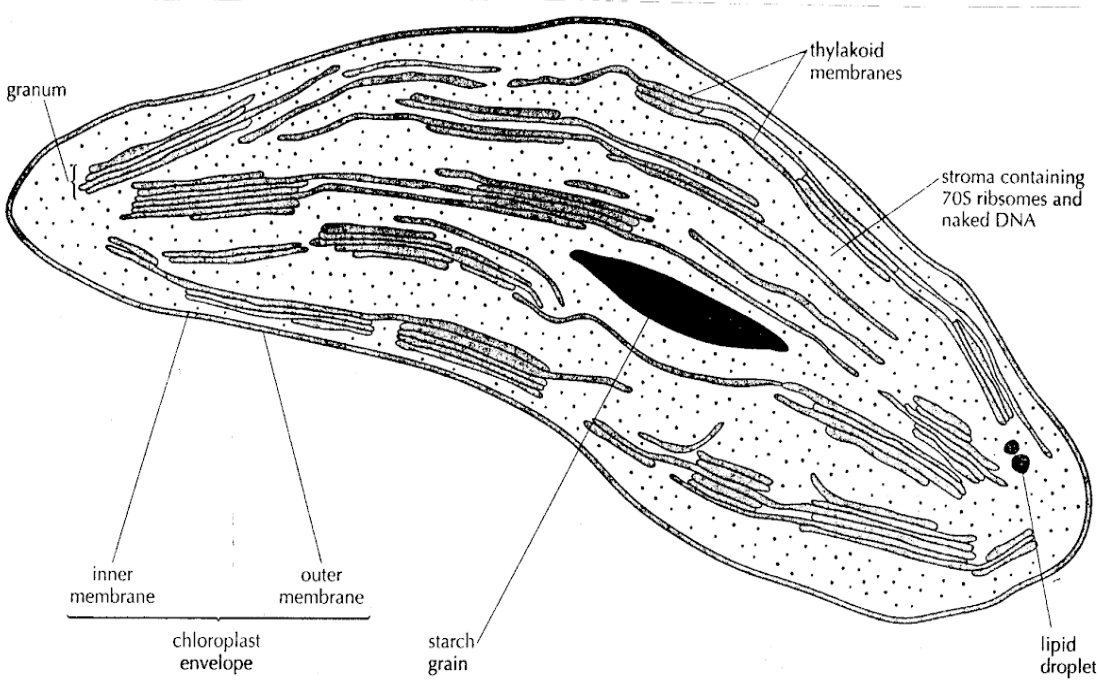
TOPIC 8: Photosynthesis & cell respiration

Photosynthesis involves many chemical reactions. Some of them need a continual supply of light, while others need light indirectly.

The structure of a chloroplast as seen in electron micrographs:



- Photosynthesis is a two stage process consisting of a) ***light - dependent*** and b) ***light - independent*** reactions.

- The light dependent reactions occur on the chloroplast membranes and the light independent reactions in the chloroplast stroma.

a) Light- dependent reactions

- Light absorption
- Production of ATP
- Production of NADP
- Production of oxygen

Light absorption

Chlorophyll absorbs light and the energy from the light raises an electron in the chlorophyll molecule to a higher energy level.

The electron at a higher energy level is an **excited electron** and the chlorophyll is **photoactivated.**

In single chlorophyll molecules the excited electron soon drops back down to its original level, re-emitting the energy.

Chlorophyll is located in thylakoid membranes and is arranged in groups of hundreds of molecules, called **photosystems**. There are two types of photosystems (I, II).

Excited electrons from absorption of photons of light anywhere in the photosystem are passed from molecule to molecule until they reach a special chlorophyll molecule at the reaction center of the photosystem (**electron transport**). This chlorophyll passes the excited electron to a chain of electron carriers.

Production of ATP

An excited e^- from the reaction center of photosystem II is passed along a chain of carriers in the thylakoid membrane. It gives up some of its energy each time that it passes from one carrier to the next.

At one stage, enough energy is released to make a molecule of ATP. The coupling of electron transport to ATP synthesis is by **chemiosmosis**, as in the mitochondrion.

Electron flow causes a proton to be pumped across the thylakoid membrane into the fluid space inside the thylakoid and a proton gradient is created.

ATP synthase, located in the thylakoid membranes, lets the protons across the membrane down a concentration gradient and uses the energy released to synthesize ATP.

The production of ATP using the energy from an excited electron from Photosystem II is called **non-cyclic photophosphorylation**.

Production of NADP

After releasing the energy needed to make ATP, the electron that was given away by Photosystem II is accepted by Photosystem I. The electron replaces one previously given away by Photosystem I.

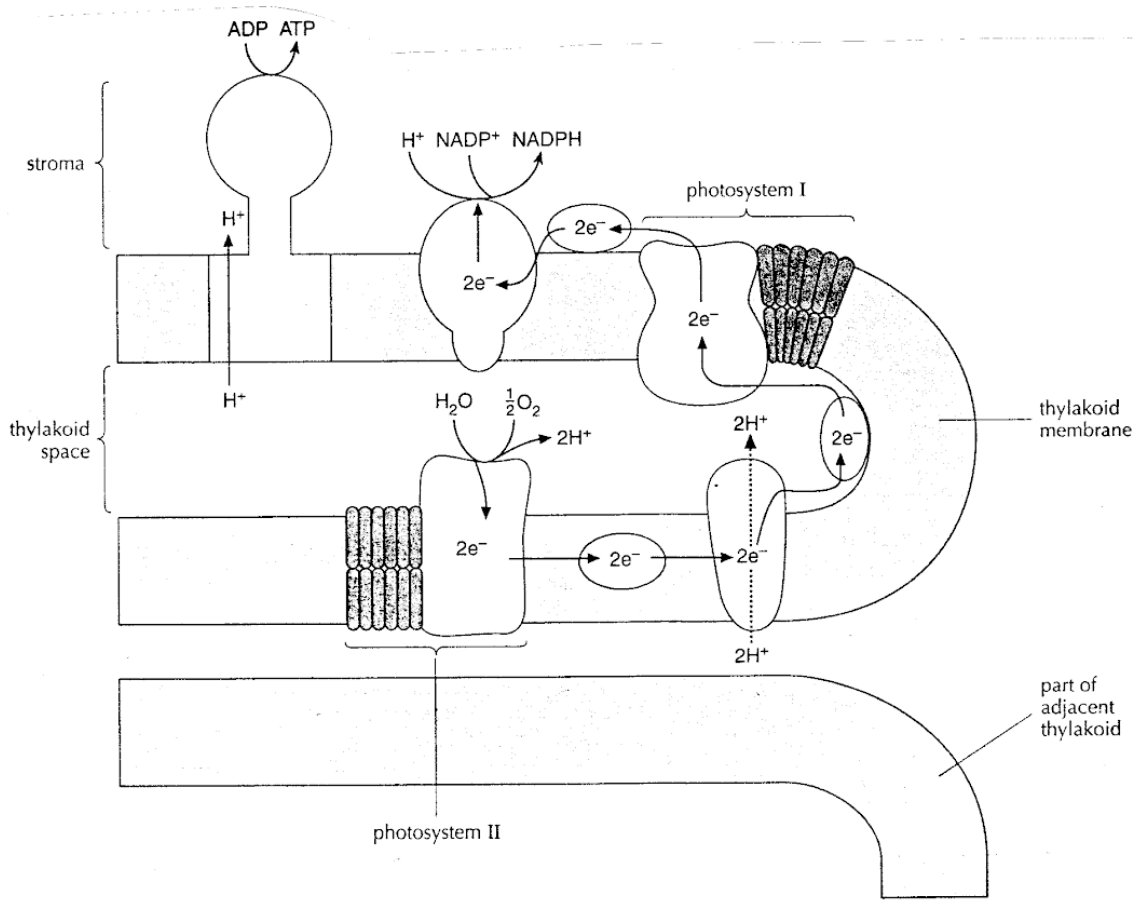
With this electron replaced, Photosystem I can be photoactivated by absorbing light and then give away another excited electron. This high-energy electron passes along a short chain of carriers to $NADP^+$ in the stroma. $NADP^+$ accepts two high-energy electrons from the electron transport chain and one H^+ ion from the stroma, to form NADPH.

Production of oxygen

Photosystem II needs to replace the excited electrons that it gives away. The special chlorophyll molecule at the reaction center is positively charged after giving away an electron. With the help of an enzyme at the reaction center, water molecules in the thylakoid space are split and electrons from them are given to chlorophyll.

Oxygen and H^+ ions are formed as by-products. The splitting of water molecules only happens in the light, so it is called **photolysis**. The oxygen produced in photosynthesis is all the result of photolysis of water. Oxygen is a waste product and is excreted.

Diagram of the light-dependent stage of photosynthesis



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Some extra notes on the light dependent reactions which you might find helpful!

Photosystem I & II

Each has each own characteristic set of chlorophyll molecules and different function and they are both involved in the light –reactions of photosynthesis.

Photolysis of water

The light dependent stage of photosynthesis occurs in the thylakoids of the chloroplasts and involves the splitting of water by light (photolysis). In the process, ADP is converted to ATP.

This addition of phosphorus is termed *phosphorylation* and as light is involved it is called *photophosphorylation.*

Cyclic and non-cyclic photophosphorylation

Electrons from chlorophyll are passed into the light-dependent reaction via $NADPH+H^+$. They are replaced by electrons from another source-the water molecule. The same electrons are *not* recycled back into the chlorophyll. This method of ATP production is thus called non-cyclic photophosphorylation.

There is a second method by which ATP can be generated. The electrons from the pigment system may return to the chlorophyll directly, via the electron carrier system, forming ATP in the process. Such electrons are recycled, harnessing energy from light and generating ATP. This is called cyclic photophosphorylation and involves only photosystem I. No reduced NADP is produced during cyclic photophosphorylation.

b) Light – independent reactions

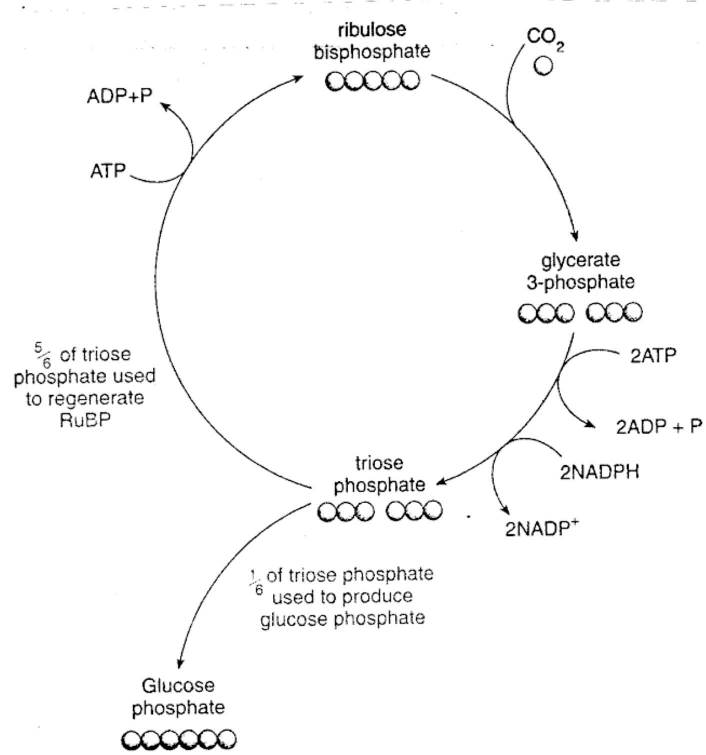
- The Calvin cycle
- Carbon fixation
- Regeneration of RuBP
- Synthesis of carbohydrate

The Calvin cycle

The light-independent reactions take place within the stroma of the chloroplast. The first reaction involves a five-carbon sugar, ribulose bisphosphate (RuBP). RuBP is also a product of the light-independent reactions, which therefore form a cycle, called the Calvin cycle.

There are many alternative names for the intermediate compounds in the Calvin cycle. Glycerate 3-phosphate is sometimes called 3-phosphoglycerate.

Diagram of the Calvin cycle



Carbon fixation

Carbon dioxide is an essential substrate in the light-independent reactions. It enters the chloroplast by diffusion. In the stroma of the chloroplast CO_2 combines with RuBP in a carboxylation reaction.

The reaction is catalyzed by the enzyme ribulose bisphosphate carboxylase **(rubisco)**. Large amounts of rubisco are present in the stroma, because it works rather slowly. The product of the reaction is a six-carbon compound, which immediately splits to form two molecules of glycerate 3-phosphate. This is therefore, the first product of carbon fixation.

Regeneration of RuBP

For carbon fixation to continue, one RuBP molecule must be produced to replace each one that is used. Triose phosphate is used to regenerate RuBP. Five molecules of triose phosphate are converted by a series of reactions into three molecules of RuBP.

This process requires the use of ATP. Finally, for every six molecules of triose phosphate formed in the light-independent reactions, five must be converted to RuBP.

Synthesis of carbohydrate

Glycerate 3-phosphate, formed in the carbon fixation reaction, is an organic acid. It is converted into a carbohydrate by a reduction reaction.

Hydrogen is needed to carry out this reaction and is supplied by NADPH. Energy is also needed and is supplied by ATP. Both NADPH and ATP are produced in the light-dependent reactions of photosynthesis.

Glycerate 3-phosphate is reduced to a three-carbon sugar, triose phosphate (TP). Linking together two triose phosphate molecules, glucose phosphate is produced. Starch, the storage form of carbohydrates in plants, is formed in the stroma by condensation of many glucose phosphate molecules.

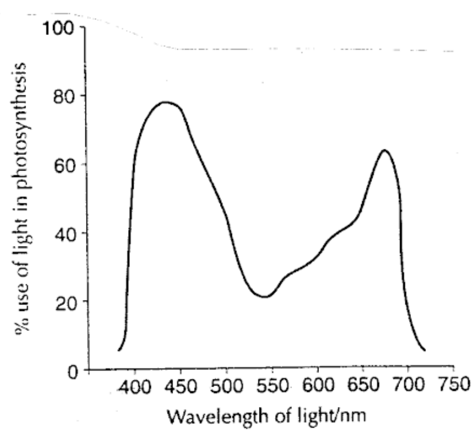
The action spectrum of photosynthesis

A spectrum is a range of wavelengths of electromagnetic radiation. The spectrum of light is the range of wavelengths from 400 nm to 700 nm. Each wavelength is a pure colour of light:

400-525 violet-blue
525-625 green-yellow
625-700 orange-red

The efficiency of photosynthesis is not the same in all wavelengths of light. The efficiency is the percentage of light of a wavelength that is used in photosynthesis. The graph shows the percentage use of the wavelengths of light in photosynthesis and it is called the action spectrum of photosynthesis. It is shown that violet, blue and red light are used most efficiently, whereas green light is used much less efficiently.

The action spectrum of photosynthesis



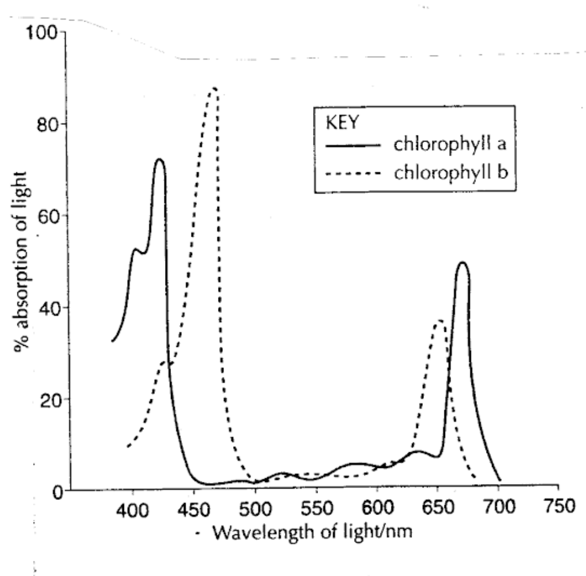
The absorption spectra of photosynthetic pigments

The action spectrum of photosynthesis is explained by considering the light-absorbing properties of the photosynthetic pigments. Most pigments absorb some wavelengths better than others. The graph shows the percentage of wavelengths of visible light that are absorbed by two common forms of chlorophyll and it is called the <u>absorption spectrum</u> of these pigments.

The graph shows strong similarities with the action spectrum for photosynthesis:

- The greatest absorption is in the violet-blue range
- There is also a high level of absorption in the red range of the spectrum
- There is least absorption in the yellow-green range of the spectrum. Most of this light is reflected

Absorption spectrum of chlorophylls a and b



Limiting factors of photosynthesis

Light intensity, CO_2 concentration and temperature are three factors that determine the rate of photosynthesis. Usually, changes to one of the factors will affect the rate of photosynthesis in a plant. Hence the factor which is nearest to its minimum is called the ***limiting factor***.

Changing the limiting factor increases or decreases the rate, but changes to the other factors have no effect. This is because photosynthesis is a special process involving many steps. The overall rate of photosynthesis in a plant is determined by the rate of whichever step is proceeding more slowly at a particular time. This is called the **rate-limiting step**. The three limiting factors affect different rate-limiting steps.

a) The effect of light intensity

At low light intensities, there is a shortage of the products of the light dependent reactions – NADPH and ATP. The rate limiting step in the Calvin cycle is the point where glycerate 3-phosphate is reduced. At high light intensities some other factor is limiting. Unless a plant is heavily shaded, or the sun is rising or setting, light intensity is not usually the limiting factor.

b) The effect of CO_2 concentration

At low and medium CO_2 concentrations, the rate-limiting step in the Calvin cycle is the point where CO_2 is fixed to produce glycerate 3-phosphate. RuBP and NADPH accumulate. At high CO_2 concentrations some other factor is limiting.

Since the level of CO_2 in the atmosphere is never very high, CO_2 concentration is often the limiting factor.

c) The effect of temperature

At low temperatures, all of the enzymes that catalyse the reactions of the Calvin cycle work slowly. NADPH accumulates. At intermediate temperatures, some other factor is limiting. At high temperatures, RuBP carboxylase does not work effectively, so the rate-limiting step in the Calvin cycle is the point where CO_2 is fixed. NADPH accumulates.

Don't forget the graphs mentioned in Standard level

Cell respiration

Cell respiration involves the production of ATP using energy released by the oxidation of glucose, fat or other substrates. If glucose is the substrate, the first stage (metabolic pathway) of cell respiration is glycolysis.

- Oxidation involves the loss of electrons from an element and frequently it involves gaining of oxygen or loosing hydrogen.
- Reduction involves a gain in electrons and frequently involves loss of oxygen or gain in hydrogen.

Hydrogen carriers accept hydrogen atoms removed from substrates in cell respiration. The most commonly used hydrogen carrier is NAD^+ (nicotinamide adenine dinucleotide).

a) GLYCOLYSIS (aerobic & anaerobic)

The process of glycolysis takes place in the cytoplasm and it involves four stages:

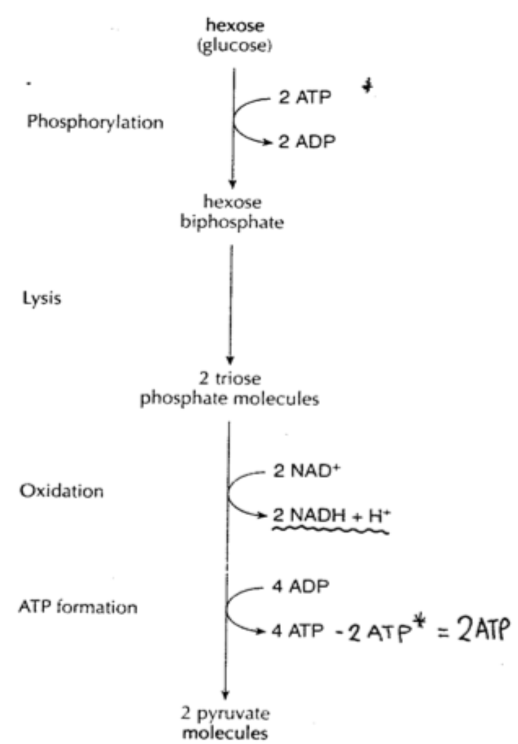
1) Two phosphate groups are added to a molecule of glucose to form hexose biphosphate. Adding a phosphate group is called **<u>phosphorylation</u>**. The phosphate groups are provided by two ATP molecules.

2) The hexose biphosphate is split to form two molecules of triose phosphate. The splitting of molecules is called **<u>lysis</u>**.

3) Two atoms of hydrogen are removed from each triose phosphate molecule. This is an **<u>oxidation</u>**. The energy released by this oxidation is used to link on another phosphate group, producing a 3- carbon compound carrying two phosphate groups. NAD^+ is the hydrogen carrier that accepts the hydrogen atoms.

4) Pyruvate is formed by removing the two phosphate groups and by passing them to ADP. This results in **ATP formation**.

Diagram of the main stages of glycolysis



Summary of glycolysis

- One glucose is converted into two pyruvates.
- Two ATP molecules are used per glucose, but four are produced so there is a net yield of two ATP molecules.
- Two NAD^+ are converted into $NADH + H^+$

b) KREBS CYCLE (aerobic)

Enzymes in the matrix of the mitochondrion catalyse a cycle of reactions called the Krebs cycle. These reactions can only occur if oxygen is available and so are part of aerobic cell respiration.

The role of acetyl CoA

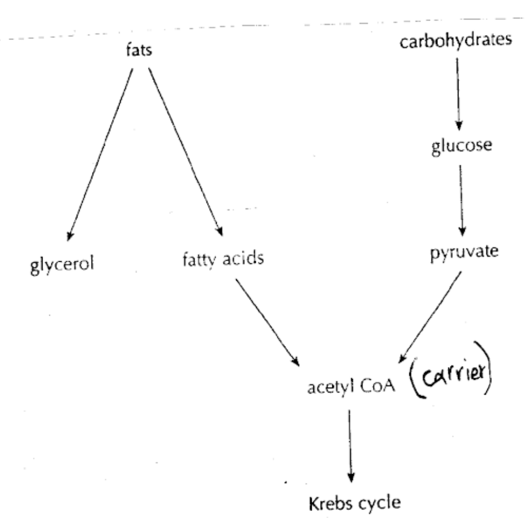
Acetyl groups (CH_3CO) are the substrate used in the Krebs cycle. A carrier called CoA accepts acetyl groups produced in metabolism and brings them for use in the cycle:

Acetyl group + CoA → acetyl CoA

Acetyl CoA is formed in both carbohydrate and fat metabolism.

- *Carbohydrates* are converted into pyruvate and the pyruvate is converted to acetyl CoA by a reaction called the **link reaction**, because it links glycolysis and the Krebs cycle.
- Fats are broken down into fatty acids and glycerol. The hydrocarbon tails of fatty acids are then broken down into two-carbon fragments and oxidized to form acetyl CoA.

Metabolic pathways involving acetyl CoA



The link reaction

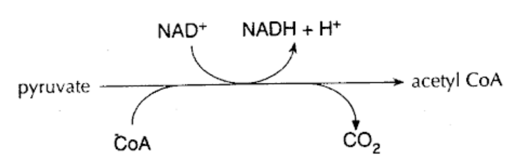
Pyruvate from glycolysis is absorbed by the mitochondrion. Enzymes in the matrix of the mitochondrion remove hydrogen and CO_2 from each pyruvate. The hydrogen is accepted by NAD^+.

Removal of hydrogen is oxidation and removal of CO_2 is decarboxylation. Therefore, the whole conversion is called **oxidative decarboxylation**. The product of oxidative decarboxylation of pyruvate is an acetyl group, which reacts with CoA.

(!) In my words:

In aerobic respiration each pyruvate is decarboxylated (CO_2 removed). The remaining two-carbon molecule (acetyl group) reacts with reduced CoA and at the same time one NADH + H^+ is formed. This is known as the *link reaction*

Summary of the link reaction



The Krebs cycle

In the first reaction of the cycle an acetyl group is transferred from acetyl CoA to a four-carbon compound (oxaloacetate) to form a six-carbon compound (citrate). Citrate is converted back into oxaloacetate in the other reactions of the cycle.

In the Krebs cycle each acetyl group formed in the link reaction yields two CO_2.

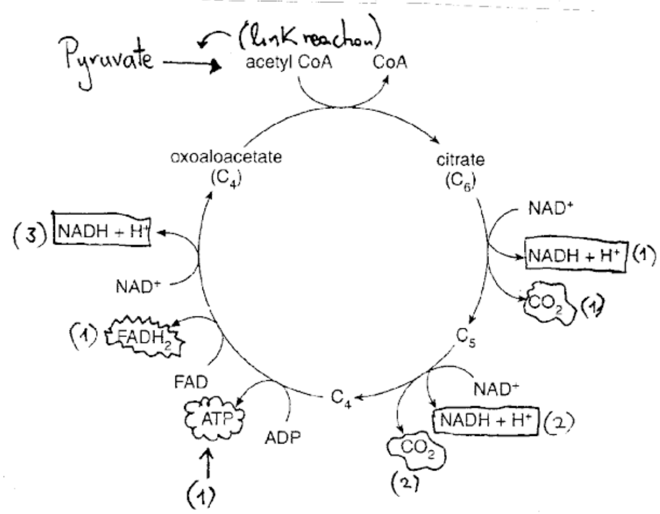
Three types of reactions are involved:

- Carbon dioxide is removed in two of the reactions. These reactions are **decarboxylations**. The CO_2 is a waste product and is excreted together with the CO_2 from the link reaction.
- Hydrogen is removed in four of the reactions. These reactions are **oxidations**. In three of the oxidations the hydrogen is accepted by NAD^+. In the other oxidation FAD (flavine adenine dinucleotide) accepts it. These oxidation reactions release energy, much of which is stored by the carriers when they accept hydrogen. This energy is later released by the electron transport chain and used to make ATP.
- ATP is produced directly in one of the reactions. This reaction is **substrate-level phosphorylation**.

In a nutshell: One turn of the Krebs cycle yields:

- 2 CO_2
- 3 x NADH + H^+
- 1 x $FADH_2$
- 1 x ATP

Diagram of the Krebs cycle



c) OXIDATIVE PHOSPHORYLATION

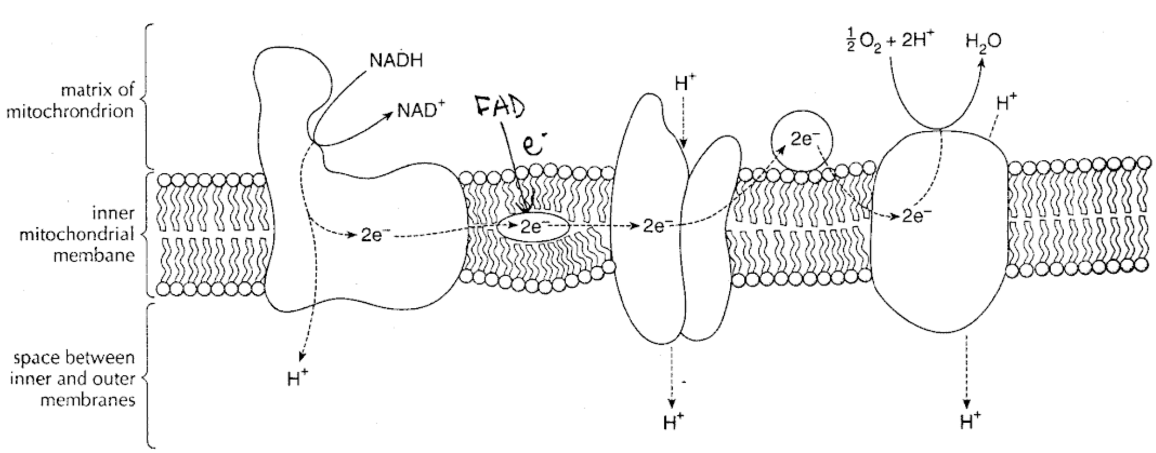
The electron transport chain is the means by which the energy from the Krebs cycle, in the form of hydrogen atoms, is converted to ATP. It involves a series of electron carriers, located in the inner mitochondrial membrane. NADH supplies two electrons to the first carrier in the chain. $FADH_2$ also feeds electrons into the electron transport chain but at a later stage.

The electrons come from oxidation reactions in earlier stages of cell respiration. The two electrons pass along the chain of carriers because they give up energy each time they pass from one carrier to the next.

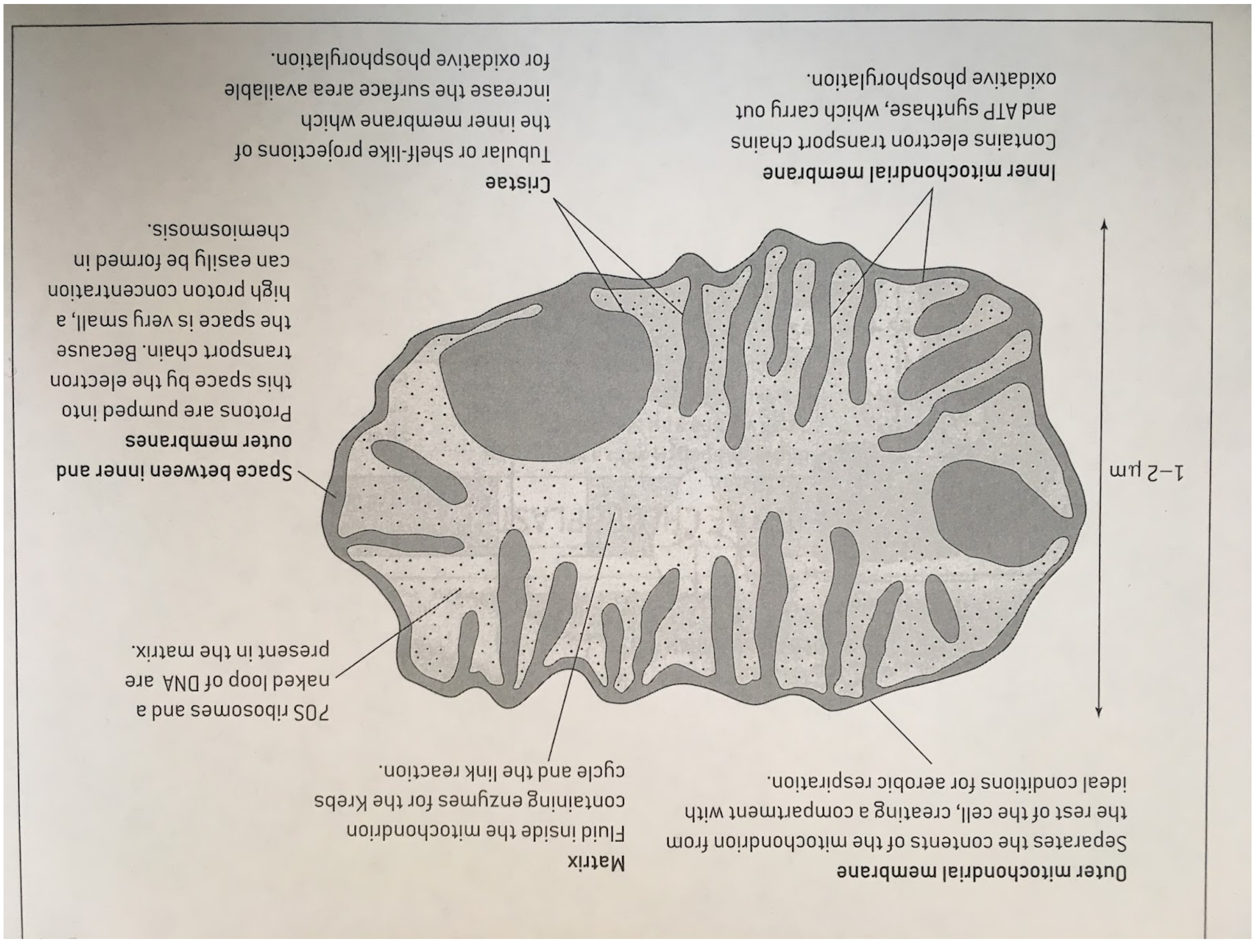
At three points along the chain enough energy is given up for ATP to be made by ATP synthase.

As this ATP production relies on energy released by oxidation, it is called **oxidative phosphorylation**.

Diagram of the electron transport chain of mitochondria



The structure of the mitochondrion



The role of oxygen

At the end of the electron transport chain the electrons are given to oxygen. At the same time O_2 accepts hydrogen ions to form water. This is the only stage at which O_2 is used in cell respiration. If O_2 is not available electron flow along the chain stops and NADH + H^+ cannot be reconverted to NAD^+. Hence, supplies of NAD^+ in the mitochondrion run out and the link reaction and Krebs cycle cannot continue.

→ Thus, O_2 greatly increases the ATP yield.

The coupling of electron transport to ATP synthesis

Energy released as electrons pass along the electron transport chain is used to pump protons (H^+) across the inner mitochondrial membrane into the space between the inner and outer membranes.

A concentration gradient is formed, which is a store of potential energy. ATP synthase, located in the inner mitochondrial membrane, transports the protons back across the membrane down the concentration gradient.

As the protons pass across the membrane, they release energy and this is used by ATP synthase to produce ATP.

The coupling of ATP synthesis to electron transport via a concentration gradient of protons is called **chemiosmosis**.

The structure of ATP synthase