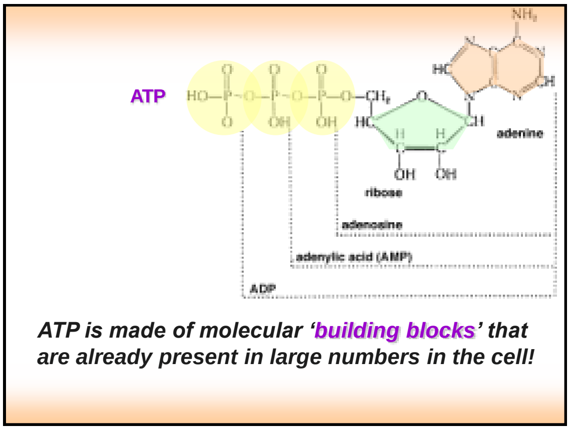

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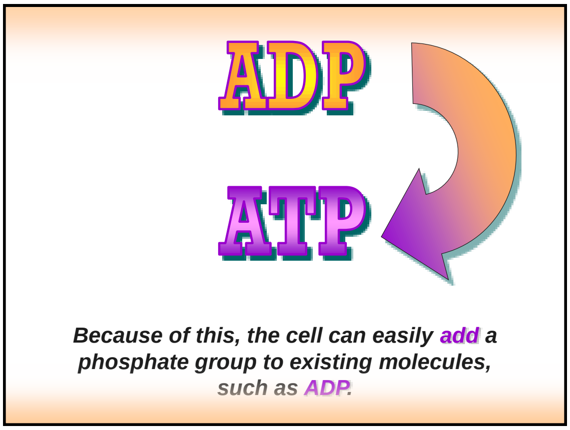
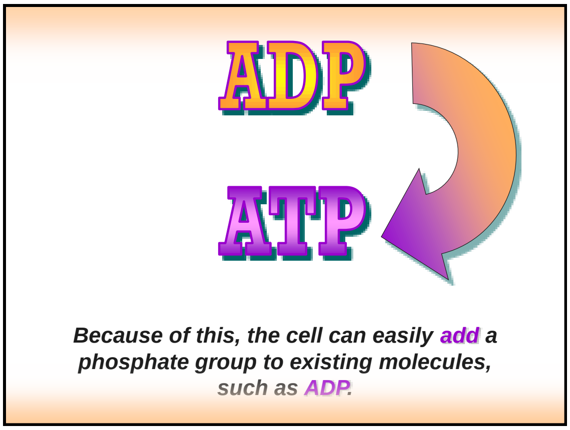


ADP

ATP

*Because of this, the cell can easily **add** a phosphate group to existing molecules,*
such as ADP.



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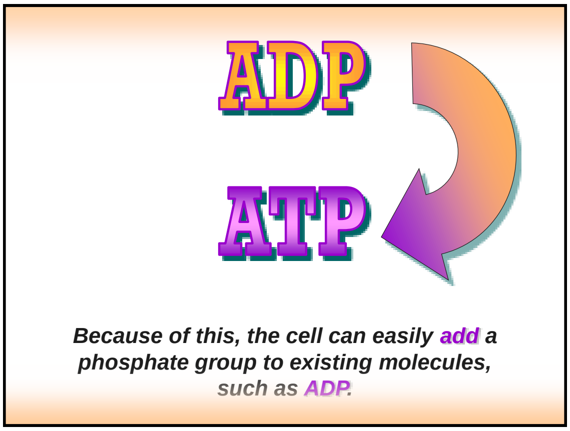

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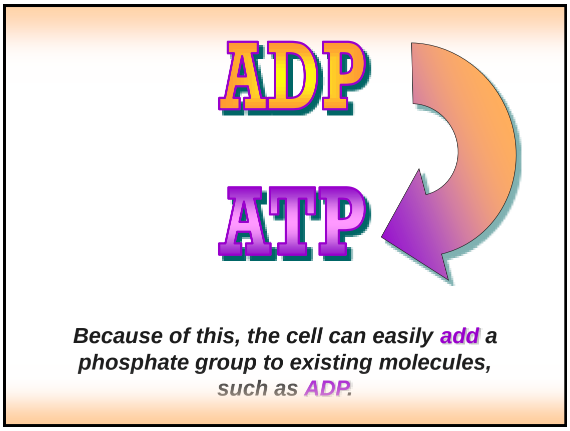

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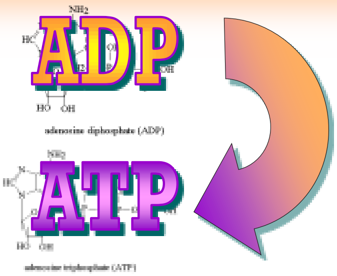
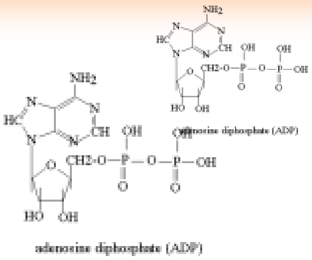
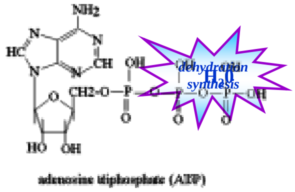


Adding *a phosphate group is called* ***phophorylation****.*



This is a form of energy ***storage****, because it takes energy to form the chemical* ***bond*** *between ADP and the phosphate group.*



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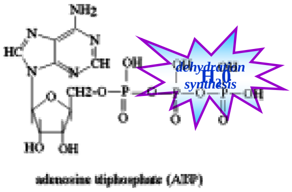

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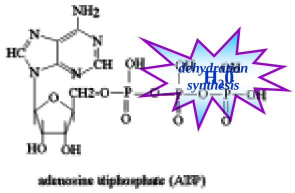

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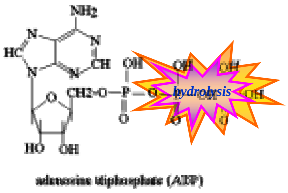
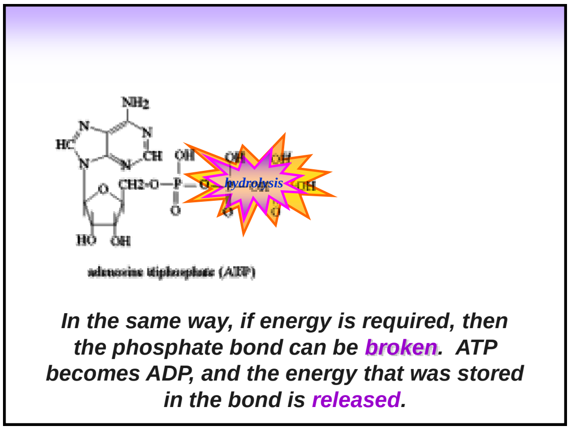
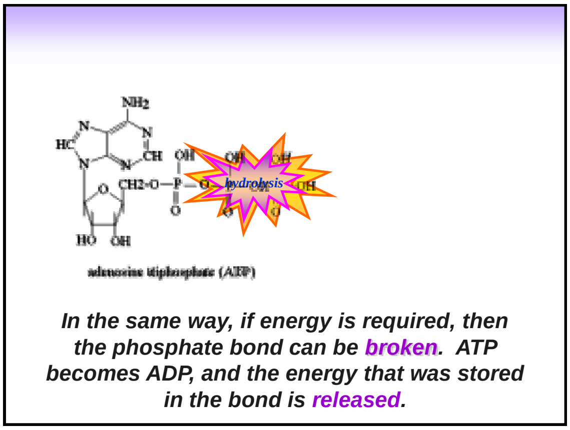


In the same way, if energy is required, then the phosphate bond can be ***broken****. ATP becomes ADP, and the energy that was stored in the bond is* ***released****.*



adenosine triphosphate (ATP)

*In the same way, if energy is required, then the phosphate bond can be **broken**. ATP becomes ADP, and the energy that was stored in the bond is **released**.*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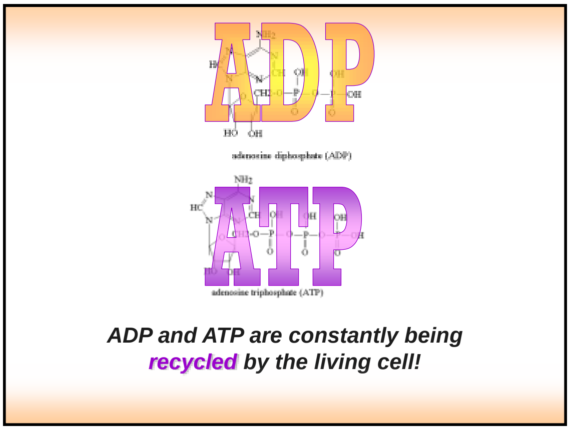
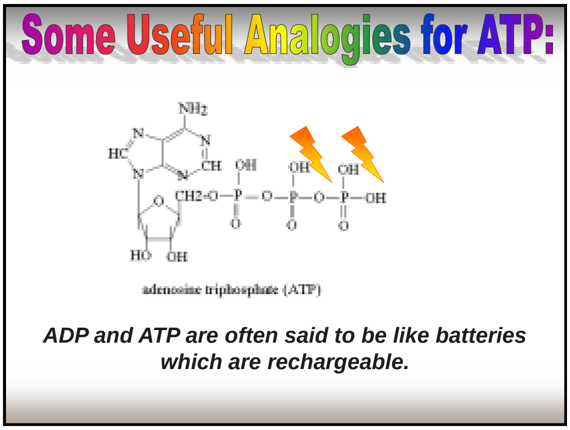


adenosine diphosphate (ADP)

adenosine triphosphate (ATP)

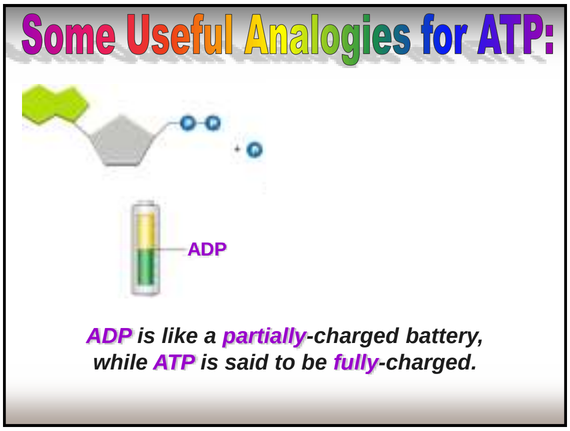
*ADP and ATP are constantly being **recycled** by the living cell!*



Some Useful Analogies for ATP:

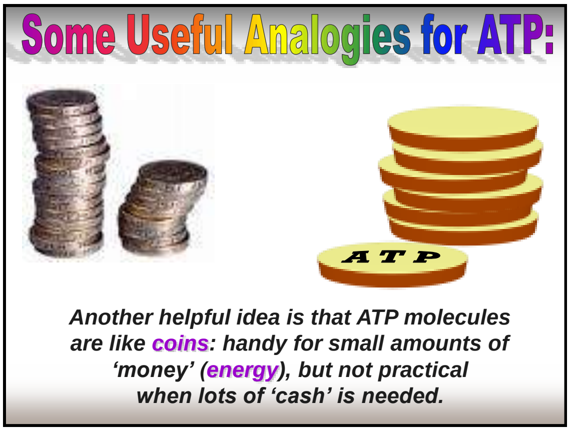
adenosine triphosphate (ATP)

ADP and ATP are often said to be like batteries which are rechargeable.



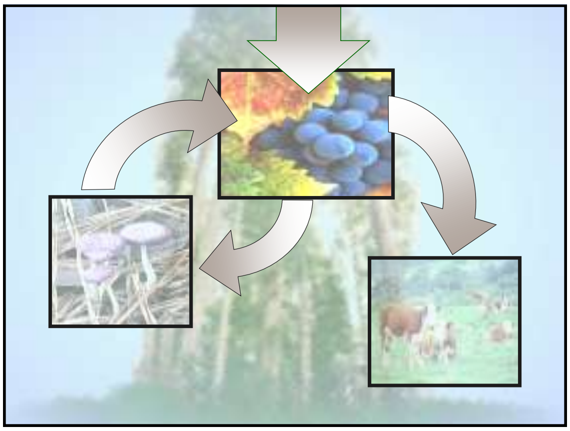
Some Useful Analogies for ATP:

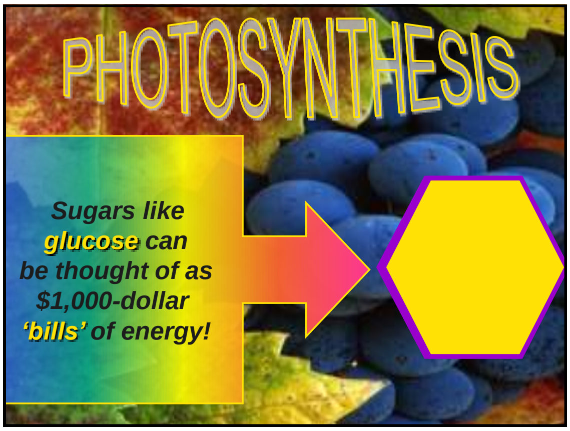
***ADP** is like a **partially**-charged battery, while **ATP** is said to be **fully**-charged.*



Some Useful Analogies for ATP:

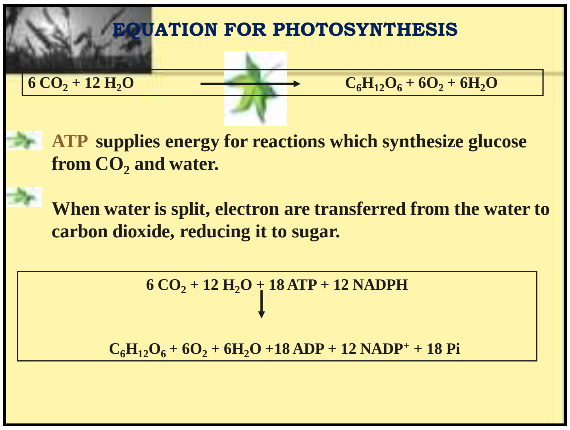
*Another helpful idea is that ATP molecules are like **coins**: handy for small amounts of ‘money’ (**energy**), but not practical when lots of ‘cash’ is needed.*





PHOTOSYNTHESIS

*Sugars like **glucose** can be thought of as $1,000-dollar **'bills'** of energy!*

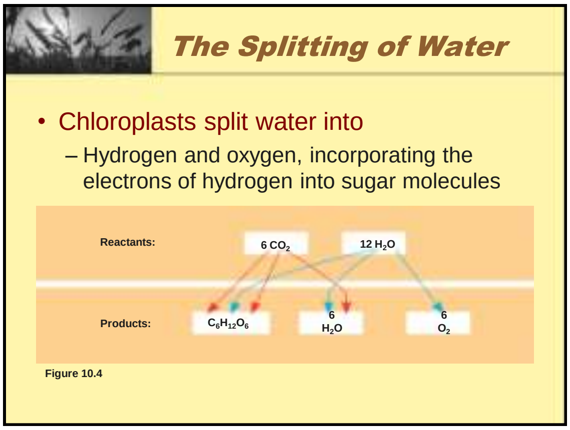


EQUATION FOR PHOTOSYNTHESIS

$$6\,CO_2 + 12\,H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

- **ATP supplies energy for reactions which synthesize glucose from CO_2 and water.**
- **When water is split, electron are transferred from the water to carbon dioxide, reducing it to sugar.**

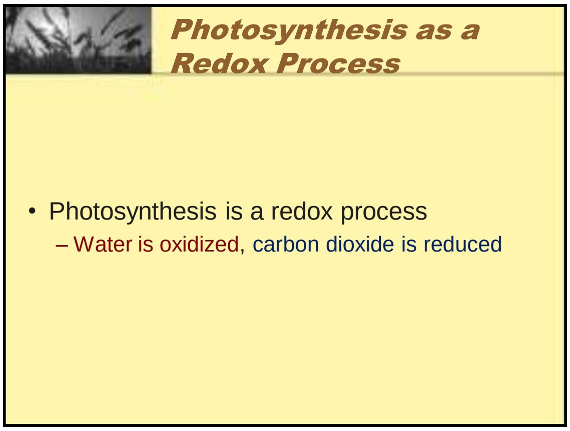
$$6\,CO_2 + 12\,H_2O + 18\,ATP + 12\,NADPH \downarrow C_6H_{12}O_6 + 6O_2 + 6H_2O + 18\,ADP + 12\,NADP^+ + 18\,Pi$$



The Splitting of Water

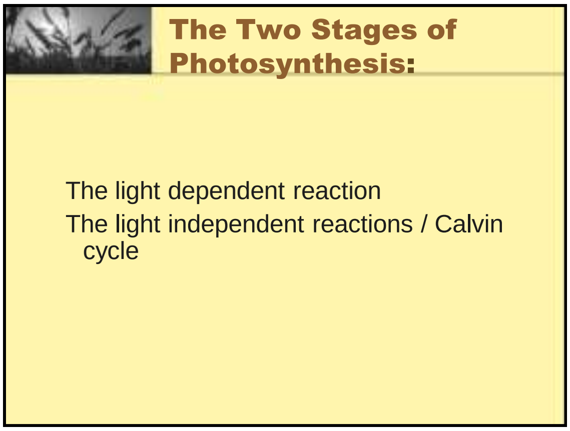
- Chloroplasts split water into
  - Hydrogen and oxygen, incorporating the electrons of hydrogen into sugar molecules

Figure 10.4



Photosynthesis as a Redox Process

- Photosynthesis is a redox process
  - Water is oxidized, carbon dioxide is reduced



The Two Stages of Photosynthesis:

The light dependent reaction

The light independent reactions / Calvin cycle

- The light reactions:
  - Occur in the grana
  - Split water, release oxygen, produce ATP, and form NADPH

- The light independent reaction / Calvin cycle
  - Occurs in the stroma
  - Forms sugar from carbon dioxide, using ATP for energy and NADPH for reducing power

- **An overview of photosynthesis**

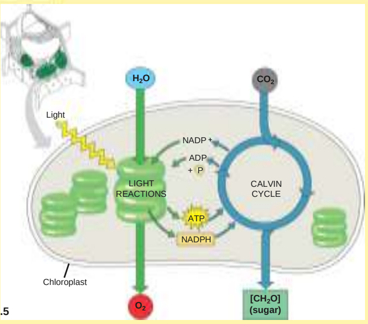


Figure 10.5

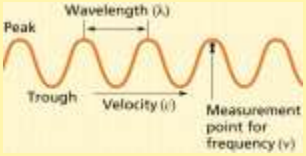
6.2 Absorption spectrum of photosynthetic pigments

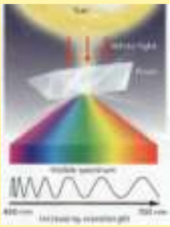
OBJECTIVES:

- To list and explain the photosynthetic pigments involved in photosynthesis.

The Nature of Light

White light is separated into the different colors (=wavelengths) of light by passing it through a prism.





- Wavelength is the distance between the crests of waves (peak to peak).
- The wavelength determines the type of electromagnetic energy
- **The energy is inversely proportional to the wavelength: longer wavelengths have less energy than do shorter ones**.

- The electromagnetic spectrum
  - Is the entire range of electromagnetic energy, or radiation

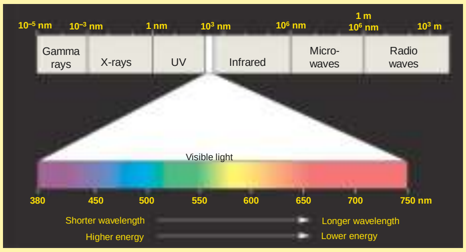


Figure 10.6

- The visible light spectrum
  - Includes the colors of light we can see
  - Includes the wavelengths that drive photosynthesis

Photosynthetic pigments

- Are substances that absorb visible light
- Reflect light, which include the colors we see

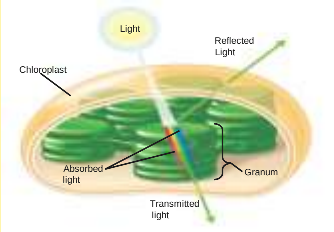


Figure 10.7

- The absorption spectra of chloroplast pigments
  - Provide clues to the relative effectiveness of different wavelengths for driving photosynthesis

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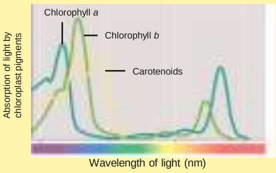
- **The absorption spectra of three types of pigments in chloroplasts**

EXPERIMENT **Three different experiments helped reveal which wavelengths of light are photosynthetically important. The results are shown below.**

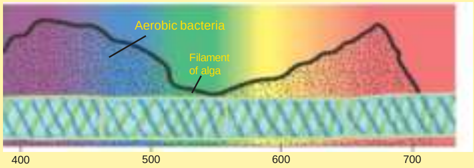
RESULTS



(a) Absorption spectra. The three curves show the wavelengths of light best absorbed by three types of chloroplast pigments.

Figure 10.9

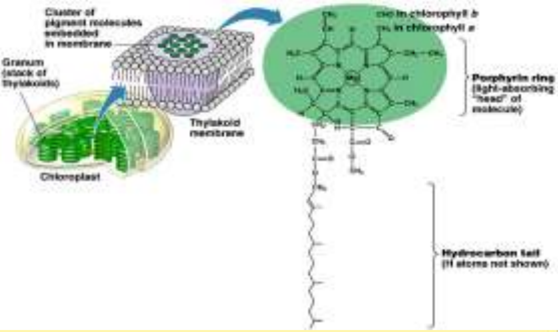
- **The action spectrum for photosynthesis**
  - **Was first demonstrated by Theodor W. Engelmann**



(c) **Engelmann's experiment.** In 1883, Theodor W. Engelmann illuminated a filamentous alga with light that had been passed through a prism, exposing different segments of the alga to different wavelengths. He used aerobic bacteria, which concentrate near an oxygen source, to determine which segments of the alga were releasing the most O_2 and thus photosynthesizing most.
Bacteria congregated in greatest numbers around the parts of the alga illuminated with violet-blue or red light. Notice the close match of the bacterial distribution to the action spectrum in part b.

CONCLUSION Light in the violet-blue and red portions of the spectrum are most effective in driving photosynthesis.

Chlorophylls absorb lights



CHROMATOGRAPHY

1. Chlorophylls and accessory pigments are separated using a technique callled chromatography.

2. Chromatography is a technique used to separate mixtures into their components

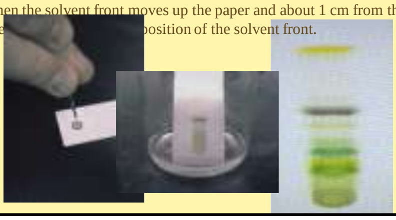
3. There are various types of chromatography; column, paper, thin-layer or gas.

4. For photosynthesis, a paper chromatography is commonly used.

5. In paper chromatography, the components of a mixture are separable into discrete zones on a sheet of filter paper.

The steps involved are as follows :

- The chlorophyll mixture is dissolved in a suitable solvent.
- Drops of the resultant solution are repeatedly placed on top of each other to form a small concentrated spot near on end of a paper strip.
- A line is drawn across the paper to mark the position of the spot.
- When the solvent front moves up the paper and about 1 cm from the end, a line position of the solvent front.



Rf VALUE

Separation of the components (solute) / pigment is usually measured by the Rf value. The Rf value is given by the equation:

$$\mathrm{Rf} = \frac{\text{Distance moved by solute}}{\text{Distance moved by solvent front}}$$

For the numerator, the distance is measured from the origin either to the center or to the leading edge of each spot.

The denominator is the distance from the origin to the solvent front.

PHOTOSYNTHESIS

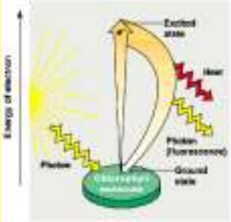
6.3 THE LIGHT DEPENDENT REACTION

OBJECTIVE :

To explain the photoactivation of chlorophyll resulting in the conversion of light energy into ATP and reduced NADP+.

LIGHT ABSORPTION

- When a molecule absorbs a photon, one of that molecule's electrons is elevated to an orbital with more potential energy.
- Photons are absorbed by clusters of pigment molecules in the thylakoid membranes.
- The energy of the photon is converted to the potential energy of an electron raised from its ground state to an excited state.
- Excited electrons are unstable.
- The molecule might return to ground stage, releasing heat energy.
- Some pigments, including chlorophyll, release a photon of light, in a process called fluorescence.



(a) Excitation of isolated chlorophyll molecule

When the molecule fluorescence, it emits a photon of a longer wavelength.

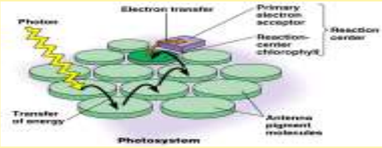
The molecule might pass some of the absorbed energy to another pigment

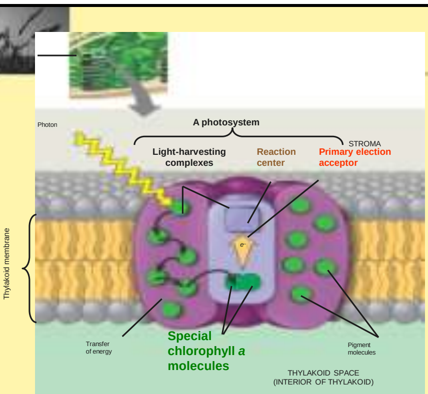
Pigments in the photosynthetic organisms arrange into energy-absorbing antenna systems.

The excitation is passed to the reaction centre of antenna complex

The pigment molecule in the centre is always a molecule of a chlorophyll a

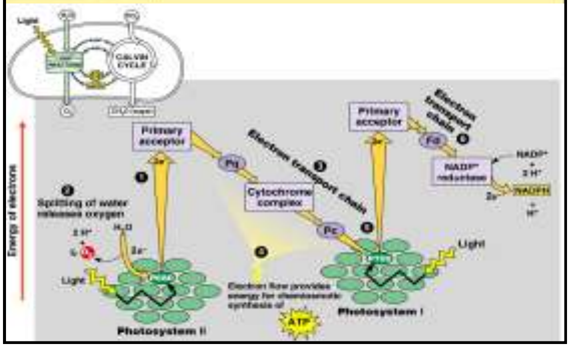
- In the thylakoid membrane, chlorophyll is organized along with proteins and smaller organic molecules into **photosystems**.
- A photosystem acts like a light-gathering “antenna complex” consisting of a few hundred chlorophyll *a*, chlorophyll *b*,and carotenoid molecules.





ure 10.12

Photoactivation, Electron flow/ Photophosphorylation, Reduction & H2O Photolysis



The passing of an electron acceptor begins an **electron flow**

The electron flow through a series of carriers (electron transport chain).

Photophosphorylation

uses the radiant energy of the sun to drive the synthesis of ATP. Light energy activates chlorophyll causing it to transfer an electron to an electron transport chain and, in the process, produce ATP from ADP and inorganic phosphate.

Reduce NADP+ to NADPH

Light absorbed by chlorophyll provides the energy to reduce NADP+ to NADPH, which temporarily stores the energized electrons transferred from water.

NADP+ is reduced by adding a pair of electrons along with a hydrogen nucleus (H+).

Water photolysis

- Photolysis is a process of spitting water molecules using light energy with the release of electrons, ion hydrogen and oxygen.
- Occur in grana
- The H+ enter the stroma and combined with NADP+ to form NADPH (reduction).
- Oxygen is given off or used in respiration.

$2H_2O \longrightarrow 4H+ + O2 + 4e$

- The electron use to stabilized chlorophyll in photosystem II
- The important of photolysis = To replace electron in photosystem II (noncyclic photophosphorylation)

Photosynthesis:

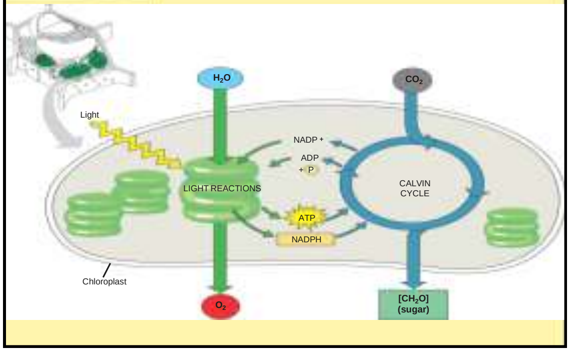
can be summarized with a simple equation:

$$6\ CO_2 + 6\ H_20 \ = \ C_6H_{12}O_6 + \ 6\ O_2$$

(carbon dioxide) *(water)* *(a simple sugar, glucose)* *(oxygen)*

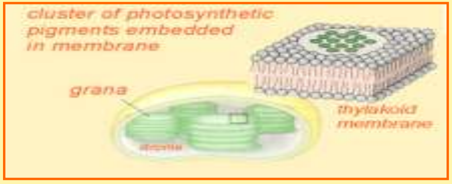
The equation is simple, but the reality behind the equation is more complex. There are actually over 20 separate chemical reactions involved in even the simplest forms of photosynthesis.

An overview of photosynthesis

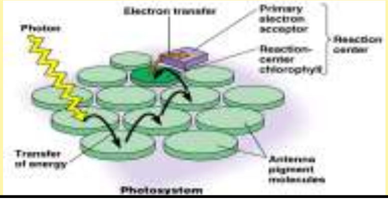


PHOTOSYSTEMS:

- ***are groups of pigments and other molecules on the surface of the thylakoid.***



- In the thylakoid membrane, chlorophyll is organized along with proteins into **photosystems**.
- A photosystem acts like a light-gathering “antenna complex” consisting of a few hundred chlorophyll *a,* chlorophyll *b,*and carotenoid molecules.



Photosystem I

- the reaction center has a specialized chlorophyll a molecule known as P700 (the far red portion of the spectrum)

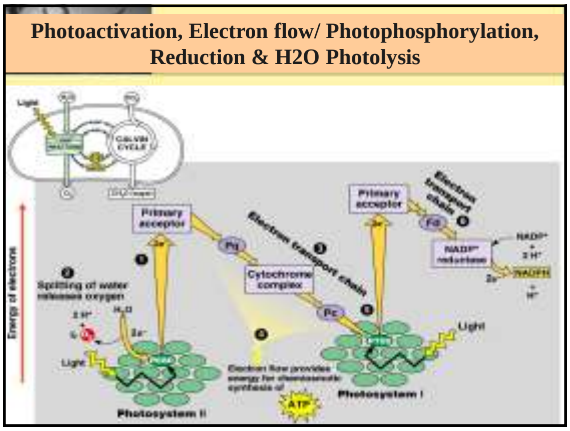
Photosystem II

- the reaction center has a specialized chlorophyll a molecule known as P680, which absorb best at a wavelength of 680nm.

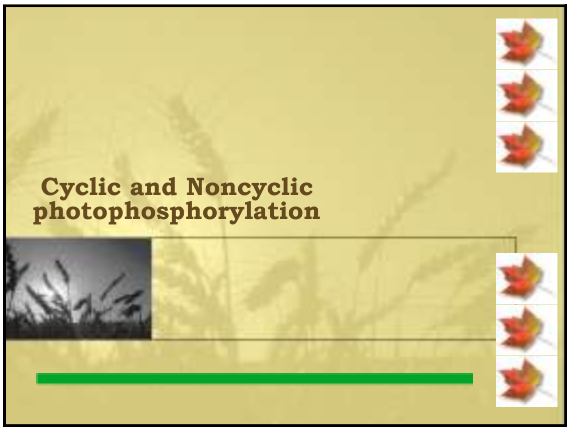
☻These two photosystems work together to use light energy to generate ATP and NADPH.

Two different systems for flow of electrons in photosynthesis,

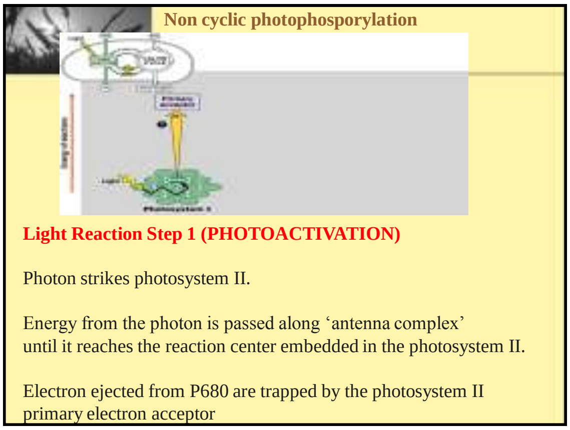
1. Non-cyclic electron flow
   - both photosystem I and photosystem II function and cooperate.
   - passes electrons continuously from water to $NADP^+$
   - produces NADPH + H^+ and ATP and also produces oxygen
2. Cyclic electron flow
   - involves only photosystem I
   - produces only ATP



Photoactivation, Electron flow/ Photophosphorylation, Reduction & H2O Photolysis



Cyclic and Noncyclic photophosphorylation



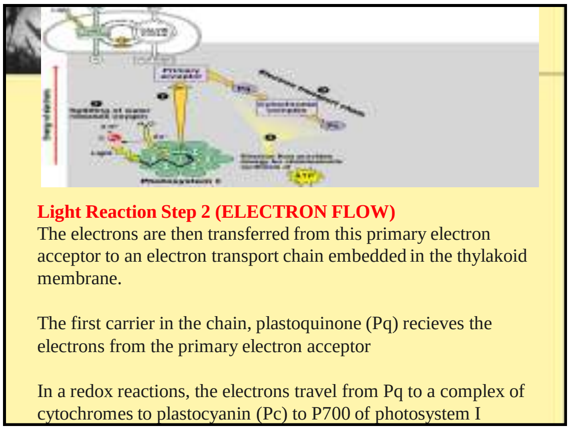
Non cyclic photophosporylation

Light Reaction Step 1 (PHOTOACTIVATION)

Photon strikes photosystem II.

Energy from the photon is passed along ‘antenna complex’ until it reaches the reaction center embedded in the photosystem II.

Electron ejected from P680 are trapped by the photosystem II primary electron acceptor

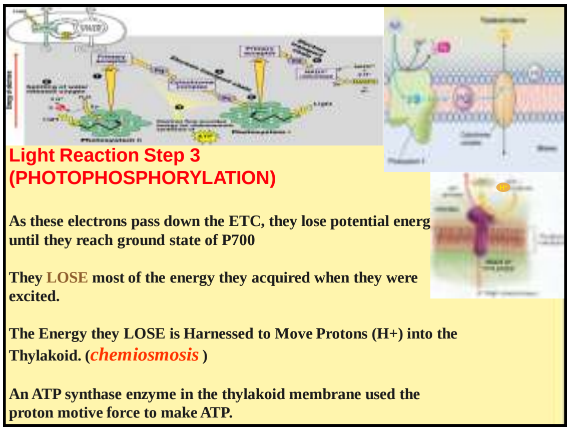


Light Reaction Step 2 (ELECTRON FLOW)

The electrons are then transferred from this primary electron acceptor to an electron transport chain embedded in the thylakoid membrane.

The first carrier in the chain, plastoquinone (Pq) recieves the electrons from the primary electron acceptor

In a redox reactions, the electrons travel from Pq to a complex of cytochromes to plastocyanin (Pc) to P700 of photosystem I



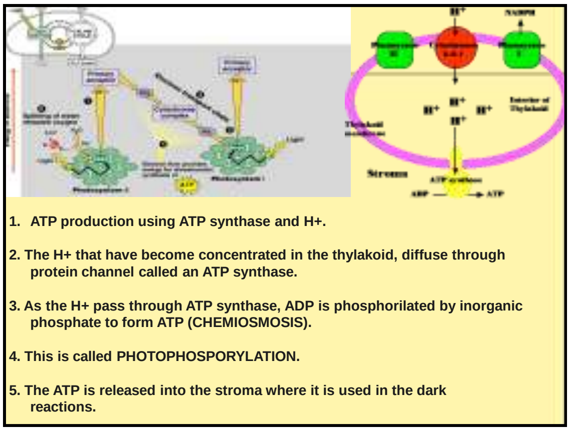
Light Reaction Step 3 (PHOTOPHOSPHORYLATION)

As these electrons pass down the ETC, they lose potential energ until they reach ground state of P700

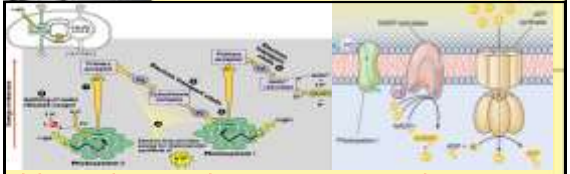
They LOSE most of the energy they acquired when they were excited.

The Energy they LOSE is Harnessed to Move Protons (H+) into the Thylakoid. (*chemiosmosis*)

An ATP synthase enzyme in the thylakoid membrane used the proton motive force to make ATP.



1. **ATP production using ATP synthase and H+.**
2. **The H+ that have become concentrated in the thylakoid, diffuse through protein channel called an ATP synthase.**
3. **As the H+ pass through ATP synthase, ADP is phosphorilated by inorganic phosphate to form ATP (CHEMIOSMOSIS).**
4. **This is called PHOTOPHOSPORYLATION.**
5. **The ATP is released into the stroma where it is used in the dark reactions.**



Light Reaction Step 4 (REDUCTION OF NADP+).

At the P700, Photon hits PSI. the excited state electrons are transferred from P700 to the primary electron acceptor for PSI

The primary electron acceptor passed these excited state electrons to ferredoxin (Fd)

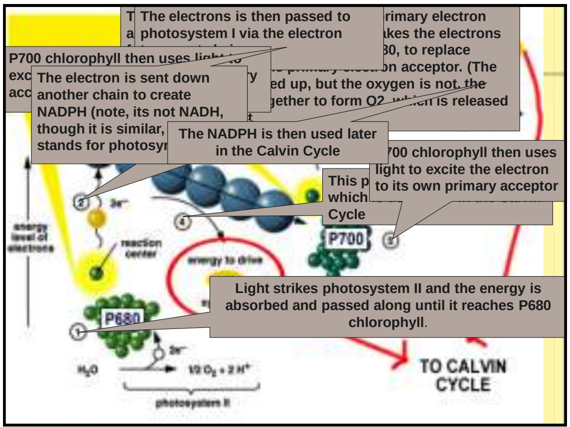
NADP+ reductase catalyzes transfers these electrons from ferredoxin to NADP+, producing NADPH. The NADPH will later carry the electrons and hydrogen ions into the Calvin cycle

The oxidized P700 chlorophyll at PSI becomes an oxidizing agent as its electron "hole" must be filled; P680 at PSII supplies the electrons to fill these holes

WATER PHOTOLYSIS

Electrons from P680 flow to P700 during noncyclic electron flow, restoring the missing electrons in P700 this however, leaves the P680 reaction center of photosystem II with missing electrons; the oxidized P680 chlorophyll thus becomes a strong oxidizing agent

- A water-splitting enzyme extract electrons from water and passes them to oxidized P680, which has high affinity for electrons.
- As water is oxidized, the removal of electrons splits water into two hydrogen ions (proton) and oxygen atom (photolysis)
- The oxygen atom is released as a by-product that used in cellular respiration



T a

The electrons is then passed to photosystem I via the electron

rimary electron akes the electrons 80, to replace on acceptor. (The ed up, but the oxygen is not. the gether to form O2 which is released

P700 chlorophyll then uses light to exc acc y

The electron is sent down another chain to create NADPH (note, its not NADH, though it is similar, stands for photosyn

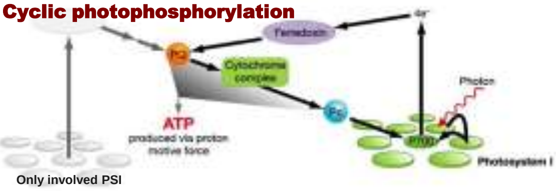
The NADPH is then used later in the Calvin Cycle

700 chlorophyll then uses light to excite the electron to its own primary acceptor

This p which Cycle

Light strikes photosystem II and the energy is absorbed and passed along until it reaches P680 chlorophyll.

Mechanical analogy



Cyclic photophosphorylation

Only involved PSI

As photon are absorbed by PSI, the P700 reaction released excited state electrons to the primary electron acceptor; which it passed them to the ferredoxin,

And to Pq, to cytochromes complex, to (Pc) before returning to chlorophyll.

During ETC, electron lose potential energy until they return to their ground-state in the P700 reaction center

This produces a proton-motive force, pumping H+ ions across the membrane; this produces a concentration gradient which can be used to power ATP.

The P700 gets back an electron from the last electron carier at the end of the chain.

The cyclic phosphorylation supplements the ATP supply required for the Calvin cycle

The noncyclic pathway produces approximately equal amounts of ATP and NADPH, which is not enough ATP to meet demand.

In Calvin cycle ATP is used more compare with NADPH. When ATP is not enough in chloroplast, Calvin cycle becomes slowly.

So **cyclic phosphorylation is take places** until the ATP is enough.

STATE THE DIFFERENCES BETWEEN CYCLIC & NON-CYLIC PHOTOPHOSPHORYLATION

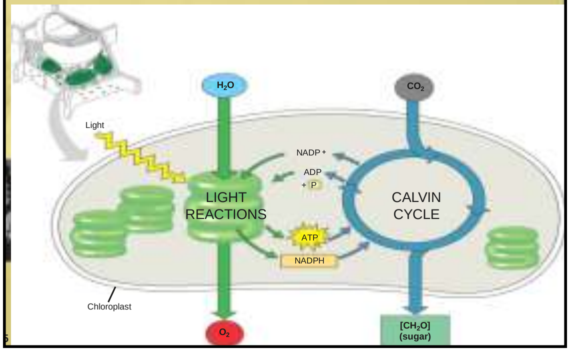
Photophosphorylation	**Cyclic**	**Non Cyclic**
Electron Flow	Cyclic	Non Cyclic
1st Electron Donor	Water	PSI
Last Electron Acceptor	NADP+	PSI
Products	ATP, NADPH & O_2	ATP
PS involved	PS I & PSII	PS I
Photolysis of Water	Occur	Not occur

PHOTOSYNTHESIS

6.4 LIGHT INDEPENDENT REACTION / DARK REACTION

CALVIN CYCLE IN C_3 PLANTS

- **An overview of photosynthesis**



❖They occur whether there is light present or not.

❖Only depend on the presence of the energy carriers **ATP and NADPH** made during the light dependent reactions.

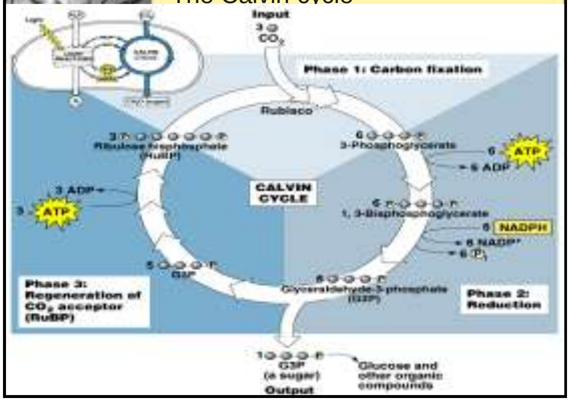
❖Occur in the part of the chloroplast known as the stroma.

❖Take the energy from ATP and energized electrons and hydrogen ions from NADPH and add them to CO2 to make glucose or sugar.

CALVIN CYCLE

- The stage of photosynthesis where the CO_2 and H_2O are converted into a carbohydrate
- The carbohydrate produced and released from the Calvin cycle is **glyceraldehyde-3-phosphate** (3 carbon compound) - not glucose!
- The ATP and NADPH from the light reaction are used to supply electrons and reducing power LIR.
- Synthesize of **one molecule of sugar** (PGAL)/simpler sugar, **three molecules of CO_2 must enter the cycle.**
- Occurs in the stroma of the chloroplast and each stage is mediated by an enzyme.

- The Calvin cycle



Stage 1 : Carbon dioxide fixation

a) To begin the Calvin cycle, a molecule of CO_2 reacts with a 5C called ribulose 1,5- bisphosphate (RuBP) , catalyzed by the enzyme RuBp carboxylase (Rubisco)

b) Producing an unstable 6C intermediate which immediately breaks down into two molecules of the 3C phosphoglycerate (PGA) per CO_2

c) For every three CO_2 molecules that enter the Calvin cycle, three RuBP molecules are carboxylated forming 6 molecules of 3-phosphoglycerate (PGA).

Stage 2 : Carbon dioxide reduction

Occurs in two steps:

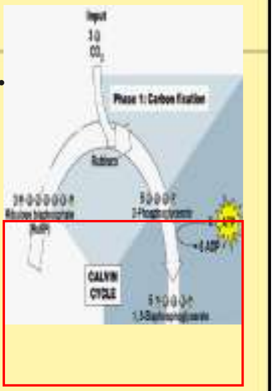
1. Phosphorylation of PGA by ATP to form a PGAP.
2. Reduction of PGAP to form PGAL (triose phosphate), a simple 3-carbon carbohydrate by NADPH

The NADP⁺ and ADP formed in this process return to the thylakoids to regenerate NADPH and ATP in the light reactions.

1.Phosphorylation of PGA by ATP to form a PGAP.

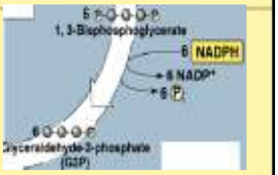
During reduction, each 3-phosphoglycerate receives another phosphate group from ATP to form **1,3-bisphosphoglycerate (PGAP)**

Uses six ATP molecules to produce six molecules of 1,3-bisphosphoglycerate.

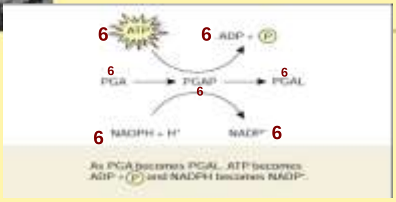


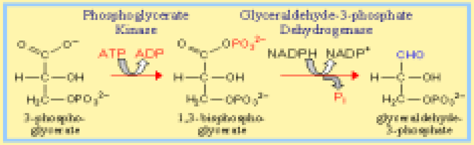
2. Reduction of PGAP to form PGAL, a simple 3-carbon carbohydrate.

- Electrons from NADPH reduce the carboxyl group of 1,3-bisphosphoglycerate (PGAP) to the aldehyde group of **glyceraldehyde-3-phosphate (PGAL)**
- The product, PGAL, stores more potential energy than the initial reactant, 3-phosphoglycerate



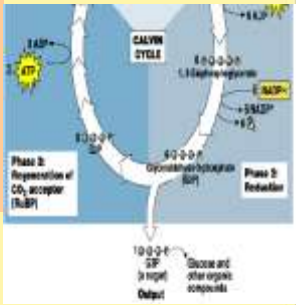
- The NADP⁺ and ADP formed in this process return to the thylakoids to regenerate NADPH and ATP in the light reactions.





- For every three CO_2 molecules that enter the Calvin cycle, 6 PGAL/G3P molecules are produced (18 carbons).
- Only 1 molecule of PGAL/ G3P (3 carbons) be used to synthesize one molecule of 6C glucose.

  - This molecule exit the Calvin cycle to be used by plant cell.
- The other 5 PGAL/G3P molecules (15 carbons) must remain in the cycle to regenerate three molecules of RuBP in order for the cycle to continue.



THE IMPORTANCE OF CALVIN CYCLE

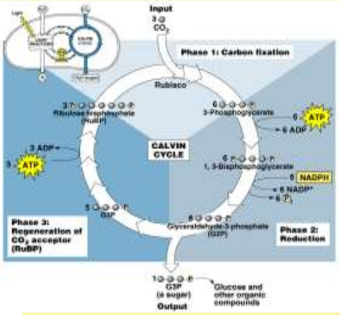
- **PGAL (glyceraldehyde-3-phosphate)** is the product of the Calvin cycle that can be converted to a variety of organic molecules.
  - A plant can utilize the hydrocarbon skeleton of PGAL to form fatty acids and glycerol, which are combined in plant oils.

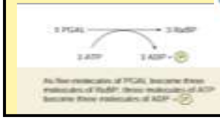
Stage 3 : Ribulose bisphosphate regeneration

Regeneration of the CO2 acceptor RuBP

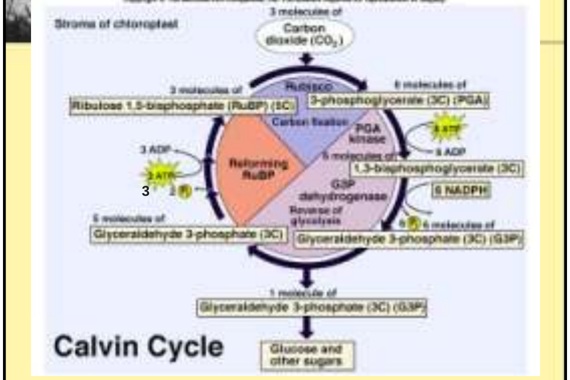
A complex series of reactions rearranges the carbon skeletons of five PGAL molecules into three RuBP molecules.

These reactions require three ATP molecules, this ATP formed in light reactions.

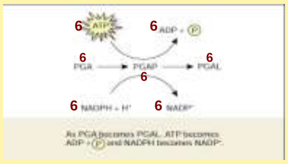




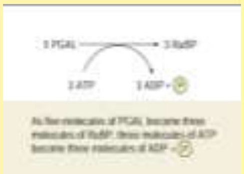
As five molecules of PGAL became three molecules of RuBP, three molecules of ATP became three molecules of ADP + P



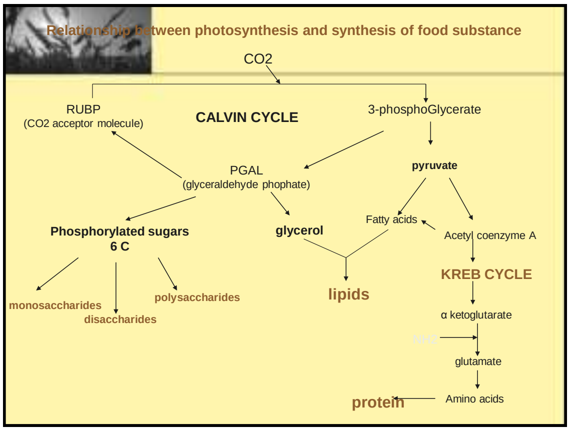
- **For the net synthesis of one PGAL/G3P molecule, the Calvin recycle consumes 9 ATP and 6 NAPDH.**
  - It "costs" three ATP and two NADPH per CO_2.
- **The Calvin cycle uses 18 ATP and 12 NADPH molecules to produce one glucose molecule.**



As PGA becomes PGAL, ATP becomes ADP + P and NADPH becomes NADP⁺.



As five molecules of PGAL became three molecules of RuBP, three molecules of ATP became three molecules of ADP + P



Relationship between photosynthesis and synthesis of food substance

CO2

RUBP
(CO2 acceptor molecule)

CALVIN CYCLE

3-phosphoGlycerate

PGAL
(glyceraldehyde phophate)

pyruvate

Phosphorylated sugars
6 C

glycerol

Fatty acids

Acetyl coenzyme A

KREB CYCLE

monosaccharides

disaccharides

polysaccharides

lipids

α ketoglutarate

NH2

glutamate

Amino acids

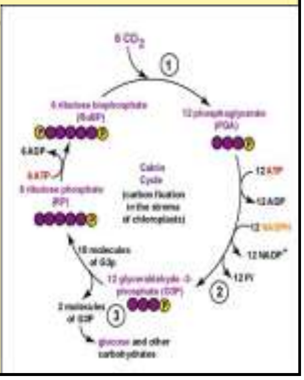
protein

Overall, for every 3 cycle, 1 molecule of product is formed ($3CO_2$:6G3P). One molecule 3-carbons (1G3P) exit the Calvin cycle as PGAL (simple sugar). The remaining 15 carbon atoms (5 G3P) re-enter the cycle to produce three molecules of RuBP

To form 1 molecule of glucose need (6 CO2: 12 G3P). Two molecule G3P exit Calvin cycle to form 1 glucose molecules

G3P formed in the Calvin cycle can remain in the chloroplast where it is converted to **starch**

Alternatively, G3P can be exported from the chloroplast where it is converted to **sucrose** in the cytosol



PHOTOSYNTHESIS

LIGHT INDEPENDENT REACTION

HATCH-SLACK PATHWAY

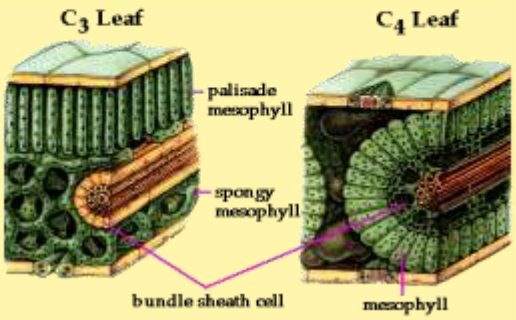
IN C_4 PLANTS

OBJECTIVES:

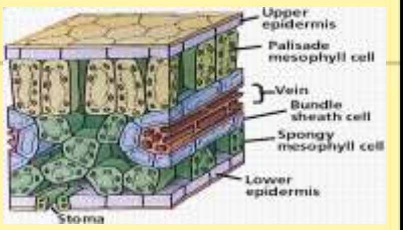
To explain the reduction of the rate of photosynthesis in C3 plants due to photorespiration.

To explain Hatch-Slack pathway (C4 plants)

Difference in the anatomy and physiology of the leaves of C_3 and C_4 plants



C_3 leaf



- C_3 Plant
  - is called a C_3 plant because the first stable compound formed from CO_2 is a three carbon compound (PGA) at the beginning of the Calvin cycle. (controlled by Rubisco)
  - The stereotypical photosynthetic plant.
  - Most plants, ex. bean, apple, tomato, tropical foliage plants
  - Day - stomata open, fix CO_2 by Dark Reaction into 3-carbon sugar acids Night - stomata close

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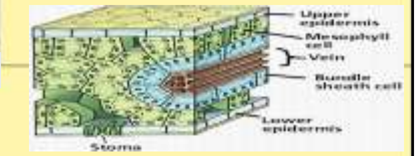
C_4 leaf



- C_4 plant
  - because the first organic compound incorporating CO_2 is a four carbon compound (malate). (controlled by PEP carboxylase)
  - C_4 plants show a leaf anatomy called Kranz anatomy.
    - mesophyll cells are arranged in a layer around the bundle sheath cells.
    - mesophyll cells and bundle sheath cells contain chloroplasts.
    - The light reactions take place in the mesophyll cells, but the Calvin cycle takes place in the bundle sheath cells.
    - Transport between mesophyll and bundle sheath cells is made possible by plasmodesmata.
    - Examples - some grasses, ex. corn, sugarcane, sorghum
    - Day - stomata open
      Night - stomata close

Alternative mechanisms of carbon fixation have evolved in hot, dry climates

- **One of the major problems facing terrestrial plants is dehydration.**
- **The stomata are not only the major route for gas exchange (CO_2 in and O_2 out), but also for the evaporative loss of water.**
- **On hot, dry days plants close the stomata to conserve water, but this causes problems for photosynthesis.**
- **In most plants (C_3 plants) initial fixation of CO_2 occurs via rubisco and results in a 3-carbon compound, 3-phosphoglycerate.**
  - **These plants include rice, wheat, and soybeans.**

- **When their stomata are closed on a hot, dry day, CO_2 levels drop but CO_2 is consumed in the Calvin cycle.**
- **At the same time, O_2 levels rise as the light reaction converts light to chemical energy.**
- **While rubisco normally accepts CO_2, when the O_2 ratio increases (on a hot, dry day with closed stomata), rubisco can add O_2 to RuBP, this process called photorespiration.**
  - **"photo" – light**
  - **"respiration" – this process uses O_2 and released CO_2**

Rubisco
(carboxylase)
High CO_2 → Carbon fixation

Rubisco
(oxygenase)
High O_2 → Photorespiration

PHOTORESPIRATION

- **A metabolic pathway that consumes oxygen, released carbon dioxide,**
  - Occurs during hot, dry and bright days.
  - Occurs because the active site of rubisco can accept O_2 as well as CO_2.
  - Used ATP and NADPH
  - Decreases photosynthetic output by reducing organic molecules used in the Calvin cycle.

- Photosynthesis than depletes available CO_2 and increases O_2 within the leaf's air spaces.
- When the O_2 concentration in the leaf's air spaces is higher than CO_2 concentration, rubisco accepts O_2 and transfers it to RuBP.
- Plants which are photorespiration can lose up to 30-40% of the carbohydrate that they would otherwise have produced under those conditions.
- When rubisco adds O_2 to RuBP, RuBP splits into a 2-carbon piece (phosphoglycolate) and a 3-carbon piece (PGAL/G3P).
- The 2-carbon fragment is exported from the chloroplast and degraded to CO_2 by mitochondria and peroxisome.

Rubisco transfer O_2 to RuBP

↓

Resulting 5-C molecule splits into

2-C molecule (glycolate)

↓

Leaves chloroplast & goes to peroxisome

↓

A metabolic pathway begins in the peroxisome and is completed in The mitochondrion

↓ glycolate is broken down into

$H_2O + CO_2$

3-C molecule (3-phosphoglycerate)

↓

stay in the Calvin cycle

Unlike normal respiration, this process produces no ATP, Photorespiration *decreases* photosynthetic output

---

- **Photorespiration can drain away as much as 50% of the carbon fixed by the Calvin cycle on a hot, dry day.**
- **Certain plant species have evolved alternate modes of carbon fixation to minimize photorespiration.**
- **Many plant species preface the Calvin cycle with reactions that incorporate CO_2 into four-carbon compounds.**
  - **These plants are called C_4 plants.**
  - **C_4 plants include corn and sugarcane.**

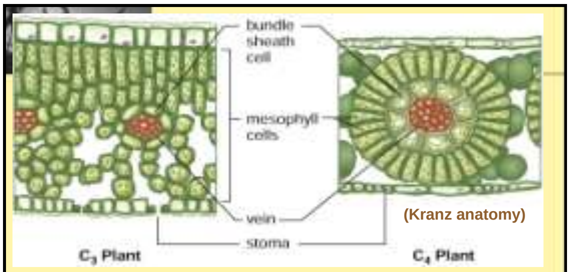
HATCH-SLACK PATHWAY
(C4 Plants)

- **This pathway is adaptive because it enhances CO_2 fixation under conditions that <u>avoid photorespiration</u>, such as hot, arid climates.**
- **Leaf anatomy of C_4 plants spatially segregates the Calvin cycle from the initial incorporation of CO_2 into organic compounds.**
- **There are 2 distinct types of photosynthetic cells:**

  1). Bundle-sheath cells

  2). Mesophyll cells

- **This distinctive arrangement is called Kranz anatomy.**



1). Bundle-sheath cells

- Arranged into tightly packed sheaths around the vein of the leaf

2). Mesophyll cells

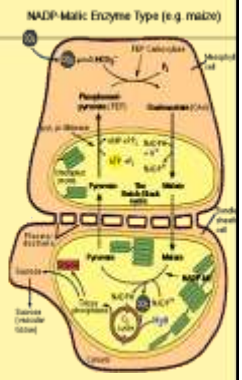
- are more loosely arranged in the area between the bundle-sheath and the leaf surface.

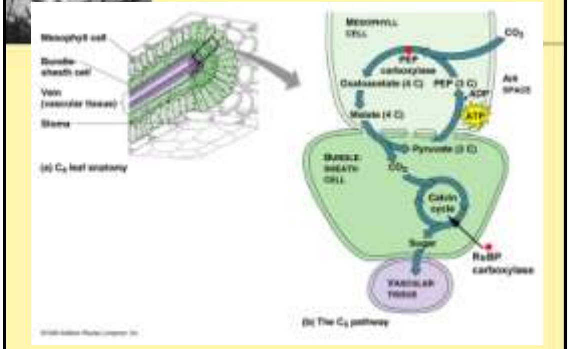
- In C4 plants, mesophyll cells incorporate CO2 into organic molecules.

- PEP carboxylase has a very high affinity for CO2and can fix CO2 efficiently when rubisco cannot, i.e. on hot, dry days when the stomata are closed.

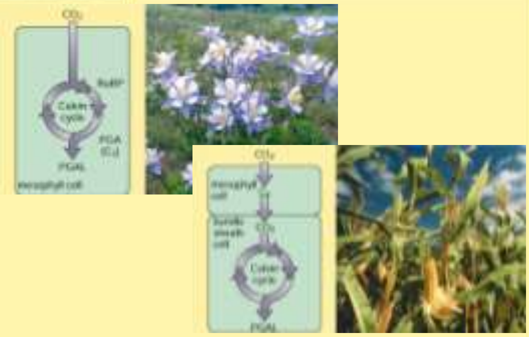
- CO_2 is added to phospoenolpyruvate (PEP) – 3C to form oxaloacetate, a four-carbon product.
  - Phosphoenolpyruvate carboxylase (pepco) is the enzyme that adds CO_2 to PEP.
  - Pepco has much greater affinity for CO_2 and has no affinity for O_2
  - Pepco can fix CO_2 efficiently when rubisco cannot, under hot, dry days with the stomata closed.

- After CO_2 has been fixed by mesophyll cells, they convert oxaloacetate to another four-carbon compound, malate.
- Oxaloacetate is in turn converted into the intermediate malate, which is transported to an adjacent bundle-sheath cell.
- Inside the bundle-sheath cell, malate is decarboxylated to produce pyruvate (3C) and releasing CO_2
- Pyruvate returns to the mesophyll cell where it is phosphorylated by ATP to become phosphoenolpyruvate (PEP), thus completing the cycle.
- C4 photosynthesis minimizes photorespiration and enhances sugar production.
- C4 plants thrive in hot regions with intense sunlight.

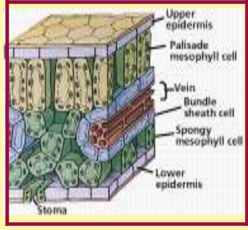
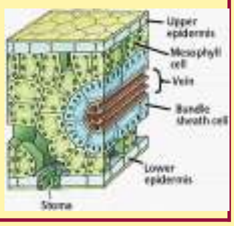




Carbon Dioxide Fixation in C_3 and C_4 Plants

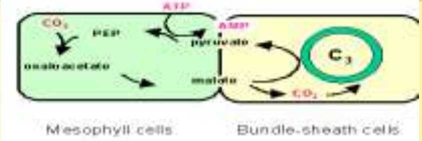


DIFFERENCES BETWEEN C3 AND C4 PLANTS

C3	C4
	

	C3	C4	
CO2 fixation	Occurs once	Occurs twice, first in mesophyll cells, then in bundle sheath cells	
CO2 acceptor	RuBP, a 5C compound	Mesophyll cells PEP, a 3C compound	Bundle sheath cells RuBP
CO2 fixing enzyme	RuBP carboxylase	PEP carboxylase which is very efficient	RuBP carboxylase
First product of photosynthesis	A C3 acid, G3P	A C4 acid, Oxaloacetate	
Photorespiration	Occurs ; therefore O2 is an inhibitor of photosynthesis	Is inhibited by high CO2 concentration. Therefore atmospheric O2 not an inhibitor of photosynthesis	
Efficiency	Less efficient photosynthesis than C4 plants. Yields usually much lower	More efficient photosynthesis than C3 plants. Yields usually much higher	

SUMMARY OF THE PROCESS



Part - I (in mesophyll cells)

(i) **First CO2 Fixation:** In the pathway, the first CO2 acceptor is the 3C phosphoenol pyruvate acid (PEP). CO2 first combines with 3C PEP to form 4C OAA (oxaloacetic acid). As OAA is a dicarboxylic acid, this is also known as the **dicarboxylic acid pathway**.

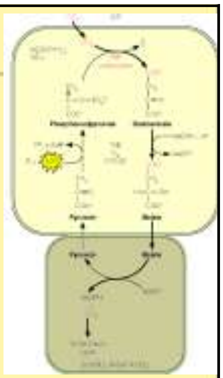
(ii) 4C OAA may be converted into 4C malic acid or 4C aspartic acid and transported to bundle sheath cells.

Part - II (in bundle sheath cells)

(i) In the chloroplasts of the bundle sheath cells, 4-C malic acid undergoes decarboxylation to form CO2 and 3-C pyruvic acid.

(ii) **Second CO2 fixation :** The CO2 released in decarboxylation of malic acid combines with 5-C RUBP (ribulose biphosphate) to form 2 molecules of 3-C PGA as in the Calvin cycle. Further conversion of PGA to sugars is the same as in the Calvin cycle.

(iii) The pyruvic acid produced in decarboxylation of malic acid is transported back to the mesophyll cells. Here it is converted into PEP and again made available for the C4 pathway.



PHOTOSYNTHESIS

LIGHT INDEPENDENT REACTION

CRASSULACEAN ACID METABOLISM (CAM)

THE CRASSULACEAN ACID PATHWAY (CAM)

- A second strategy to minimize photorespiration is found in **succulent plants, cacti, pineapples** and several other plant families.
- These plants, known as **CAM plants** for crassulacean acid metabolism (CAM), open **stomata during the night and close them during the day.**
  - Temperatures are typically lower at night and humidity is higher

Cacti

teddy bear cholla

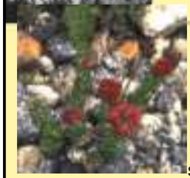
Barrel

Agave (yucca)

yucca

Century plant

Crassulaceae



Sedum rosea

Crassula aquatica

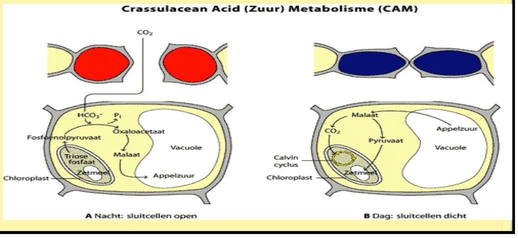
Orchids

Dendrobium

Bromeliads

(pineapples, "air plants"--epiphytes such as Spanish moss)

- **During the night, these plants fix CO_2 into organic acids in mesophyll cells using the C_4 pathway.**
- **These organic compound accumulate throughout the night (in the vacuole) and are decarboxylated during the day.**
- **During the day, the light reactions supply ATP and NADPH to the Calvin cycle and CO2 is released from the organic acids made the previous night**



- Both C_4 and CAM plants add CO_2 into organic intermediates before it enters the Calvin cycle.
  - In C4 plants, carbon fixation and the Calvin cycle are spatially separated.
  - In CAM plants, carbon fixation and the Calvin cycle are temporally separated.
- Both eventually use the Calvin cycle to incorporate light energy into the production of sugar.
- Less than 5% plants (e.g. cactus) have another biochemical adaptation that allows them to survive hot and dry environments – CAM plants (*crassulacean acid metabolism*)
- They utilize PEP carboxylase to fix CO2, just like C4 plants
- Unlike C4 plants, CAM plants conduct the light dependent reactions and CO2 fixation at different times of the day, rather than in different cells of the leaf

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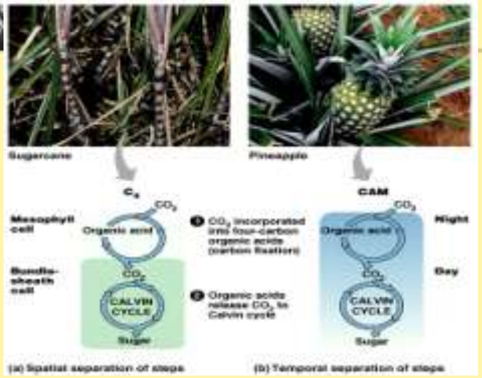
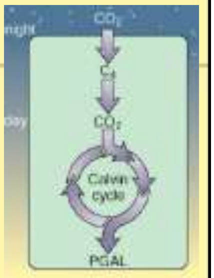


Steps of CAM photosynthesis in a mesophyll cell:



During the Night

stomates are open – CO_2 is taken up

↓

CO_2 is fixed by PEP carboxylase
by combining with PEP

↓

to form oxaloacetate - 4-C organic acid

↓

transformed (reduced by NADPH) to malate

↓

Malate (in chloroplast) is then shuttled
into the vacuole, where it is stored
in high concentrations

During daylight

Stomata are closed - preventing CO_2 uptake

↓

Light dependent reaction – ATP and NADPH

↓

malate is transported out of the vacuole to chloroplast,
where it is decarboxylated to

CO_2 pyruvate

↓

combining with RuBP

↓

Calvin cycle
(CO_2 is fixed by C_3 photosynthesis)

CAM MECHANISM

- During the night, stomata are open
- CO_2 enters the leaf tissue
- CO_2 + PEP → Oxaloacetate → Malate
- Malate is transported into the vacuole
- During the day, stomata are closed
- Malate is moved into the chloroplasts
- Malate → CO_2 + Pyruvate
- CO_2 enters Calvin cycle

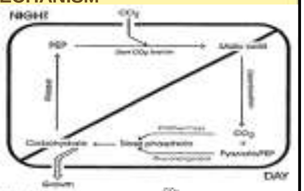


Fig. 1

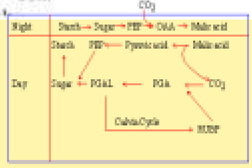


Figure 4.8 Schematic representation of the CAM pathway

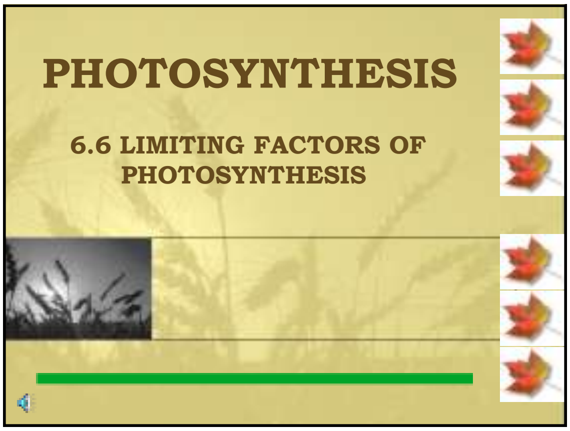
Variation in Carbon Fixation

- C3 Plants
  - 3-Carbon PGA is first intermediate
  - Evergreen trees and shrubs, temperate nonwoody plants
- C4 Plants
  - 4-Carbon oxaloacetate is first intermediate
  - Carbon is fixed twice; two different locations
  - Grasses and plants that evolved in tropics
- CAM Plants
  - Fix carbon in same cells at different times
  - Stomata open at night
  - Adaptation to desert conditions

CO_2 fixation in a C_3 plant

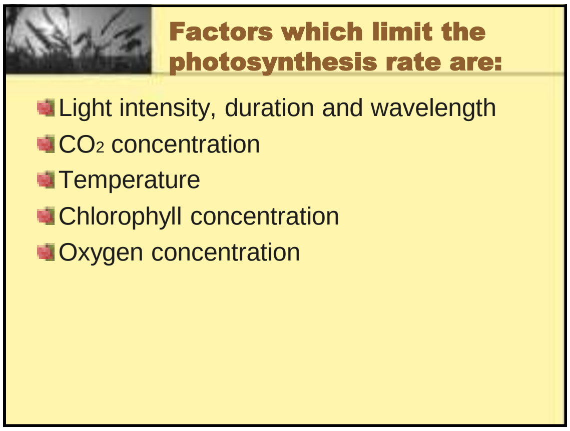
CO_2 fixation in a C_4 plant

CO_2 fixation in a CAM plant



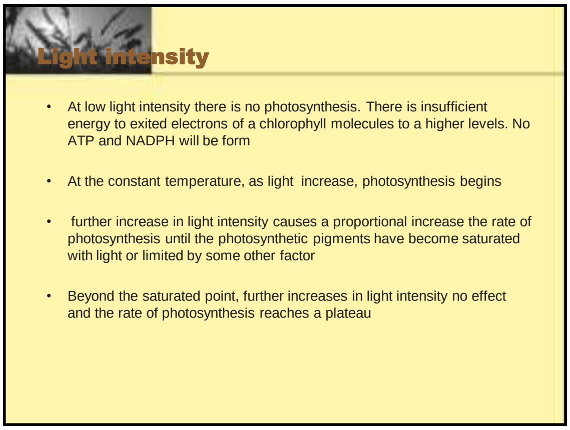
PHOTOSYNTHESIS

6.6 LIMITING FACTORS OF PHOTOSYNTHESIS



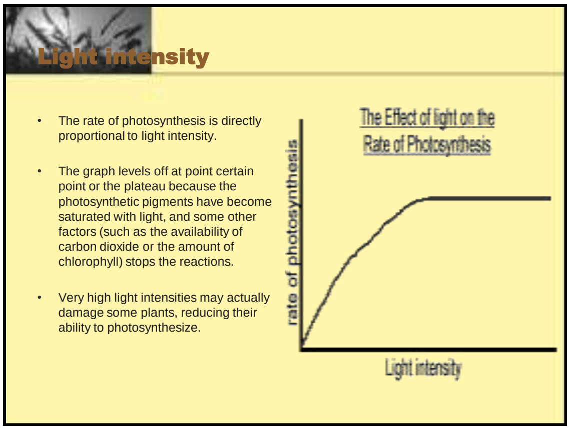
Factors which limit the photosynthesis rate are:

- Light intensity, duration and wavelength
- CO2 concentration
- Temperature
- Chlorophyll concentration
- Oxygen concentration



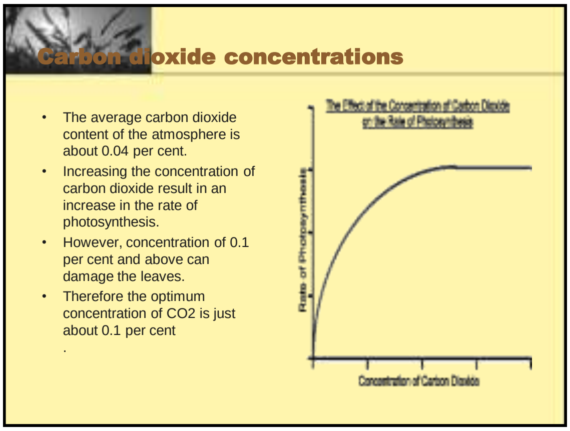
Light intensity

- At low light intensity there is no photosynthesis. There is insufficient energy to exited electrons of a chlorophyll molecules to a higher levels. No ATP and NADPH will be form
- At the constant temperature, as light increase, photosynthesis begins
- further increase in light intensity causes a proportional increase the rate of photosynthesis until the photosynthetic pigments have become saturated with light or limited by some other factor
- Beyond the saturated point, further increases in light intensity no effect and the rate of photosynthesis reaches a plateau



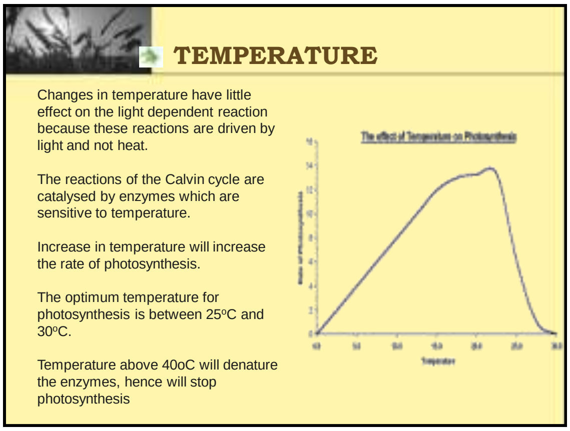
Light intensity

- The rate of photosynthesis is directly proportional to light intensity.
- The graph levels off at point certain point or the plateau because the photosynthetic pigments have become saturated with light, and some other factors (such as the availability of carbon dioxide or the amount of chlorophyll) stops the reactions.
- Very high light intensities may actually damage some plants, reducing their ability to photosynthesize.



Carbon dioxide concentrations

- The average carbon dioxide content of the atmosphere is about 0.04 per cent.
- Increasing the concentration of carbon dioxide result in an increase in the rate of photosynthesis.
- However, concentration of 0.1 per cent and above can damage the leaves.
- Therefore the optimum concentration of CO2 is just about 0.1 per cent
  .



TEMPERATURE

Changes in temperature have little effect on the light dependent reaction because these reactions are driven by light and not heat.

The reactions of the Calvin cycle are catalysed by enzymes which are sensitive to temperature.

Increase in temperature will increase the rate of photosynthesis.

The optimum temperature for photosynthesis is between 25ºC and 30ºC.

Temperature above 40oC will denature the enzymes, hence will stop photosynthesis

Law of limiting factors.

- Under natural condition, plants are subjected to many factors such as temperature, carbon dioxide concentration and light intensity simultaneously.

Compensation point.

- Compensation point is defined as *the point at which the rate of photosynthesis in a plant is in exact balance with the rate of respiration, so there is no net exchange of carbon dioxide or oxygen.*
- The compensation point is usually related to a particular light intensity or carbon dioxide level.
- Light compensation point is the light intensity at which the rate of photosynthesis is exactly balanced by the rate of respiration.

Reactant and Product Summary

Molecule	Source	Other
CO_2	Reactant. Enters leaf from the air.	Created by glycolysis and respiration processes in the cell.
H_2O	Reactant. Enters leaf through roots.	Naturally occurring. Also made in respiration.
$C_6H_{12}O_6$	Product. Made in chloroplast.	Primary chemical energy source for plants and animals. Made during light independent reactions (Calvin Cycle).
O_2	Product. Made in chloroplast.	Used by plants and animals in respiration. Made during light dependent reactions.

Concept Map on Photosynthesis