Biochemistry of microorganisms and plants

EVROPSKÁ UNIE
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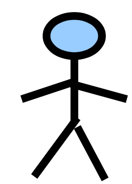
Energy	Photo-				Chemo-			
Source of electrons	Organo-		Litho-		Organo-		Litho-	
Carbon source	Auto-	Hetero-	Auto-	Hetero-	Auto-	Hetero-	Auto-	Hetero-

Examples

Haloarchaea



$H_2S \rightarrow S$

$S \rightarrow SO_4^{2-}$

$S_2O_3^{2-} \rightarrow SO_4^{2-}$

$NH_3 \rightarrow NO_2^-$

$NO_2^- \rightarrow NO_3^-$

$Fe^{2+} \rightarrow Fe^{3+}$

$CH_4 \rightarrow CO_2$

$CH_3OH \rightarrow CO_2$

Organisms can be classified based on energy source, source of electrons or source of carbon. Humans are chemo-, organo- and heterotrophs. They cannot use photosynthesis, they oxidize organic compounds and they eat other organisms. Plants are photo-, litho- and autotrophs. Chemolithotrophs oxidize inorganic compounds. Some organisms are capable of anaerobic respiration, i.e. they can use inorganic compounds other than oxygen as acceptors of electrons (oxidating agents). *Haloarchaea* use a primitive photosynthesis to produce ATP, but not NADPH.

Fermentation

Fermentation is a non-respirating anaerobic metabolism of organic nutrients. Most common chemoorganothrophs, including humans, metabolize sugars (e.g. glucose) under aerobic conditions to water and carbon dioxide. This produces lot of energy in the form of ATP. However, this is not possible under anaerobic conditions. Fermentation process is chemically speaking a disproportionation reaction, i.e. redox reaction converting the substrate into one oxidized and one reduced product. For example yeast convert glucose to reduced ethanol and oxidized carbon dioxide.

Glycolysis produces little energy in the form of ATP (two molecules per one molecule of glucose). Moreover, pyruvate as the terminal product of glycolysis is in an oxidized state relative to glucose. Glycolysis to pyruvate therefore requires conversion of NAD^+ to NADH. Absence of oxygen or other mechanism oxidizing NADH would lead to accumulation of NADH, lack of NAD^+ and termination of glucose metabolism. It is necessary to oxidize NADH by other reactions.

Intensively working human or animal muscle, erythrocytes or some cancer cells use NADH to reduce pyruvate to lactate.

Yeast reduce acetaldehyde to ethanol.

Some lactic acid bacteria produce lactate by reduction of pyruvate.

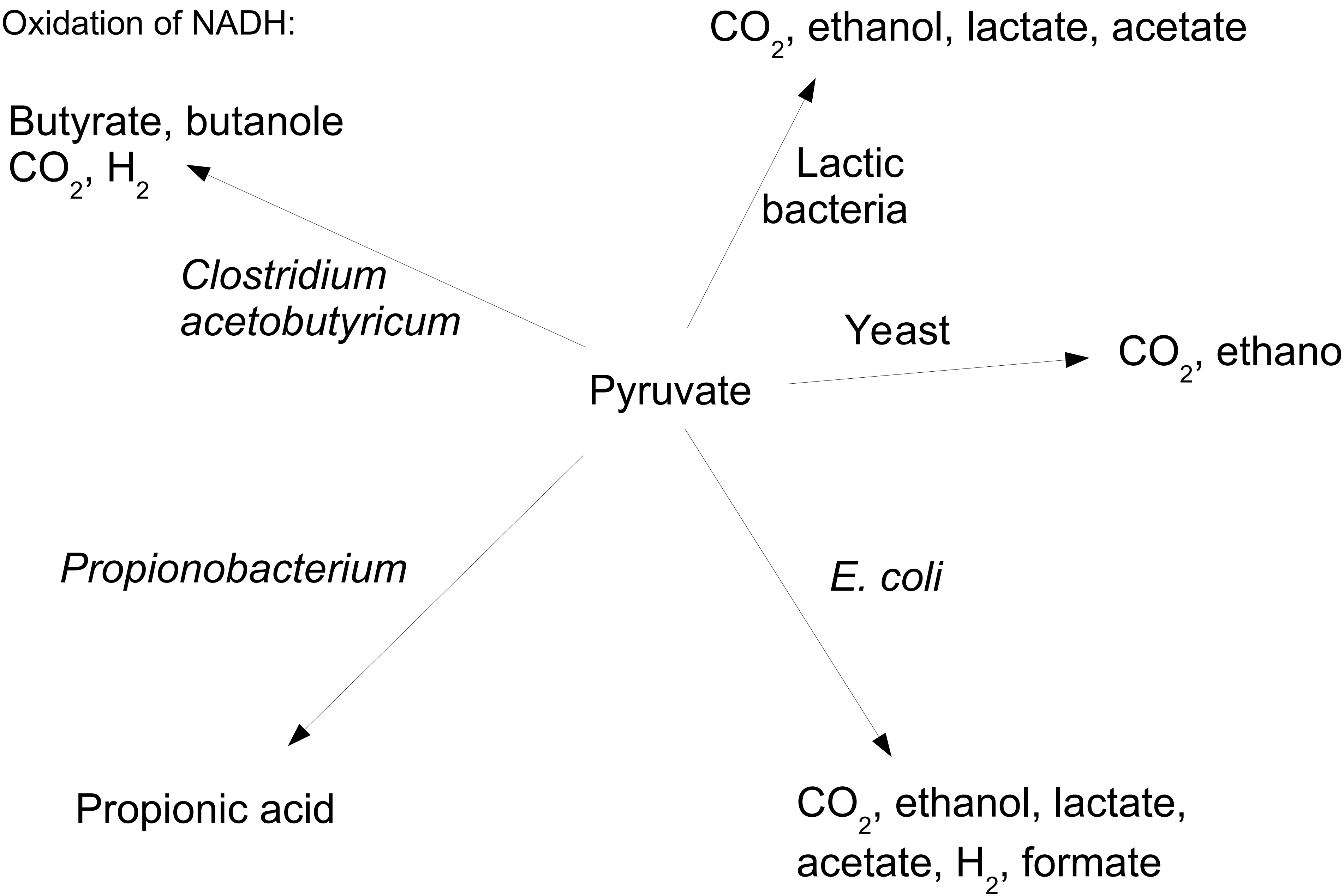
E. coli and some other bacteria produce acetate, formate and/or hydrogen.

Propionobacterium produces propionate.

Clostridium acetobutylicum produces butanol.

Fermentation

Oxidation of NADH:



Fermentation
Yeast

$$\text{pyruvate} \xrightarrow{\text{pyruvate decarboxylase}} \text{acetaldehyde} \xrightarrow{\text{alcohol dehydrogenase}} \text{ethanol}$$

Side products:
biacetyl

CH_3-CO-CO-CH_3

acetoin

CH_3-CO-CHOH-CH_3

butandiol

CH_3-CHOH-CHOH-CH_3

Pyruvate decarboxylase requires thiamine diphosphate. As an alternative product it can produce biacetyl, acetoin or butandiol. These compounds are sometimes favoured, sometimes disfavoured in fermented products.

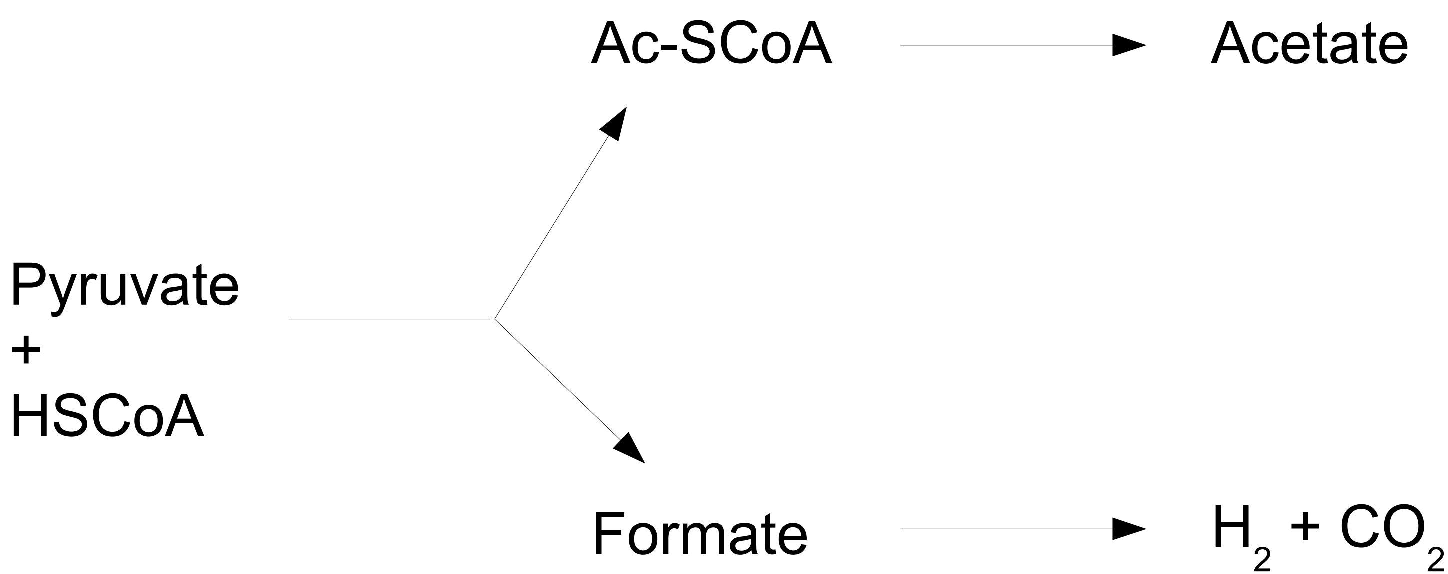
Fermentation
Lactic acid bacteria

Lactic acid bacteria ferment glucose to lactate in a similar way as human muscles under anaerobic conditions. This is done by *Lactococcus, Enterococcus, Streptococcus* and *Pediococcus*.

Leuconostoc or *Weissella* use partial pentose phosphate pathway. They convert glucose to Glc-6-P. This is oxidized to 6-phosphogluconate and then decarboxylated to pentose-5-phosphate. This molecule is decomposed into glyceraldehyde-3-P and acetyl phosphate. Glyceraldehyde-3-P goes to truncated glycolysis to form lactate. Acetyl phosphate is reduced to ethanol.

$$\text{Glc-6-P} \xrightarrow{\text{NADP}^+} \text{6-phosphogluconate} \xrightarrow{-\,CO_2} \text{xylulose-5-phosphate} \rightarrow \text{glyceraldehyde-3-P and acetyl phosphate}$$

Fermentation
E. coli



E. coli and similar gut microorganism can grow on a low-sugar and high-protein (or high-peptide, high-amino-acid) medium. Alternatively they can grow on sugar-rich medium to produce acetate and formate. This is also used to identify microorganisms in microbiological diagnostics. *E. coli* and similar organisms are often tested based on their ability to hydrolyse oligosaccharides. For example, *E. coli* can hydrolyse lactose. When growing on a medium containing lactose it produces acids and this causes change of colony colour due to presence of acidobasic indicator. In contrast, *Salmonella* cannot ferment lactose, so it metabolizes protein hydrolysates producing basic amines.

Fermentation
Propionobacterium

$$\text{Pyruvate} \xrightarrow[+CO_2]{} \text{oxalacetate} \xrightarrow[\text{red.}]{} \text{malate} \longrightarrow \text{fumarate}$$

$$\text{fumarate} \xrightarrow{\text{red.}} \text{succinate} \longrightarrow \text{Propionate} + CO_2$$

Propionobacterium uses some reactions from the Krebs cycle to produce succinate, which is in turn decarboxylated to propionate. This compound is found in some types of cheese, especially in Emmental, due to fermentation by this microorganism.

The reason for two reductions is the fact that one of pyruvate goes to acetate.

Fermentation
Clostridium acetobutylicum

2 Ac-CoA → acetoacetyl -CoA → 2-hydroxy- butyryl -CoA → crotonyl -CoA

↓

butyryl -CoA

↓

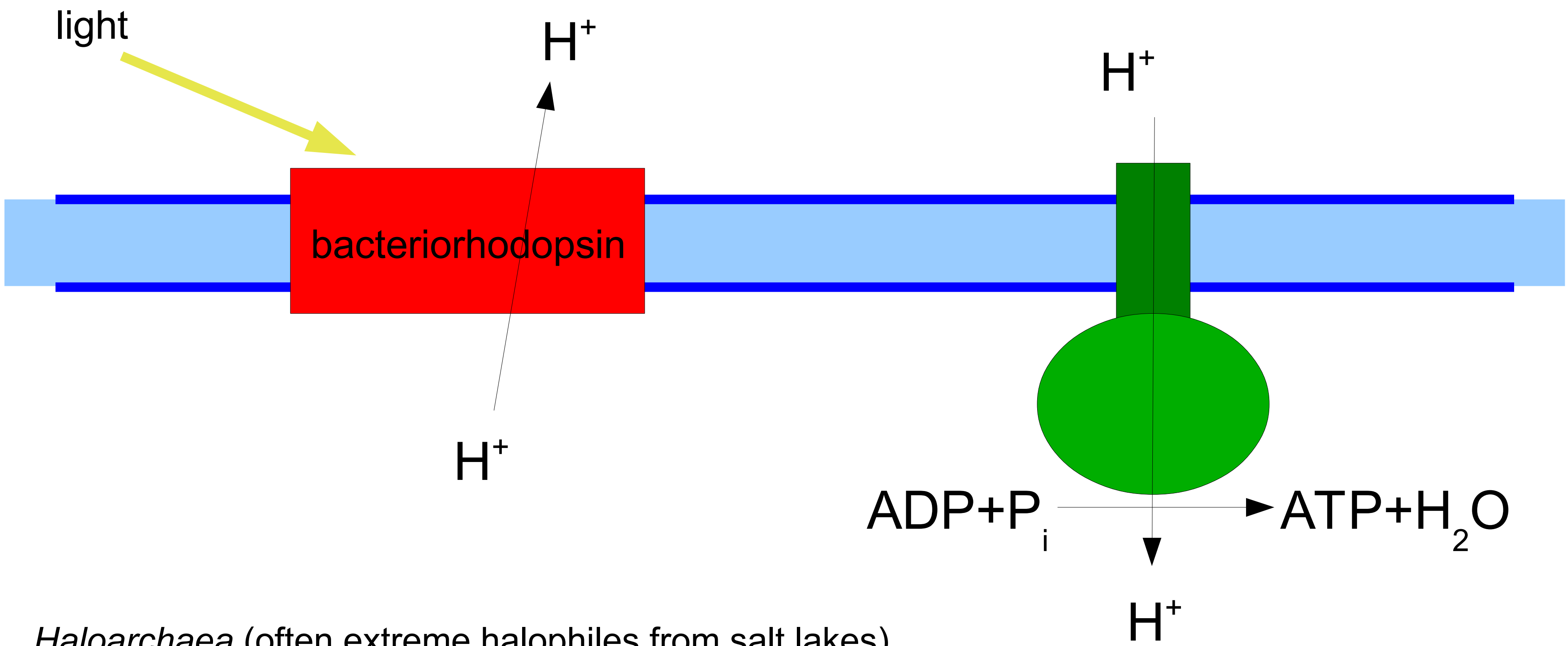
Butanal

↓

Butanol

Clostridium acetobutylicum ("Weizmann Organism") ferments sugars, including cellulose, to butanol. It is a valuable organism for production of biofuels and butanol as a synthetic precursor. It employs enzymes from fatty acid metabolism.

Photosynthesis
Haloarchaea



Haloarchaea (often extreme halophiles from salt lakes) can run a primitive photosynthesis. Light is used as a source of energy for an active transport of H^+ by bacteriorhodopsin. Proton motive force is used to produce ATP. Unlike plants they do not photolyze water and produce NADPH. Membranes of these microorganisms are packed with bacteriorhodopsin, which is in a quasi-crystalline form. This enabled determination of its structure in 1990.

Photosynthesis

There are similarities between mitochondria and non-photosynthetic prokaryotes as well as between chloroplasts and photosynthetic prokaryots.

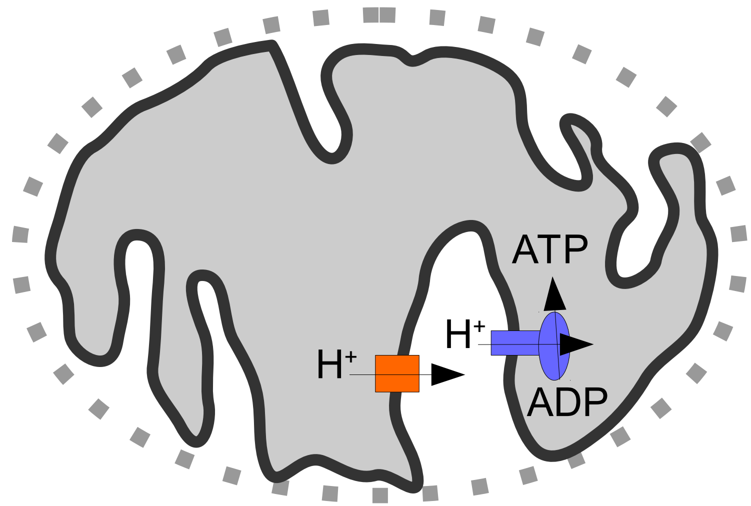
There is a widely accepted theory that mitochondria used to be a prokaryotic microorganism that invaded some pro-eukaryotic cell, started to live there in a symbiosis and later lost most of its genetic information.

Beside physical similarity of mitochondria and prokaryotic cell it is also mitochondrial genome with few intronless genes that supports the theory.

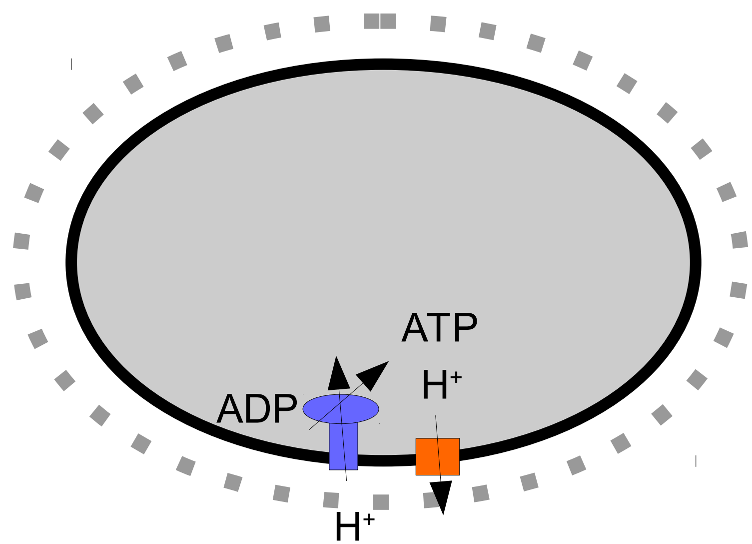
Mitochondria pump protons across its inner membrane into the intermembrane space. Protons return via ATP synthase (F_OF_1-ATPase) producing ATP.

Also prokaryotes pump protons out. Protons produce energy on their way back.

mitochondrion



prokaryotic cell



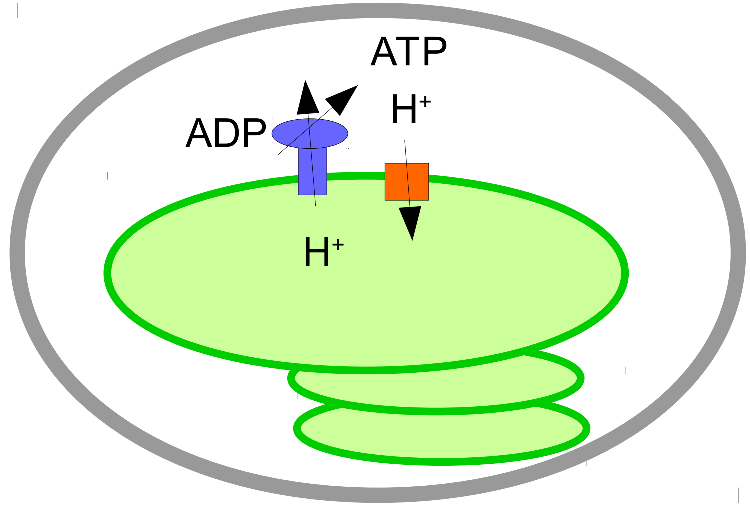
Photosynthesis

Analogously, chloroplasts are believed to be former photosynthetic prokaryots. Here, comparison with *Halloarcheum* is provided.

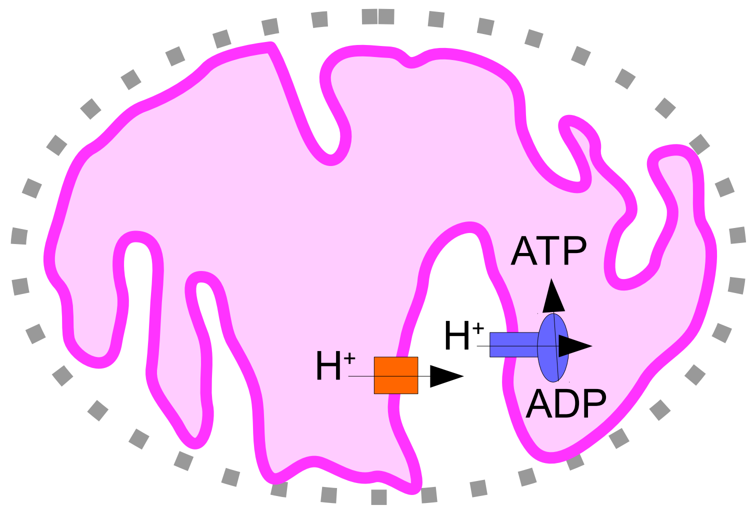
Chloroplast also has its own genome.

In contrast to mitochondria, chloroplasts contain disk-shaped membrane compartments called thylakoids. Protons are not pumped outside chloroplasts, instead they are pumped into thylakoids. Thylakoids are arranged to maximize the surface for efficient harvesting of light. The interior of thylakoid is called lumen.

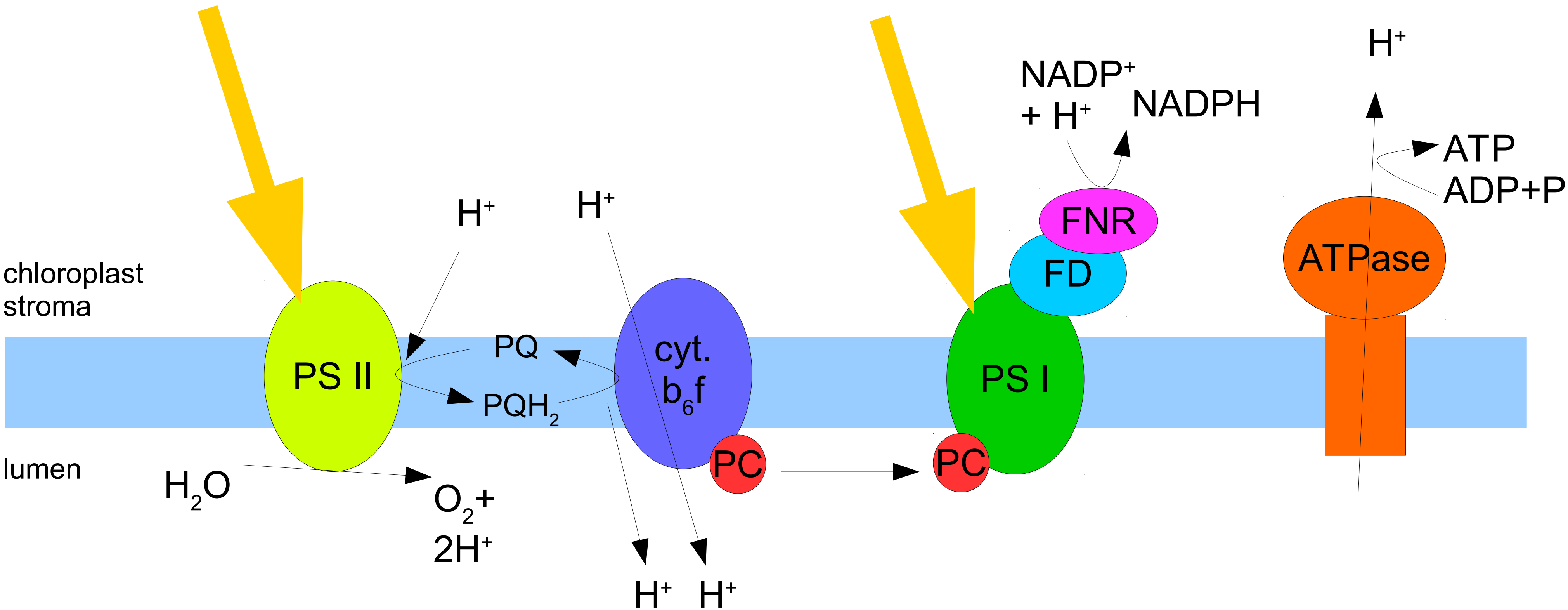
chloroplasts



Halloarcheum

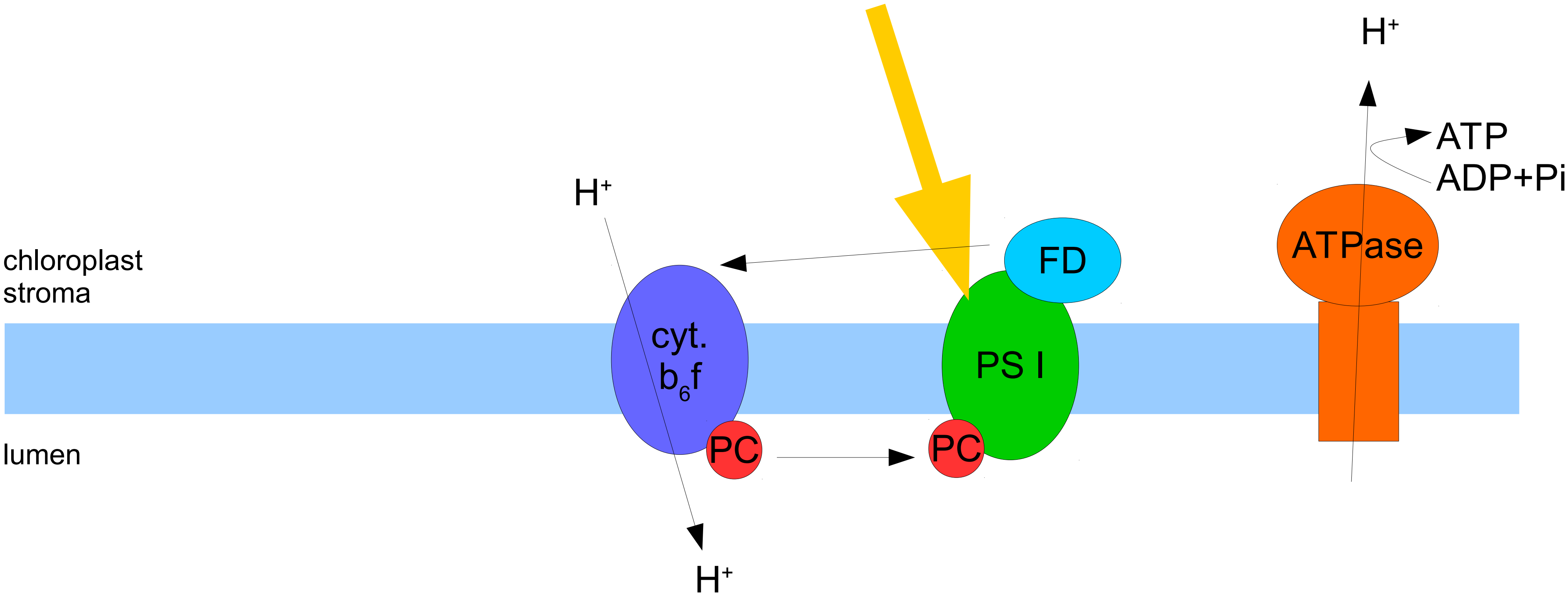


Photosynthesis
Plants, alga



In plant non-cyclic photosynthesis photons are captured by photosystem II. The energy is used to photolyze water to oxygen and H^+ while electrons are used to reduce plastoquinone (plant analogy to Q10). They travel to cytochrome b6f where electrons are transferred to plastocyanine (plant analogy to cytochrome C). These electrons travel to photosystem I where other photons are captured and finally they are used to reduce $NADP^+$ to NADPH. Protons transported across the membrane are used to produce ATP by ATPase.
(FD=Ferredoxin, FNR=Ferredoxin-NADP+ reductase)

Photosynthesis
Plants, alga



In plant cyclic photosynthesis photons are captured only by photosystem I and electrons travel from cyt. b6f and PS I. Protons transported across the membrane are used to produce ATP by ATPase, but no water is photolysed and no NADPH produced. Plants can regulate it to fulfill their ATP and NADPH needs.

Photosynthesis
Plants, alga

Ribulose-1,5-bisphosphate carboxylase/oxygenase – RuBisCO

RuBisCO is the most common protein on Earth. It catalyses carboxylation reaction (C in RuBisCO, depicted) or oxygenase reaction (O in RuBisCO, producing 3-phosphoglycerate and phosphoglycolate)

Photosynthesis
Plants, alga

Calvin cycle

3 ribulose-1,5-bisphosphate + 3 CO_2 $\rightarrow$ 6 3-phosphoglycerate

6 3-phosphoglycerate $\rightarrow$ 6 glyceraldehyde-3-P

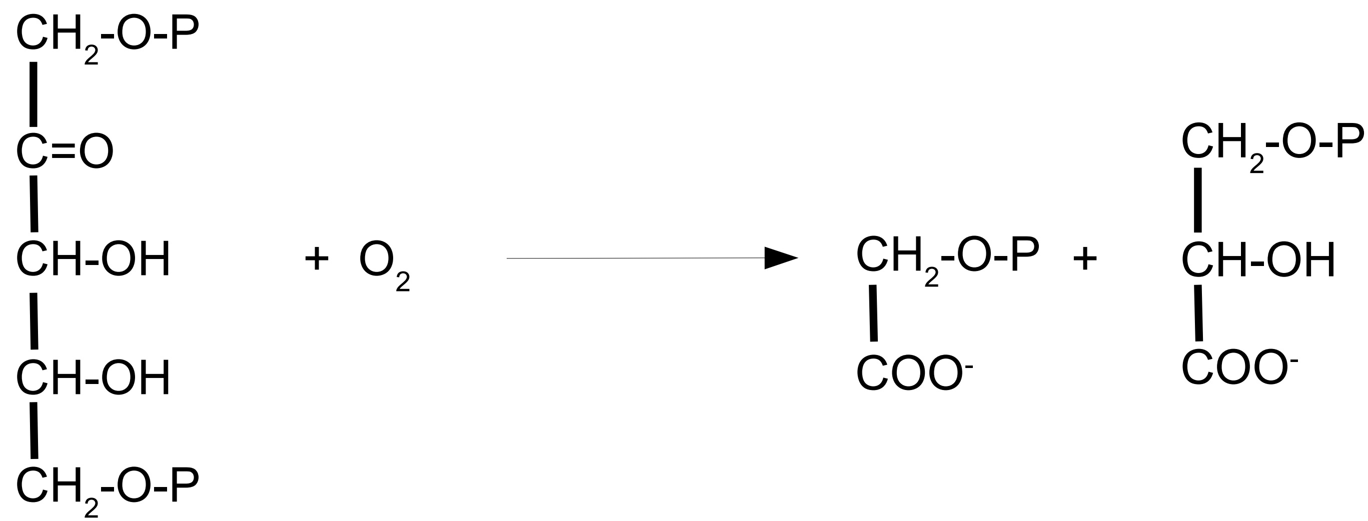
6 glyceraldehyde-3-P $\rightarrow$ 5 glyceraldehyde-3-P $\rightarrow \rightarrow \rightarrow \rightarrow$ 3 ribulose-1,5-bisphosphate

6 glyceraldehyde-3-P $\rightarrow$ 1 glyceraldehyde-3-P $\rightarrow \rightarrow \rightarrow \rightarrow$ ½ glucose

When three ribulose-1,5-phosphate molecules are converted by RuBisCO to six 3-phosphoglycerates, one of them is used to produce glucose in a gluconeogenesis-like pathway. Other five molecules are converted into the staring three molecules of ribulose-1,5-bP using NADPH and ATP by reactions similar to the pentose phosphate pathway. This is known as light-independent photosynthesis or Calvin cycle.

Photosynthesis
Plants, alga

Photorespiration



RuBisCO may produce one 3-phosphoglycerate and one phosphoglycolate by its alternative oxygenase reaction. The role of this reaction is bit enigmatic, if there is any role. The process recovering phosphoglycolate is known as photorespiration.
Phosphoglycolate is hydrolysed to glycolate and then transported to cytoplasm. There it is oxidized to glyoxylate. By condensation with ammonium it produces glycine. Two glycine molecules produce serine in mitochondria. Serine is converted to glycerate and finally 3-phosphoglycerate.
Photorespiration causes loss of energy (up to 25 %), produced hydrogen peroxide and makes other negative impacts. The reasons for photorespiration is unclear. Regulatory, redox homeostasis and other explanations have been proposed.

Photosynthesis
Plants, alga

Photorespiration

Oxygenase reaction of RuBisCO can be reduced by high concentration of carbon dioxide. Some plants, called C4 and CAM plants, use different tricks to do this.

Most plants are called C3 plants. The name comes from the product of carbon dioxide fixation, which is 3-phosphoglycerate with 3 carbons.

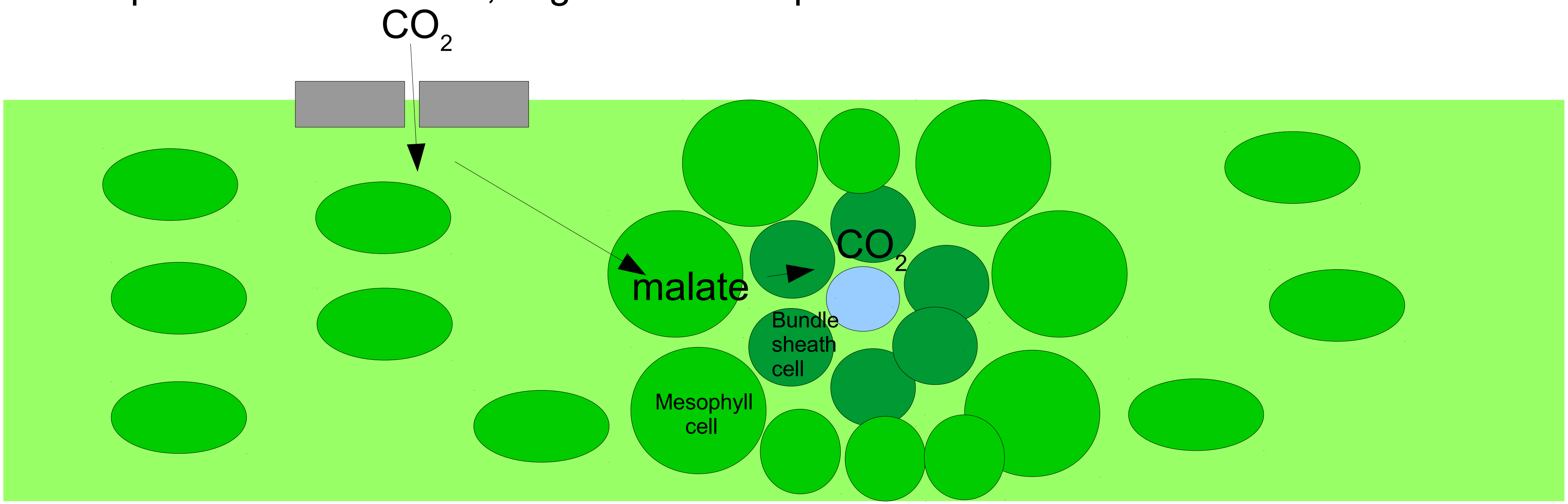
C3 plants do not have any special mechanism to increase carbon dioxide concentration in cells. The level of photorespiration is high. These plants cannot adapt to hot and dry areas.

Photosynthesis
Plants, alga

Photorespiration

C4 plants separate carbon fixation and RuBisCO reaction in the space. At some cells they catalyse reaction of carbon dioxide with phosphoenolpyruvate catalysed by phosphoenolpyruvate carboxylase. This forms oxalacetate. Oxalacetate (C4) is reduced to malate and transported to other cells where it serves as a source of carbon dioxide. These pathways may differ between individual C4 plants (some involve aspartate).

C4 plants include maize, sugar cane or rape.



Photosynthesis
Plants, alga

Photorespiration

CAM (Crassulacean acid metabolism) plants separate carbon fixation and RuBisCO reaction not only in the space, but also in time. In night these plants open stomata (“air vents”) and accumulate CO_2 to form malate. Malate is stored in vacuols.

During the day plants close their stomata. CO_2 is released from malate and used in photosynthesis.

CAM plants are tropical plants such as pineapple. The term crassulacean acid metabolism comes from jade tree (*Crassula ovata*) that was used as a model plant.