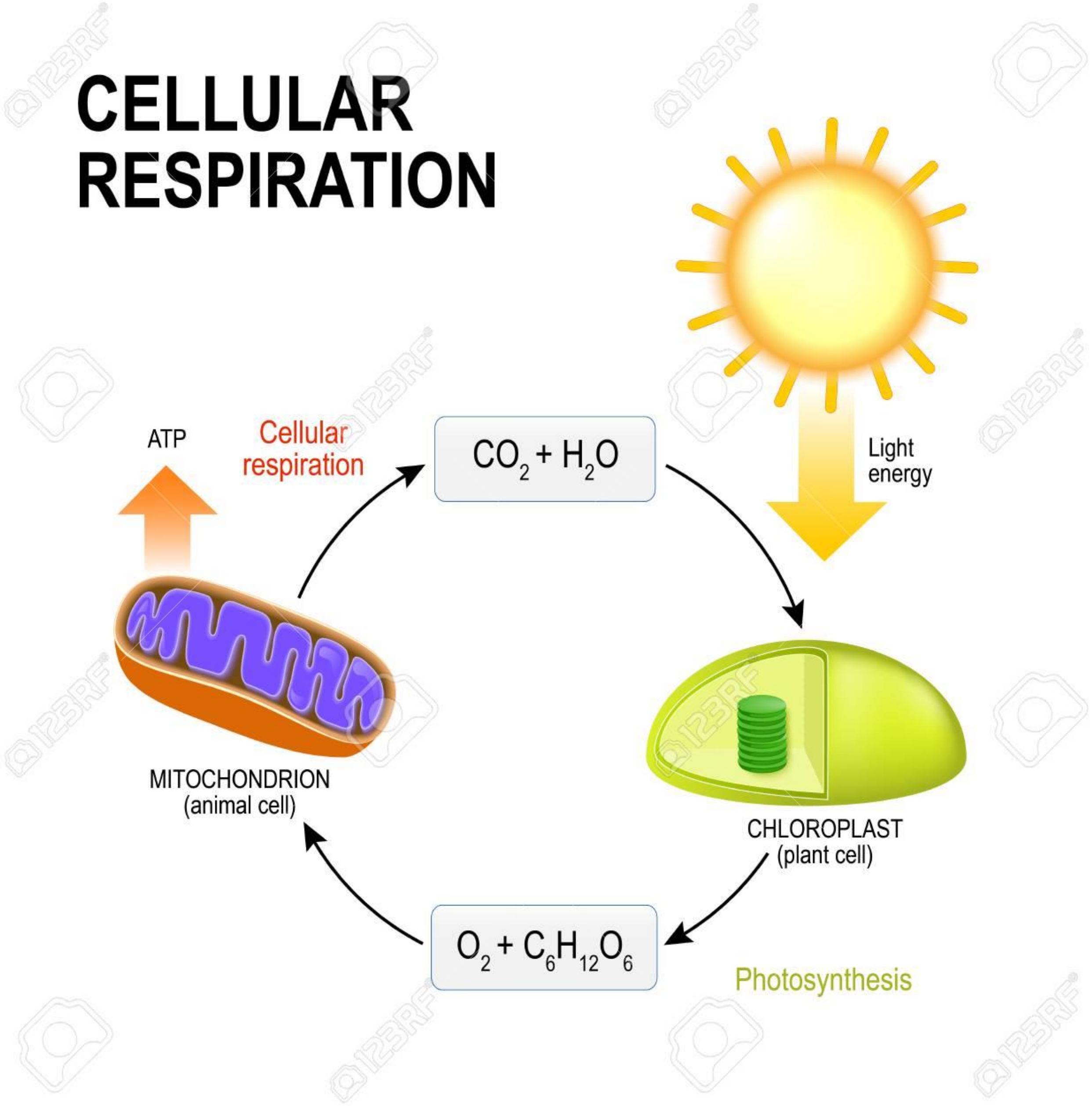
# Chap 4_2. Metabolism of the plants

# B. Cellular respiration (energy catabolism)

# Introduction

- The energy requirements for growth and function of all living organisms are met by ATP generated during respiration. In plants, light energy is conserved in the form of ATP and NADPH.
- ATP and NADPH are used to assimilate $CO_2$.
- Carbohydrates synthesised by plants are consumed by animals as their main source of energy.
- Carbohydrates synthesised by plants remain the main source of energy. Plants store carbohydrates mainly in the form of starch.

Any accumulation of carbon in plants is the result of photosynthesis, which remains the source of energy as well as for the biosynthesis of various other biomolecules.

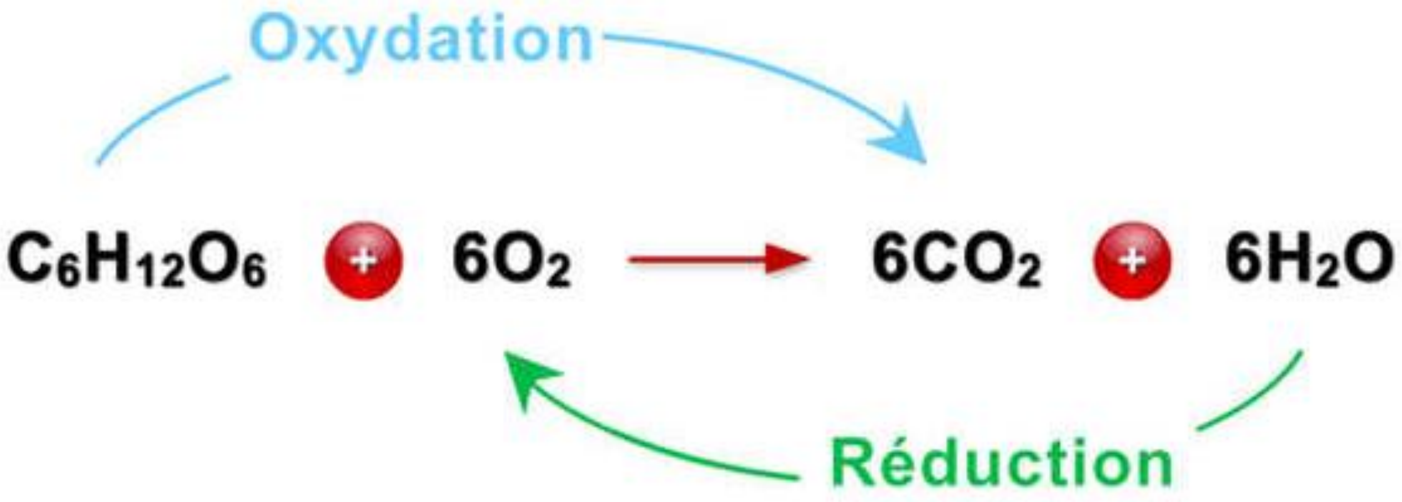


The **respiration** reaction is the opposite of photosynthesis, which is also a redox chemical reaction. In **photosynthesis**, the oxidation of $H_2O$, resulting in the release of $O_2$, is accompanied by a reduction of $CO_2$ to carbohydrates. This is an endergonic reaction in which light energy is used. As glucose is mainly used as an energy source, starch is converted into simple sugars in the plant's storage organs.

A fuel: glucose, fatty acids or other organic molecules (amino acids, ketone bodies);

An oxidant, oxygen. This reaction produces: carbon dioxide; water; sometimes urea, if the fuel contains nitrogen (e.g. amino acids).

**General Formula of the respiration**



## Definition of the respiration

Cellular respiration is the complete breakdown of glucose in the presence of $O_2$, allowing its energy to be released in full. The glucose synthesised during the 2nd stage of photosynthesis (dark phase) is burnt in the presence of oxygen in animal and plant cells.

## 2. Localisation of the respiration

Cellular respiration takes place in organelles called mitochondria. These are the place of cellular respiration;

- The word mitochondrion comes from the Greek "mitos" meaning "filament" and "khondros" meaning "grain".

- All the mitochondria in a cell (300 to 800 mitochondria/cell) form the chondriome. Mitochondria are functional units of the cell, they are "energy factories".

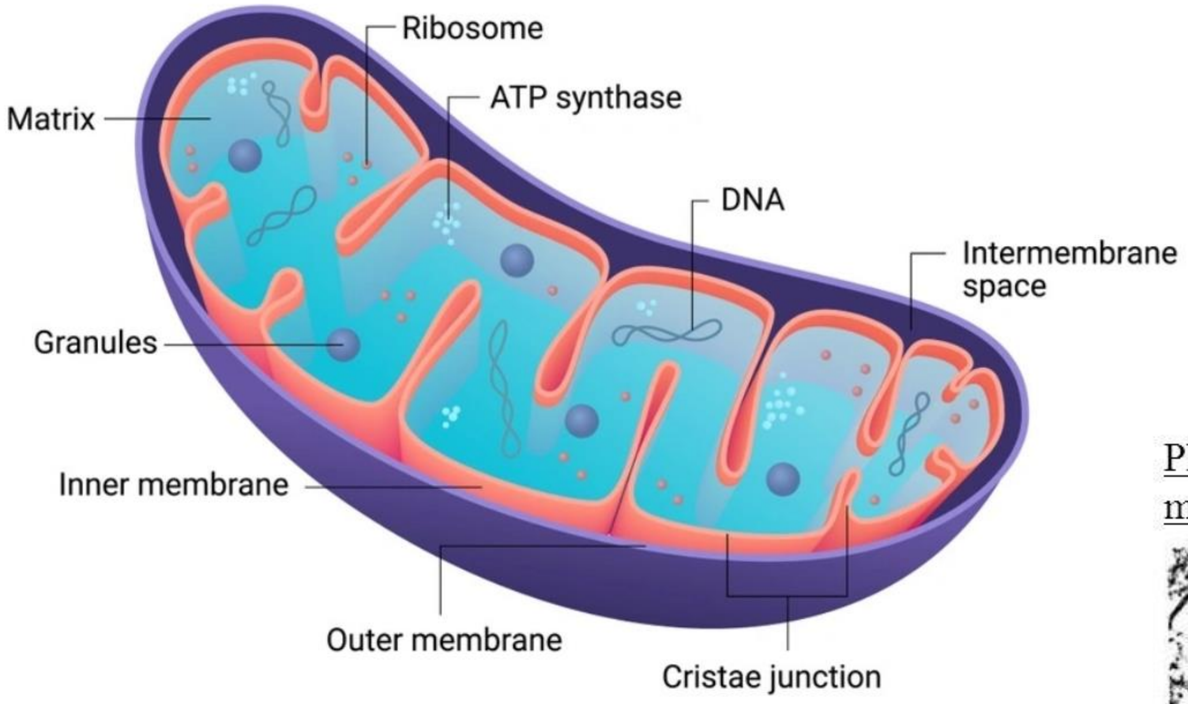
- Mitochondria are found in all plant and animal cells. Mitochondria are visible under a light microscope, after specific staining. The detailed structure of mitochondria can be seen under an electron microscope.
- The shape of mitochondria can vary from one cell type to another or within the same cell depending on its activity: short grains or rods measuring 0.5 μm by 1μm or more, or long, flexuous filaments, sometimes branched.

## 3. Ultra-structure of mitochondria

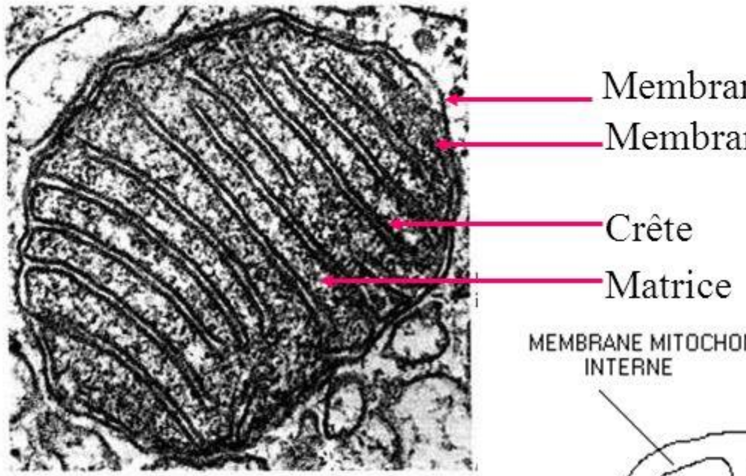
Under the electron microscope, the mitochondrion is seen to be composed of a system of membranes resembling the plasmalemma, separating 2 very distinct spaces:

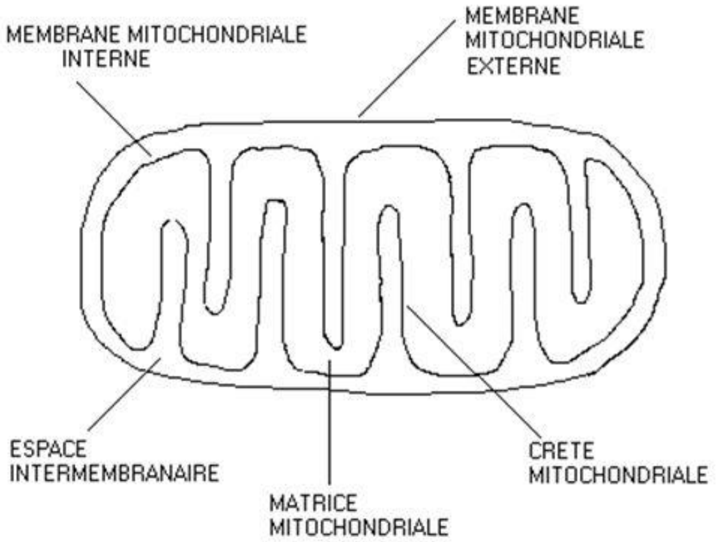
- An intermembrane space is located between the 2 outer and inner membranes of the mitochondrion, which projects several folds towards the centre of the organelle;

- The matrix, the central fluid of the mitochondrion, circumscribed by the inner membrane. The folds of the inner membrane form mitochondrial ridges to the surface of which are attached numerous tiny spherical structures immersed in the matrix.




<u>Photo d'une mitochondrie au microscope électronique</u>

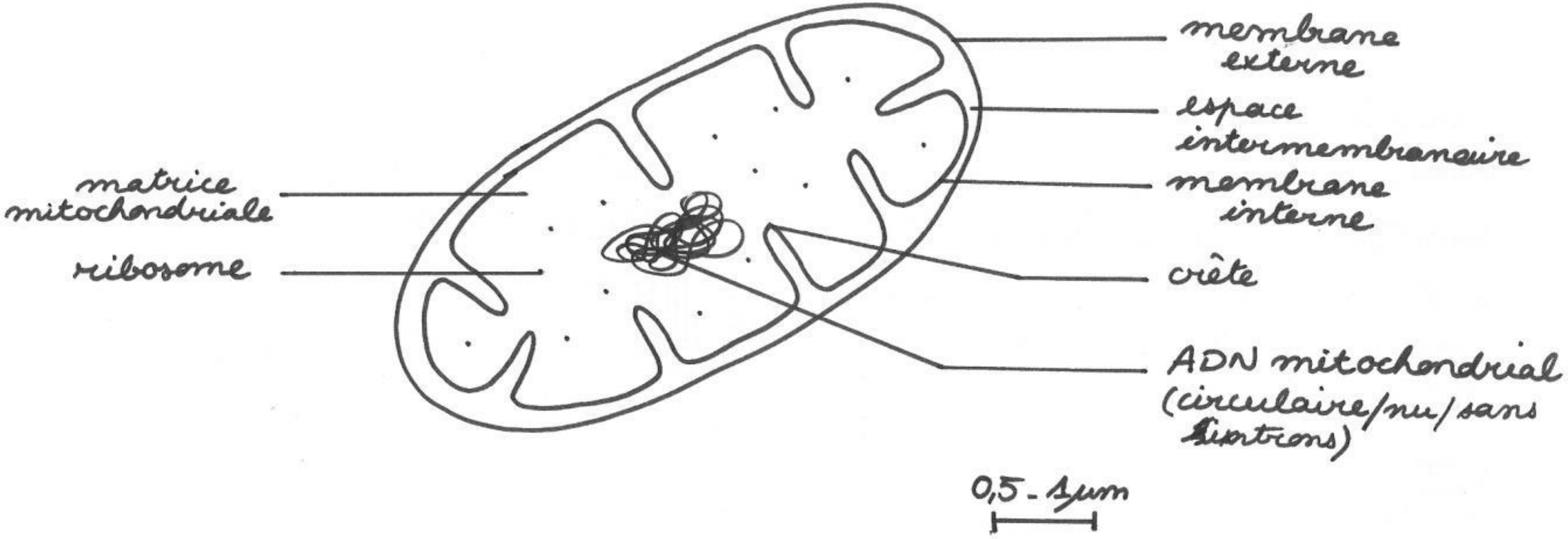



http://www.bio.espci.fr/scolarite/c_BIO/energ/cata2.htm

http://membres.lycos.fr/renejacquemet/sport/glucose/glucose.html

# Schéma d'une mitochondrie



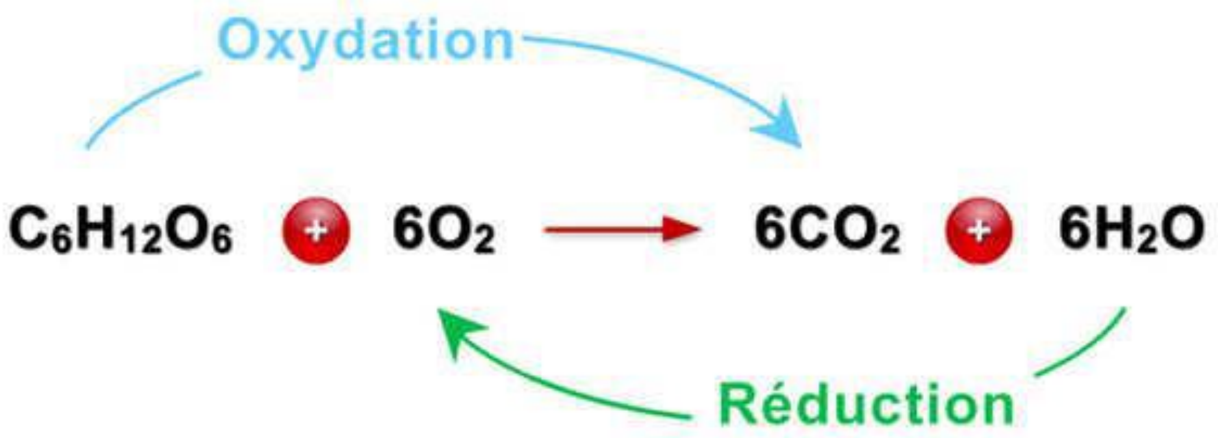
**4. ATP formation from carbohydrates**

- The main role of carbohydrates is to provide energy to produce ATP. There are 2 main metabolic pathways for this energy:

Cellular respiration in an aerobic environment (presence of $O_2$ in the environment);Fermentation (alcoholic, butyric, etc.) in an anaerobic environment ($O_2$-free environment). During cellular respiration, glucose is broken down by electron transfer (energy release).

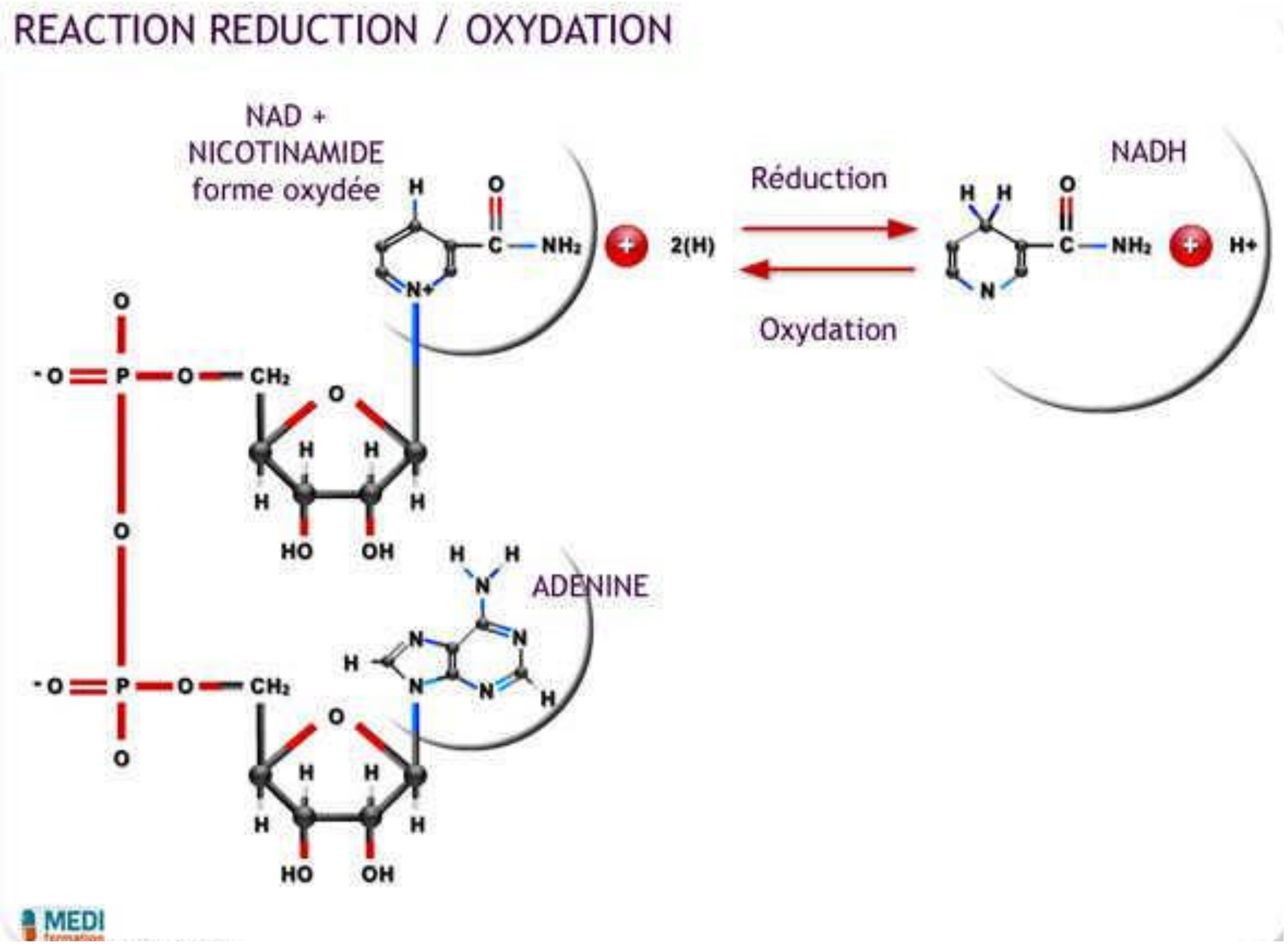
$$\mathbf{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + ENERGY}$$

- **Glucose** is oxidised and $O_2$ is reduced. Hydrogen is transferred from glucose to oxygen. Glucose is broken down in a series of reactions. Each reaction is catalysed by an enzyme. H atoms are removed from the glucose and first pass through an organic intermediate called Nicotinamide Adenine Dinucleotide (or NAD+), which receives the electrons (Fig.), then are transferred to the O2 .



NAD+ is an oxidised form, it has a charge (+) and captures electrons and hydrogen from glucose using enzymes called dehydrogenases. But rather than becoming NAD by capturing a single electron, these enzymes remove a pair of hydrogen atoms (2H) from the glucose. A hydrogen atom contains 1 electron and 1 proton. So 2H is equivalent to 2 electrons and 2 protons.

Dehydrogenase transfers 2 electrons and 1 proton (H+) to NAD+, and the other proton is released into the environment. NAD+ therefore becomes NADH (reduced form).



Electrons lose very little energy when they are transferred to NAD+, which means that NADH molecules are energy-storing molecules.

NAD+ + 2e- + 2H+ -> NADH + H+ (proton released into the environment). Each NADH formed during cellular respiration represents a small reserve of energy.

## 5. How Cellular Respiration works

NADH is only rich in energy, but it does not store it. Later, during cellular respiration, it will give its energy to ATP. Cellular respiration therefore takes place in stages:

**Glycolysis**, which is the 1st stage of fermentation

and **The Krebs cycle**

## 1. Glycolysis

**Glucose** undergoes glycolysis (a chemical reaction) in the cytoplasm of the cell. This reaction takes place under anaerobic conditions (absence of $O_2$). This metabolic pathway is a series of oxidation-reduction reactions:

**Glucose is oxidised to form pyruvate** (1 molecule with 3 carbon atoms). During glycolysis, glucose is first converted to glucose 6-phosphate by hexokinase, a kinase enzyme that catalyses the transfer of a phosphate group from one molecule to another. This reaction is carried out by coupling the hydrolysis of ATP to ADP + Pi, because this reaction **requires energy**: it is a synthesis.

## Definition

**Pyruvate** is an important chemical compound in biochemistry. It is the result of glycolysis. One molecule of glucose splits into 2 molecules of pyruvate, which will be used to provide energy later.

The **6-P glucose** is then converted to 6-P fructose by another enzyme, phosphohexose isomerase. This is a reversible isomerisation (conversion of the molecule into one of its isomers) catalysed by an isomerase.

**Fructose 6-P** is then converted into fructose 1,6 diphosphate by phosphofructokinase. This reaction also involves the hydrolysis of a molecule of ATP.

Two molecules of phosphoglyceraldehyde are formed: this reaction is catalysed by an aldolase (lyase groupe, enzyme that breaks various chemical bonds by means other than hydrolysis and oxidation).

Then, 2 molecules of **1,3-diphosphoglycerate** are synthesised: this reversible oxidation-reduction reaction (exchange of electrons) is catalysed by a triose phosphate dehydrogenase (oxidation-reduction: enzymes that catalyse oxidation-reduction reactions). There is therefore an oxidising agent and a reducing agent: NAD+ is reduced to NADH; and phosphoglyceraldehyde is oxidised to 1,3-diphosphoglycerate.

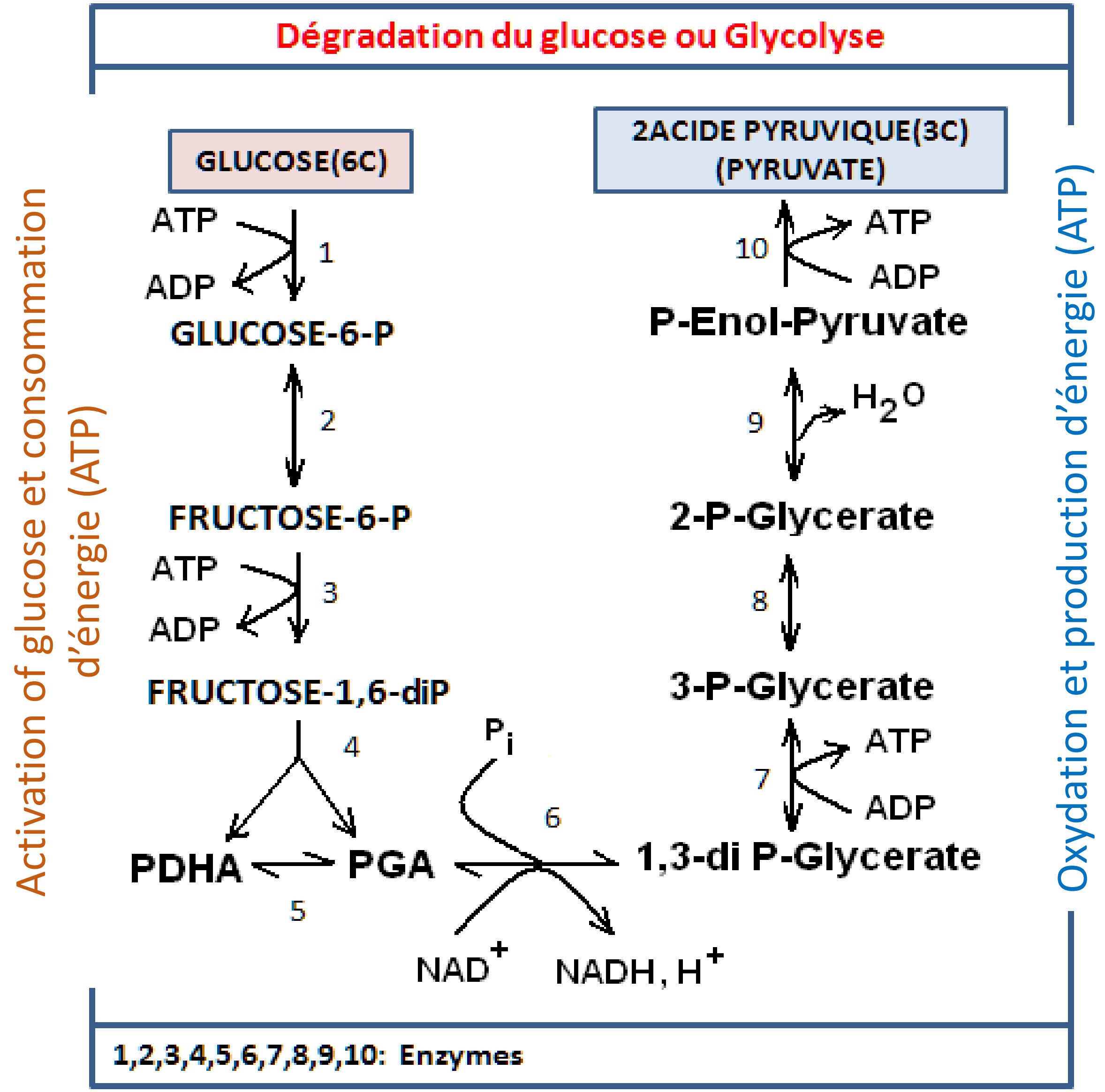
And so on until the final stage of pyruvate formation by the enzyme pyruvatekinase.

Each step is catalysed by a specific enzyme. If just one of these enzymes were missing, the reaction could not continue until pyruvate synthesis.

At the end of this 1st stage, 2 molecules of ATP are produced for 1 molecule of glucose.

This balance is low compared with the other stages of cellular respiration. Summary of this 1st stage: Production of pyruvate which will be consumed during the Krebs cycle in aerobiosis, in the mitochondria.

# Glycolysis




Steps of transformation of glucose to Pyruvate

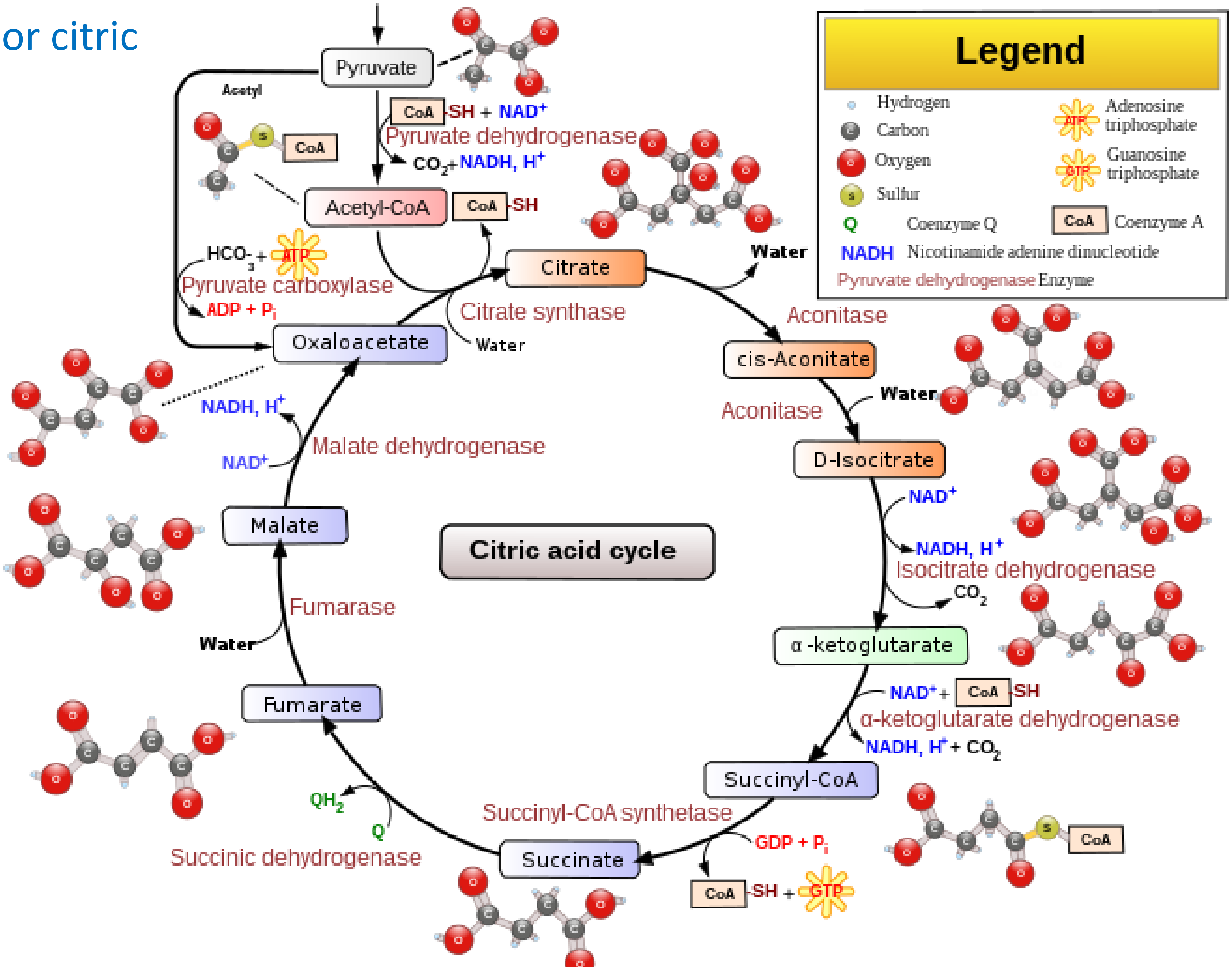
Listing of **enzymes** involved in **glycolysis**

(1) Hexokinase
(2) Glucose-6-phosphate isomérase
(3) Phosphofructokinase
(4) Aldolase
(5) Triose-phosphate-isomérase
(6) PGA déshydrogénase
(7) Phosphoglycérate kinase
(8) Phosphoglycérate mutase
(9) Enolase
(10) Pyruvate kinase

## 2. The Krebs cycle

or citric acid (citrate) cycle is at the heart of cellular metabolism. The **Krebs cycle** takes place in the mitochondrial matrix under **aerobic conditions**. **Pyruvate** is oxidised, resulting in the formation of 10 reduced compounds, NADH. Pyruvate also undergoes total decarboxylation (removal of carbon atoms) which leads to the release of CO2, a waste product of respiration. Once degraded by glycolysis, **glucose is converted into pyruvate**, **acetyl coenzyme A (acetyl CoA) and oxaloacetate**. These 2 compounds are the starting point of the Krebs cycle.

# **Cycle of Krebs** or citric acid cycle



- **Steps of the cycle Krebs**

*Citrate synthesis. Reaction catalysed by citrate synthetase to synthesise citrate.*

*Dehydration of citrate. Reversible dehydration reaction catalysed by a lyase (cis-aconitase), producing cis-aconitate.*

*Hydration of cis-aconitate. Reversible reaction catalysed by the same enzyme (lyase). H2O is added to the double bond in a different position: iso-citrate is synthesised.*

*Oxidation of iso-citrate.* *This reversible reaction is catalysed by an oxidoreductase: isocitrate dehydrogenase. It is therefore a redox reaction with electron exchange: NAD+ is reduced to NADH, H+ (with the proton released into the medium).*

*Decarboxylation of oxalosuccinate.* *CO2 is released during this irreversible reaction. Oxidative decarboxylation of a-ketoglutarate. This redox reaction is the same as that from pyruvate to* ***acetyl CoA****. The enzyme complex involves numerous enzymes in this reaction. In addition, CO2 is released and NAD+ is reduced.*

*Formation of succinate.* *This reversible reaction is catalysed by a transferase, succinate thiokinase. This reaction is coupled to the synthesis of ATP.*

*Oxidation of succinate.* *This reaction is catalysed by the enzyme succinate dehydrogenase.*

*Hydration of fumarate.* *This reaction involving the addition of a molecule of H2O is catalysed by a lyase, fumarase.*

*Oxidation of malate.* *Oxaloacetate is formed, a redox reaction catalysed by malate dehydrogenase (oxidoreductase). The oxidised compounds are reduced to NADH.*

- Reoxidation of reduced compounds: NADH At this stage, the glucose molecule is completely broken down: all its carbons are eliminated in the form of $CO_2$. For the moment, only 4 ATPs are produced, as most of the energy remains stored in the NADHs. The biochemical process is not complete: it is necessary to regenerate the $NAD^+$ acceptors that have been reduced to NADH compounds. This means that the NADH must be oxidised again. This operation takes place at the mitochondrial cristae (folds of the inner membrane) in aerobic conditions and enables remarkable production of ATP: this is the respiratory chain.