Lecture 5 - Cellular Respiration

Introduction

Photosynthesis

Photosynthesis is therefore a process in which the energy in sunlight is stored in the chemical bonds of glucose ($C_6H_{12}O_6$) for later use.

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

Carbon dioxide is ***reduced*** to glucose and water is ***oxidized***. Oxidation is the loss of an electron or hydrogen atom. Reduction is the gain of an electron or hydrogen atom. Oxidation reactions release energy and reduction reactions store energy in chemical bonds.

What is Cellular Respiration?

Cellular respiration allows organisms to use (release) the energy stored in glucose. The energy in glucose is first used to produce ATP. Cells use ATP to supply their energy needs. Cellular respiration is therefore a process in which the energy in glucose is transferred to ATP.

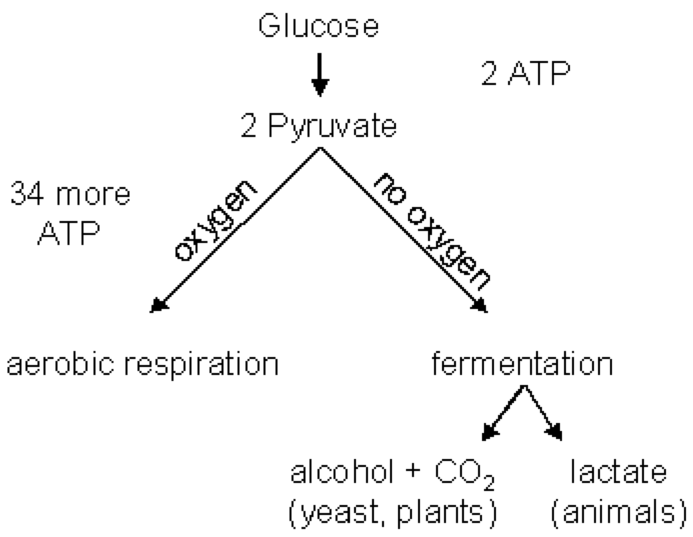
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy\ (36\ ATP)$$

In respiration, glucose is ***oxidized*** (releasing energy) and oxygen is ***reduced*** to form water.

The carbon atoms of the sugar molecule are released as ***carbon dioxide*** (CO_2).

The complete breakdown of glucose to carbon dioxide and water requires two major steps: 1) glycolysis and 2) aerobic respiration. Glycolysis produces two ATP. Thirty-four more ATP are produced by aerobic pathways if oxygen is present.

In the absence of oxygen, fermentation reactions produce alcohol or lactic acid but no additional ATP.



Review of Electron Carriers

$NAD^+ + 2H \rightarrow NADH + H^+$

$FAD + 2H \rightarrow FADH_2$

Glycolysis

During glycolysis, glucose (C_6) is broken down to two molecules of pyruvate (C_3). (*Compounds that end in "___ate" can be called "___ic acid". Example lactate is lactic acid and malate is malic acid.)

Glycolysis occurs in the ***cytoplasm*** (***cytosol***) and does not require oxygen.

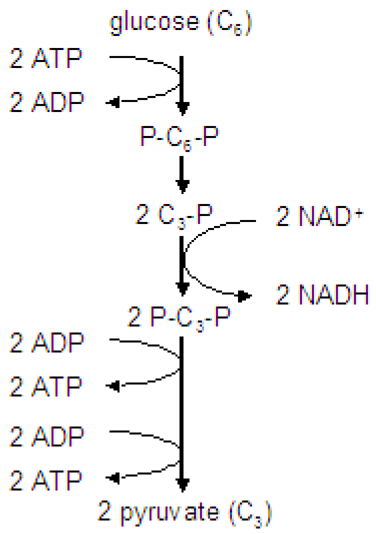
There are ten steps in glycolysis and each one is catalyzed by a specific enzyme. A brief summary of these reactions is presented here.

2 ATP molecules are used to phosphorylate and activate compounds that will eventually become converted to ***pyruvate*** (or ***pyruvic acid***) (see diagram below).

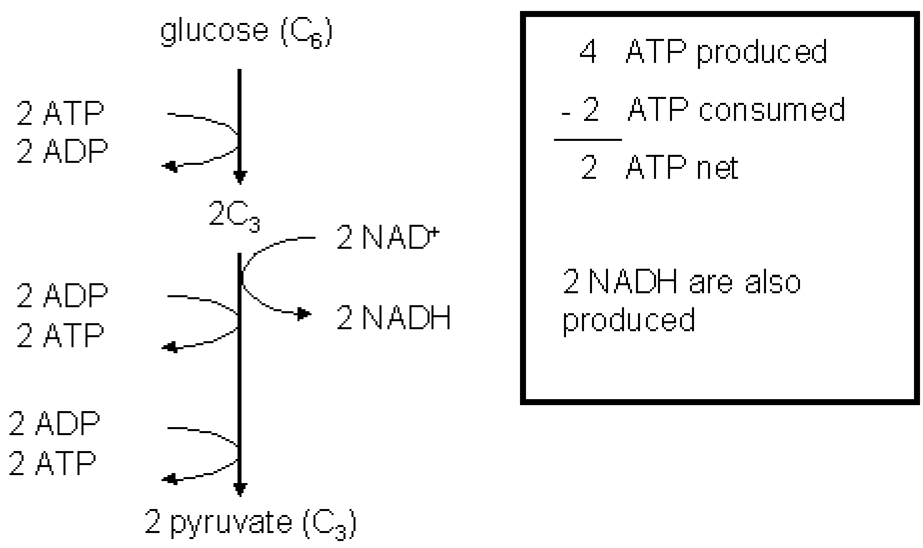
Two hydrogen atoms are removed by NAD^+ forming 2 NADH (see diagram).

Additional phosphorylation results in intermediate 3-carbon molecules with 2 phosphate groups.

Four ATP are produced by ***substrate-level phosphorylation***. Recall that substrate-level phosphorylation is the production of ATP using energy from other high-energy compounds but without the use of the electron transport system in the mitochondria.



The net yield of ATP in glycolysis is 2 for each glucose molecule (2 are used but 4 are produced).



Some bacteria have alternative energy-producing reactions. Two of these are the pentose phosphate pathway and the Entner-Doudoroff pathway.

Formation of Acetyl CoA

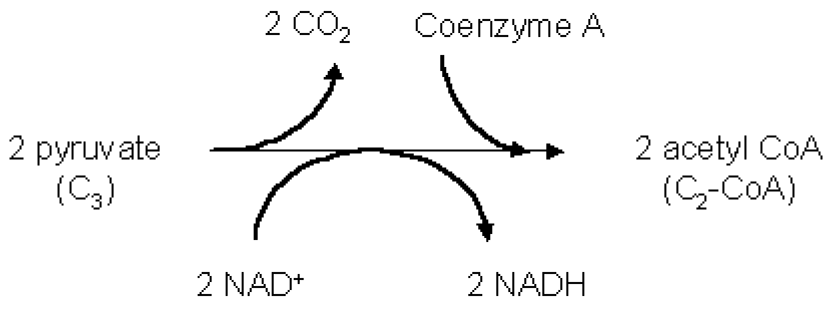
Pyruvate produced by glycolysis (see above) enters the ***mitochondrion*** and is converted to ***acetyl CoA*** by the reaction below. The remainder of the reactions of cellular respiration occur in the ***mitochondrion***.

pyruvate (C_3) $\rightarrow$ acetyl CoA (C_2) + CO_2

During this step, NADH is produced from NAD^+ + 2H (oxidation).

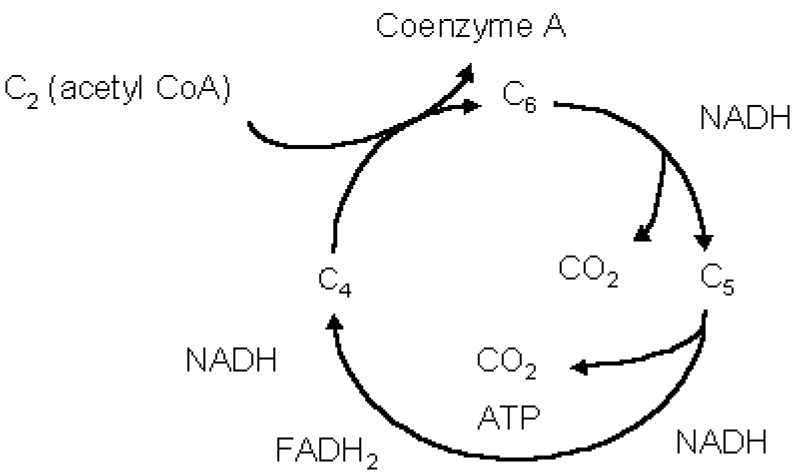
This step must occur twice for each glucose molecule because each glucose molecule produces two pyruvate molecules in glycolysis (above).

The two-carbon compound produced is attached to Coenzyme A to produce acetyl CoA.



Krebs Cycle

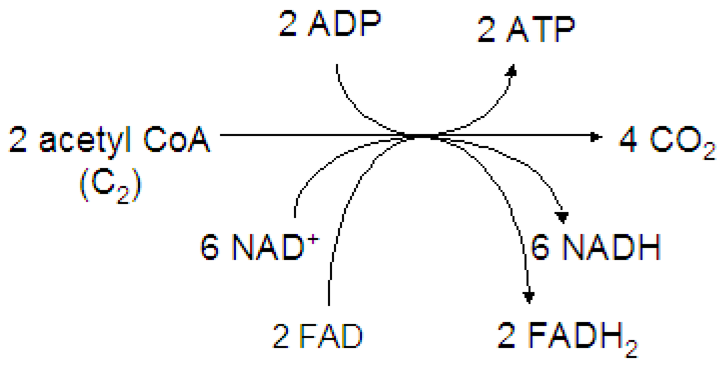
The Krebs cycle can be summarized by either of the diagrams below. The diagram below occurs twice, once for each acetyl CoA.



When acetyl CoA attaches to a C_4 molecule in the Krebs cycle, the Coenzyme A is released.

Two acetyl CoA molecules are consumed to produce 4 CO_2, 2ATP, 6 NADH and 2 $FADH_2$. The ATP molecules are produced by substrate-level phosphorylation.

The diagram below also summarizes the Krebs Cycle.



Electron Transport and Oxidative Phosphorylation

Mitochondrion structure

The inner membrane forms folds called ***cristae***. These folds contain the carriers of the electron transport system.

Acetyl CoA formation and the Krebs cycle occur in the inner space called the matrix.

The space outside the inner membrane is the ***intermembrane space***. The electron transport system pumps hydrogen ions (H^+) into this space for oxidative phosphorylation.

Oxidative Phosphorylation

The ***electron transport system*** is found in the mitochondrion and chloroplast of eucaryotes and in the plasma membrane of procaryotes. It consists of a series of carrier molecules which pass electrons from a high-energy compound to a final low-energy electron acceptor. Energy is released during these oxidation-reduction reactions to produce ATP.

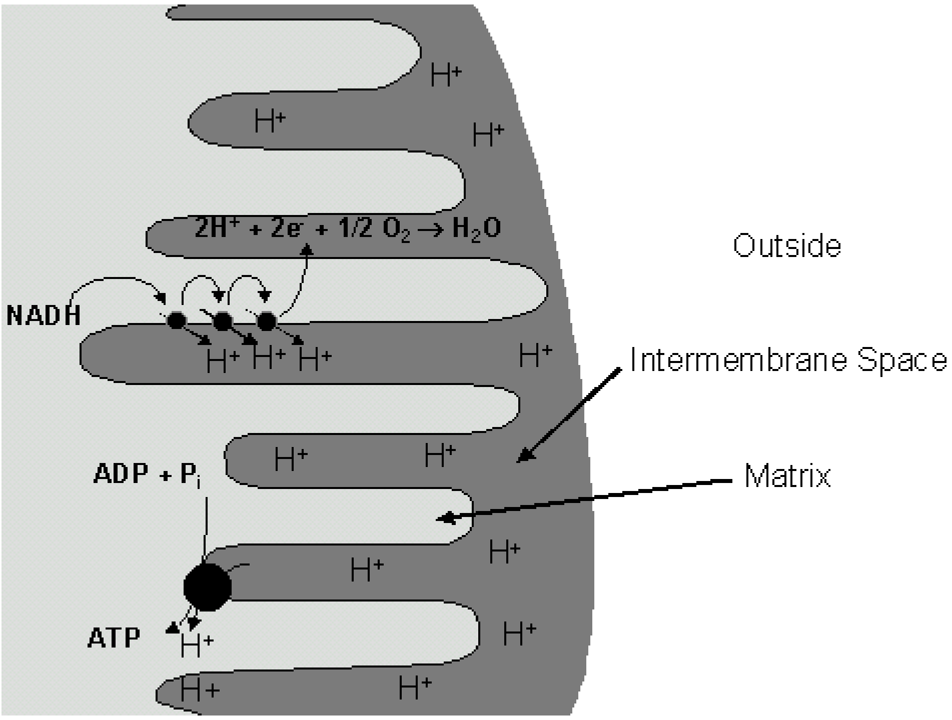
The discussion below applies to the mitochondria of eucaryotes.

NADH or $FADH_2$ bring electrons to the electron transport system in the mitochondria.

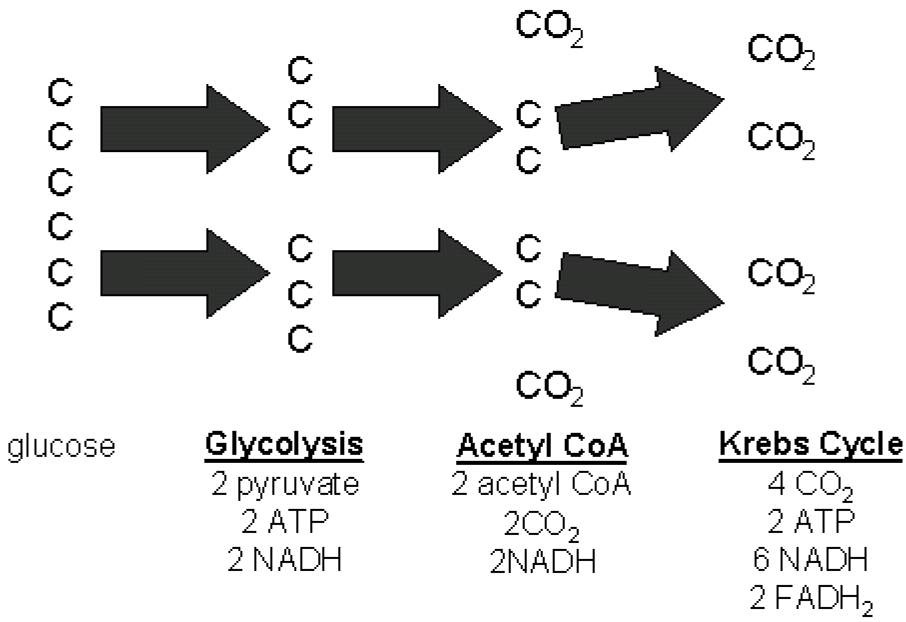
The system contains membrane-bound electron carriers that pass electrons from one to another. When a carrier reduces another, some of the energy that is released as a result of that reduction is used to pump hydrogen ions across the membrane into the intermembrane space. The remaining energy is used to reduce the next carrier.

As a result of the electron transport system, hydrogen ions become concentrated in the intermembrane space. These concentrated ions contain energy much like a dam. The enzyme ***ATP synthase*** is able to use the energy of this osmotic gradient to produce ATP as the hydrogen ions move under osmotic pressure through the enzyme back into the matrix of the mitochondrion.

Oxygen is the final electron acceptor. The low-energy electrons that emerge from the electron transport system are taken up by O_2. The negatively charged oxygen molecules take up protons from the medium and form water ($2H^+ + 2e^- + 1/2\ O_2 \rightarrow H_2O$).



Summary of Glycolysis and Cellular Respiration



Glycolysis

During glycolysis, glucose (C_6) is converted to two pyruvates (C_3).

C-C-C-C-C-C → C-C-C + C-C-C

Formation of Acetyl CoA

One acetyl CoA is formed for each pyruvate produced by glycolysis (see the step above).

C-C-C → C-C + CO_2

pyruvate → acetyl CoA + CO_2

Krebs Cycle

C-C → 2 CO_2

The Krebs Cycle produces NADH, $FADH_2$, and ATP.

NADH and $FADH_2$ carry electrons to the electron transport system.

Electron Transport System

In the electron transport system, NADH and $FADH_2$ are oxidized and the energy is used to produce ATP.

Total ATP yield per glucose

Conversions

NADH produced in the cytoplasm produces two ATP by the electron transport system.

NADH produced in the mitochondria produces three ATP.

$FADH_2$ adds its electrons to the electron transport system at a lower level than NADH, so it produces two ATP.

Glycolysis

2 ATP

2 NADH (= 4 ATP; these are converted to ATP in the mitochondria during cellular respiration)

Formation of Acetyl CoA

2 NADH (= 6ATP)

Krebs Cycle

6 NADH (= 18 ATP)

2 $FADH_2$ (= 4 ATP)

2 ATP

Total Yield

Glycolysis produces 2 ATP; aerobic respiration produces 34 more ATP

Pathway	**Substrate-Level Phosphorylation**	**Oxidative Phosphorylation**	**Total ATP**
Glycolysis	2 ATP	2 NADH = 4 - 6 ATP*	6 - 8*
CoA		2 NADH = 6 ATP	6
Krebs Cycle	2 ATP	6 NADH = 18 ATP 2 $FADH_2$ = 4 ATP	24
TOTAL	4 ATP	32 ATP	36 - 38

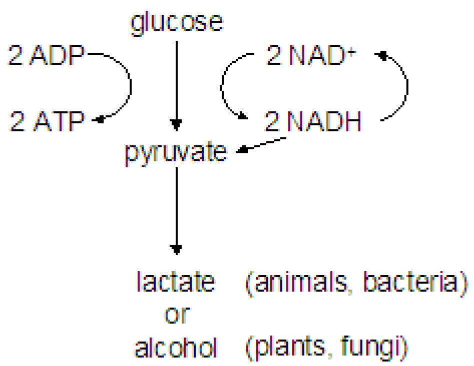
Fermentation

Without oxygen, cellular respiration could not occur because oxygen serves as the final electron acceptor in the electron transport system. The electron transport system would therefore not be available.

Glycolysis can occur without oxygen. Although glycolysis does not require oxygen, it does require NAD^+. Cells without oxygen available need to regenerate NAD^+ from NADH so that in the absence of oxygen, at least some ATP can be made by glycolysis.

To regenerate NAD^+ from NADH, the electrons from NADH are added to pyruvate to produce alcohol (plants, yeast) or lactate (animals, bacteria).

The total ATP yield of fermentation comes from glycolysis; 2 ATP molecules are produced per glucose.



Usefulness of Fermentation

Anaerobic exercise

During vigorous exercise, oxygen is consumed faster than it is needed. Additional ATP energy is provided to the muscles by glycolysis and the result is a buildup of lactate in the muscles.

When lactate builds up, the blood pH drops and the muscles fatigue.

At rest, lactate is converted back to pyruvate (the oxygen debt is repaid). This is why you continue to breathe hard after you have finished running or rapid stair climbing.

Yeast

Yeast produce alcohol which accumulates in their environment. As the concentration of alcohol in their environment increases, it becomes more and more toxic to them. Beer and wine have a maximum alcohol concentration because a higher concentration will kill the yeast cells.

Evolution of Cellular Respiration

Early cells probably fermented organic molecules in the oceans.

Today, nearly all organisms show some form of fermentation which indicates that it evolved early in evolutionary history.

Evolution typically operates by building upon or adding to what is already there. Aerobic respiration appears to have been added to fermentation.

Summary

Glycolysis

Two ATP molecules are used to phosphorylate and activate glucose.

Two hydrogen atoms are removed by NAD^+ forming 2 NADH.

Four ATP molecules are produced by substrate-level phosphorylation.

The net yield of ATP is two; two are used and four are produced.

Fermentation

Fermentation is needed to regenerate NAD^+ from NADH so that at least some ATP can be made in glycolysis.

Electrons from NADH are added to pyruvate (reduction) to produce alcohol (plants, yeast) or lactate (animals, bacteria)

Aerobic Respiration

Aerobic respiration occurs when oxygen is available.

pyruvate $\rightarrow CO_2 + H_2O$

It occurs in the mitochondrion.

[NAD]+ and FAD carry electrons to the electron transport system.

In the electron transport system, NADH and $FADH_2$ are used to produce ATP as electrons are passed from one carrier to another. Eventually the electrons combine with hydrogen ions and oxygen (reduction) to form water.