Respiration

What is respiration?

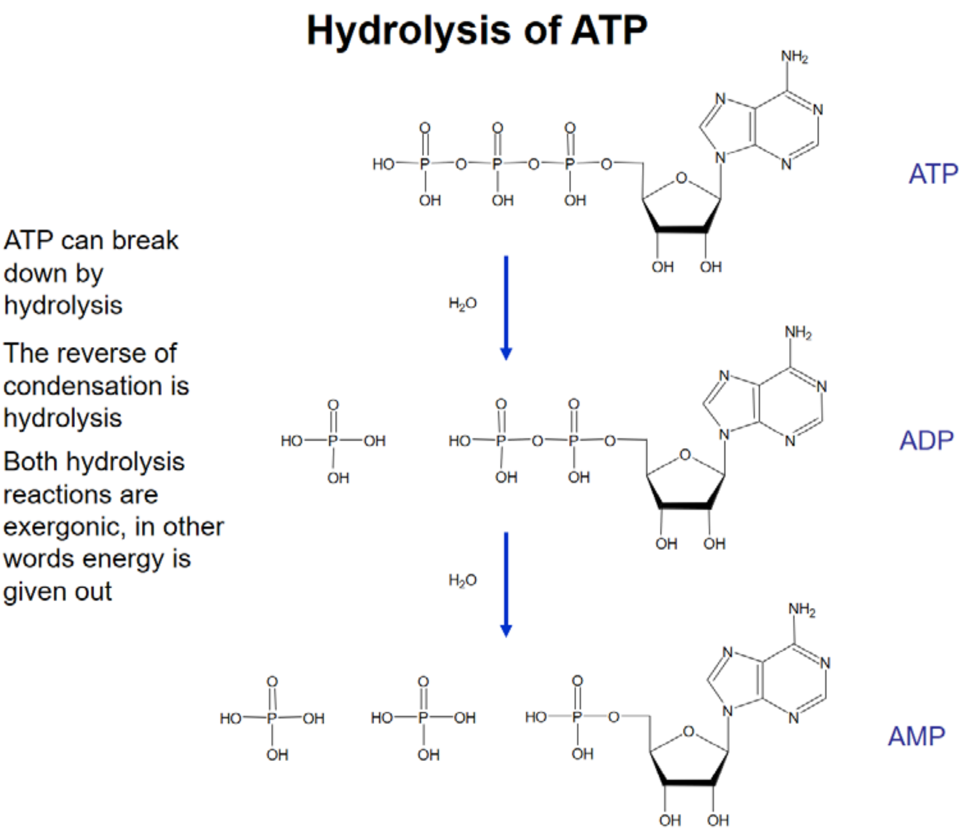
Respiration is the chemical process by which organic compounds release energy. The compounds change into different ones by **exergonic** reactions.

There are two types of respiration:

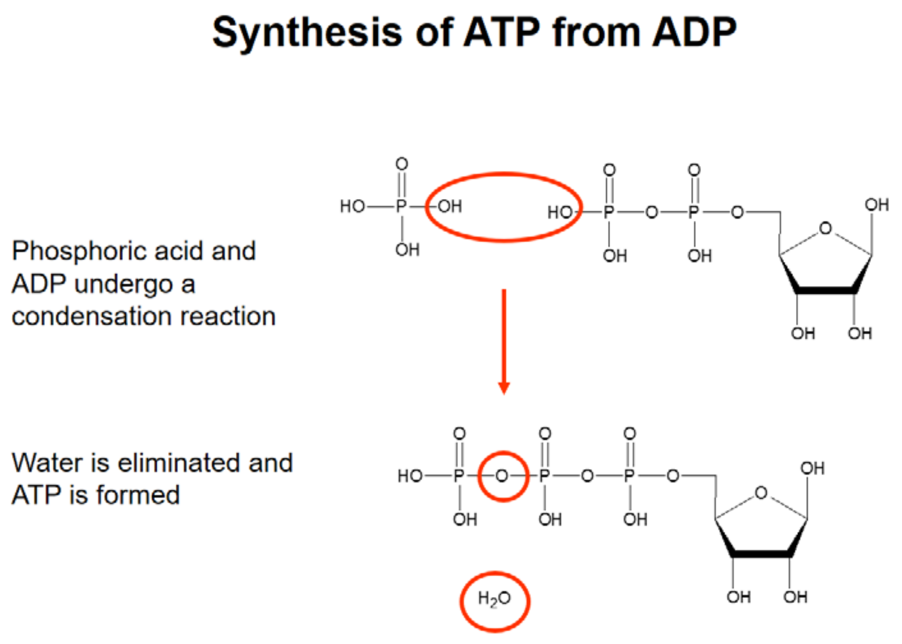
- aerobic, which requires oxygen and releases lots of energy
- anaerobic, which does not require oxygen but releases much less energy per mole of starting material

ATP and cells

The hydrolysis of adenosine triphosphate (ATP) to adenosine diphosphate (ADP) and phosphoric acid (Pi) releases energy (it is an exergonic reaction). Some chemical reactions that occur in cells require energy. Hydrolysis reactions of ATP can provide this energy.



Cells must replenish ATP by synthesising it from ADP and phosphoric acid.



This requires energy, and one way of providing this is from the oxidation of glucose which is an exergonic reaction.

There are two reasons why energy from the oxidation of glucose is not used directly to drive chemical reactions in the cell:

- the hydrolysis of ATP releases small amounts of energy compared to the oxidation of glucose, and in a controlled way
- energy is released instantaneously from the hydrolysis of ATP, but the oxidation of glucose takes time

Oxidation and reduction

The types of chemical reactions called **oxidation** and **reduction** lie at the heart of respiration. They always occur together - one substance is oxidised as another is reduced. We often use the term **redox** reactions to describe this.

There are two useful ways of thinking about redox reactions. One is that oxidation is the addition of oxygen and reduction is the removal of oxygen from a substance. For example:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ (oxidation of glucose).

However, a more useful definition is in terms of electron transfer:

- Oxidation is the removal of electrons, e.g. $Fe^{2+} \rightarrow Fe^{3+} + e^-$
- Reduction is the addition of electrons, e.g. $Fe^{3+} + e^- \rightarrow Fe^{2+}$

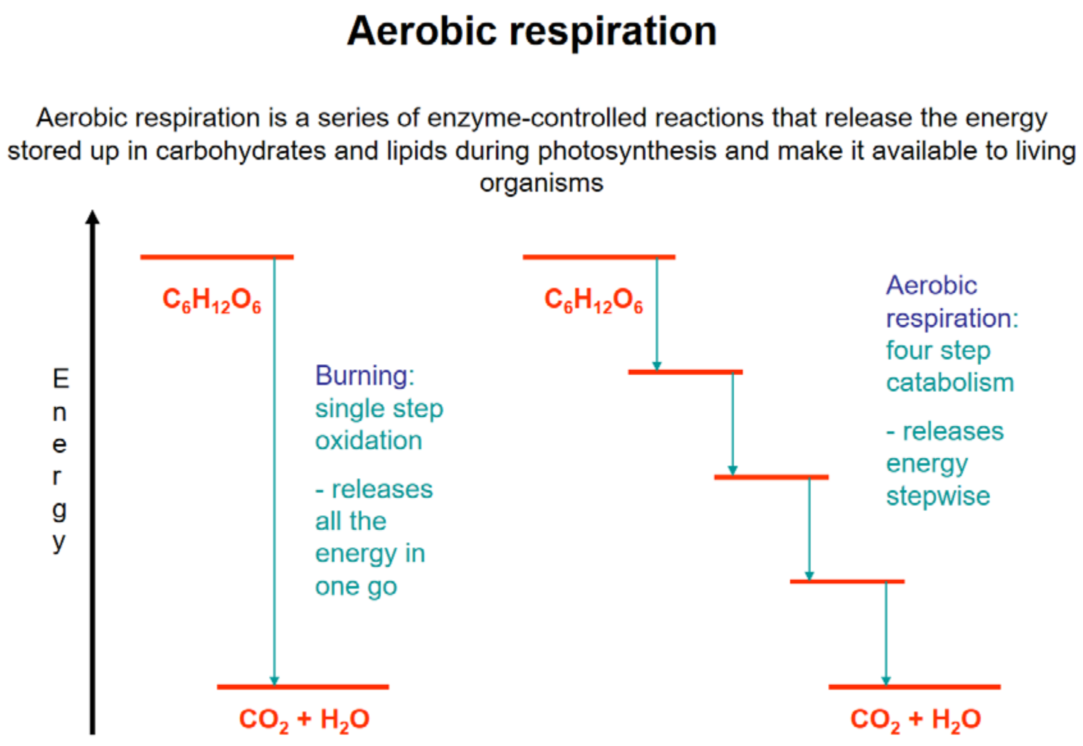
A chemical that supplies electrons is called a reducing agent (or a **reductant**), and a chemical that accepts electrons is called an oxidising agent (or an **oxidant**).

Aerobic respiration

Aerobic respiration may be represented by the general equation

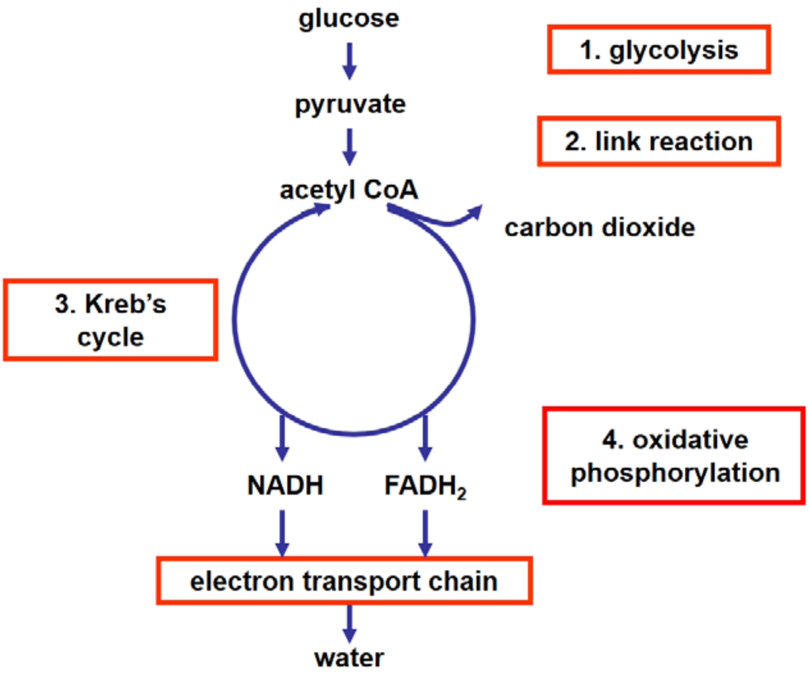
$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

About 3000 kJ mol^{-1} of energy is released. Burning glucose in air would release this amount of energy in one go. However, it is not as simple as this in aerobic respiration. Aerobic respiration is a series of enzyme-controlled reactions that release the energy stored up in carbohydrates and lipids during photosynthesis and make it available to living organisms.



There are four stages: **glycolysis**, the **link reaction**, the **Krebs cycle** and **oxidative phosphorylation**.

The four stages of glucose catabolism



Glycolysis

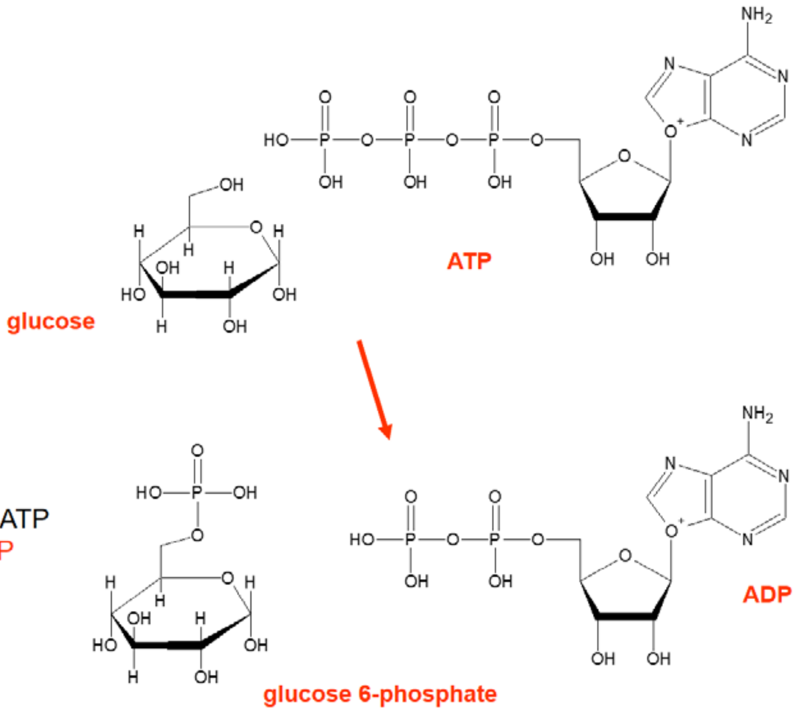
During glycolysis, glucose molecules (six-carbon molecules) are split into two pyruvates (three-carbon molecules) during a sequence of enzyme-controlled reactions. This occurs in both aerobic and anaerobic respiration.

Phosphorylation

During **phosphorylation** glucose is converted into glucose 6-phosphate using energy and phosphate groups from ATP. This is converted to fructose 1,6-diphosphate, again using ATP as a source of energy and phosphate groups. ATP is hydrolysed to ADP + phosphoric acid (P_i).

Formation of glucose 6-phosphate

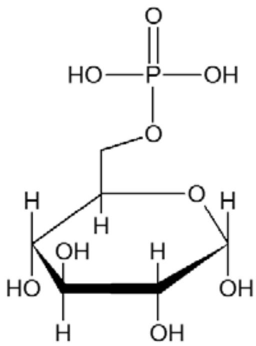
Glucose reacts with ATP in an enzyme-catalysed reaction



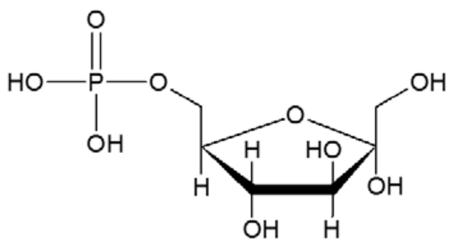
Glucose is phosphorylated and ATP is converted into ADP

Formation of fructose 6-phosphate

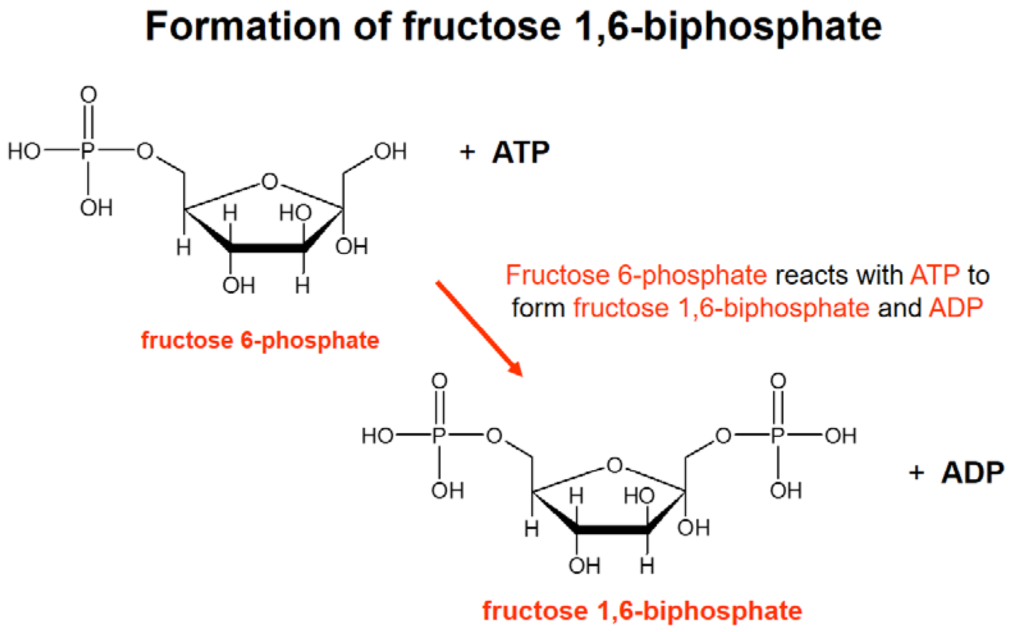
In the presence of an enzyme (which catalyses the reaction), a glucose 6-phosphate molecule rearranges itself to form fructose 6-phosphate



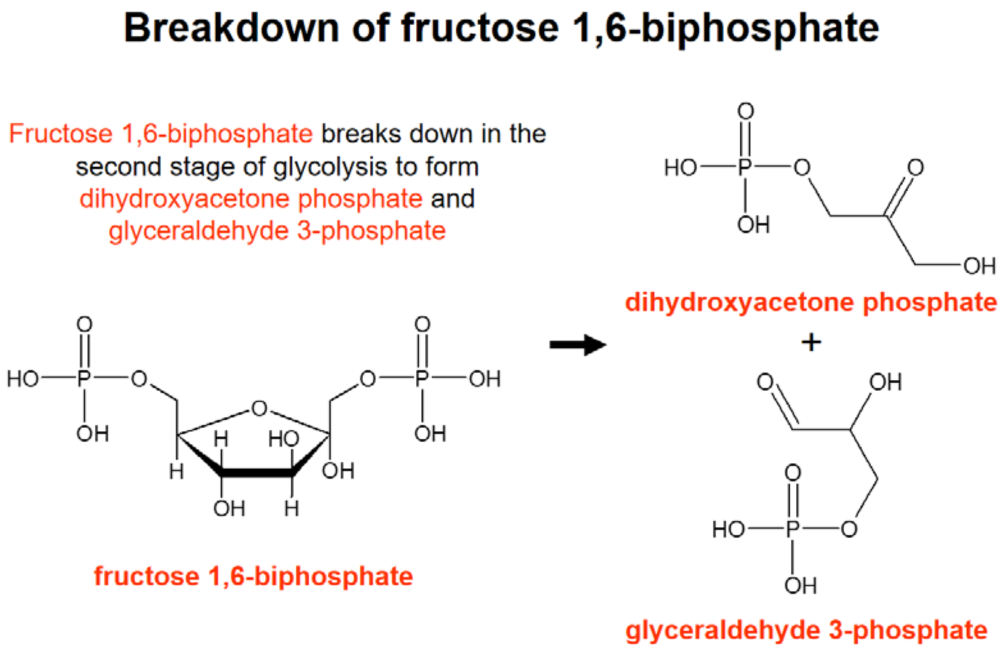
glucose 6-phosphate



fructose 6-phosphate

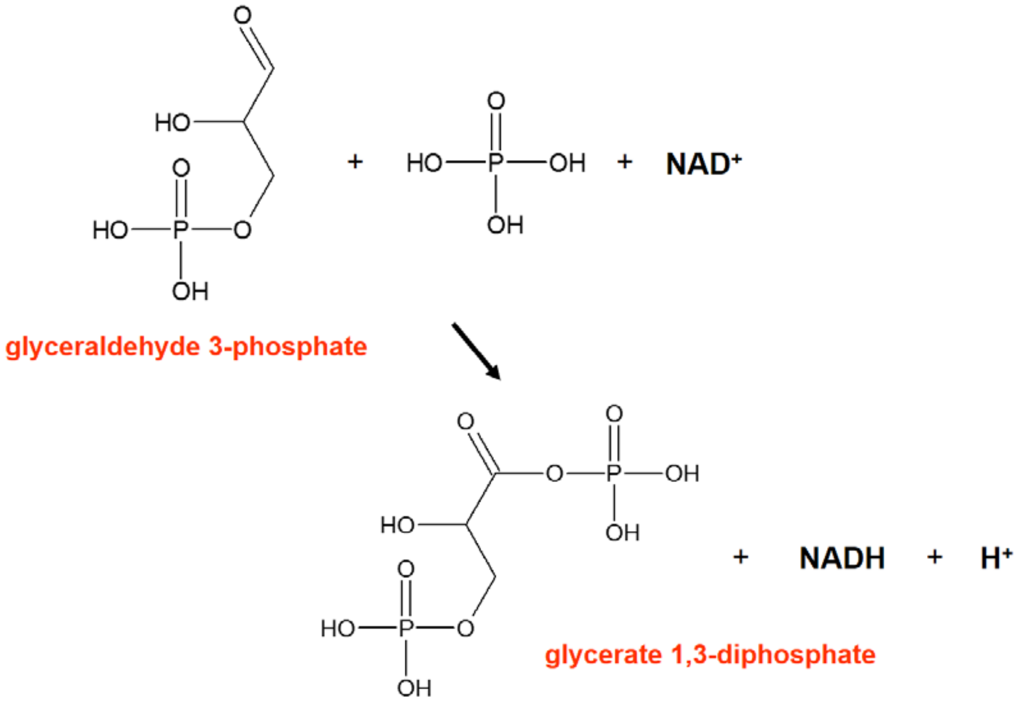


Fructose 1, 6-diphosphate breaks down into glyceraldehyde 3-phosphate and dihydroxyacetone phosphate.



These three-carbon molecules are phosphorylated further, forming diphosphates. This reaction requires phosphoric acid and energy gained from the reduction of NAD^+ (oxidised form of nicotinamide adenine dinucleotide) to NADH (reduced form of nicotinamide adenine dinucleotide).

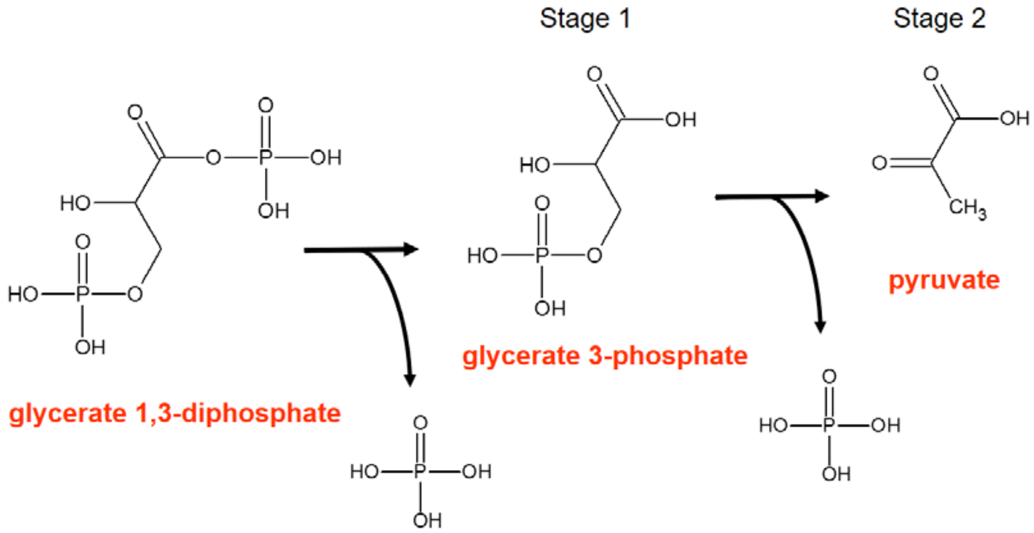
Further phosphorylation of glyceraldehyde 3-phosphate



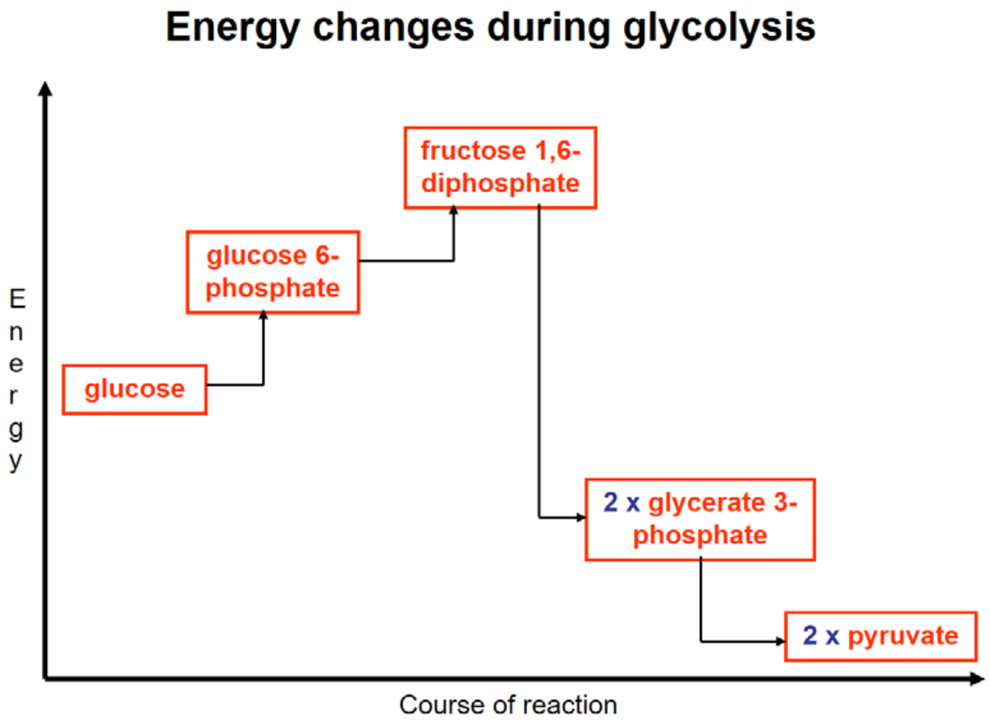
Glycerate 1,3-diphosphate molecules are dephosphorylated to form glycerate 3-phosphate molecules (a hydrolysis reaction). The energy released and the phosphate group that splits out are used to make more ATP from ADP.

Dephosphorylation of glycerate 1,3-diphosphate

Glycerate 1,3-diphosphate dephosphorylates in two stages:



Each glycerate 3-phosphate molecule is converted to a pyruvate molecule. Again, the energy released and the phosphate group that splits out are used to make more ATP from ADP.



The link reaction

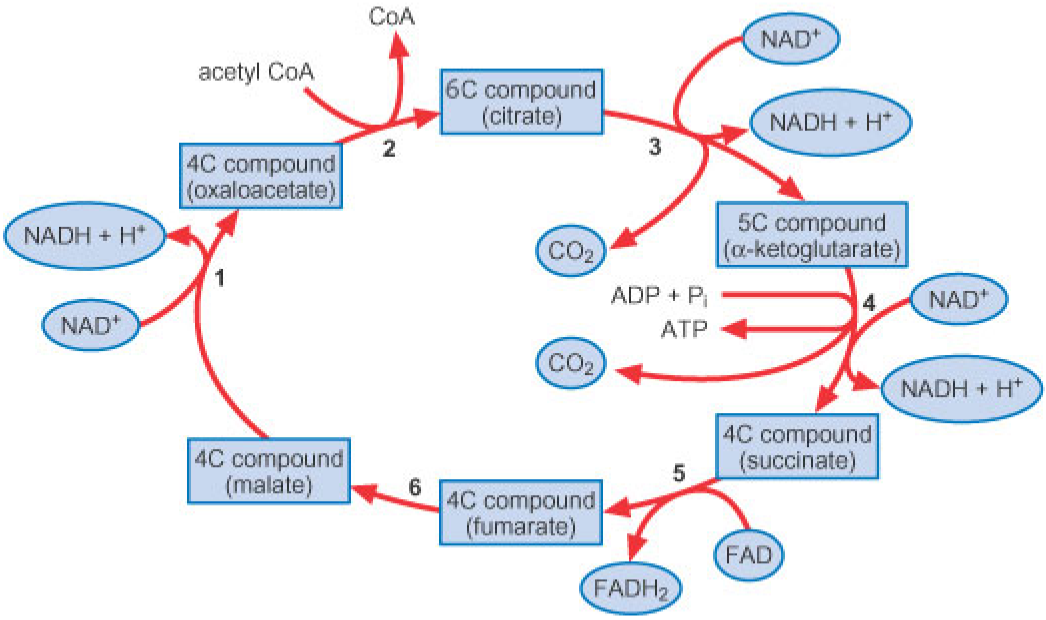
This links glycolysis to the Krebs Cycle (sometimes called the citric acid cycle). Pyruvate molecules are **decarboxylated** (they lose a molecule of carbon dioxide) in the mitochondria. Pyruvate molecules are oxidized and converted to acetylcoenzyme A, usually abbreviated to acetyl CoA.

$2CH_3COCOO^- + 2NAD^+ + 2H_2O \rightarrow 2CH_3COO^- + 2NADH + 2H^+ + 2CO_2$

The oxidised form of nicotinamide adenine dinucleotide, NAD^+, is reduced to its reduced from NADH.

The Krebs cycle

This is a complicated cycle. It may be summarised:



Citrate (a six-carbon molecule) forms when an acetyl CoA molecule combines with oxaloacetate (a four-carbon atom molecule) in a condensation reaction. The citrate then undergoes a sequence of redox reactions:

- two decarboxylations (oxidation - removal of carbon dioxide); in each case NAD+ is reduced to NADH
- two dehydrogenations (removal of hydrogen);

The overall reaction is:

2 acetyl CoA + $6NAD^+$ + 2FAD + 2ADP + $2H_3PO_4$ $\rightarrow$ $4CO_2$ + 6 NADH + $6H^+$ + $2FADH_2$ + 2ATP

Oxidative phosphorylation

NADH 'carries' hydrogen ions and high-energy electrons. In oxidative phosphorylation the hydrogen ions combine with oxygen to form water and the electrons pass along an **electron transfer chain**(also called the respiratory chain) using their energy to form ATP molecules. One molecule of NADH forms three ATP molecules.

ATP production is greatly increased by oxygen. By combining with hydrogen ions (and accepting electrons) to form water it allows more hydrogen ions to be released from the electron carrier system.

During aerobic respiration, oxidation of one molecule of glucose produces 38 ATP molecules (net).

To find out more about the role of mitochondria as a site for the Krebs cycle and the electron transfer chain as well as the location of electron carriers and the role of oxido reductases visit: http://www.biology-pages.info/C/CellularRespiration.html

Anaerobic respiration (without oxygen)

Anaerobic respiration in humans may be summarised by the word equation:

glucose $\rightarrow$ lactic acid + energy

In yeast anaerobic respiration may be summarised by:

glucose $\rightarrow$ ethanol + carbon dioxide + energy

During glycolysis, glucose molecules (six-carbon molecules) are split into two pyruvates (three-carbon molecules) during a sequence of enzyme-controlled reactions. This is the same reaction as occurs in aerobic respiration. Without oxygen, pyruvate is converted to lactic acid in animals or ethanol in plants and yeast. It produces only about 10% of the energy released in the complete oxidation of glucose.

Anaerobic respiration in humans takes place when muscle undergoes extreme contraction as in vigorous exercise. When oxygen is limited the oxidation of NADH to NAD^+ by the electron transport chain is insufficient to maintain glycolysis. Under these conditions NAD^+ is regenerated by the reduction of pyruvate to lactate.

In yeast pyruvate is converted to ethanal and then to ethanol. The latter stage oxidises NADH to NAD^+, allowing glycolysis to continue.

Test your knowledge

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