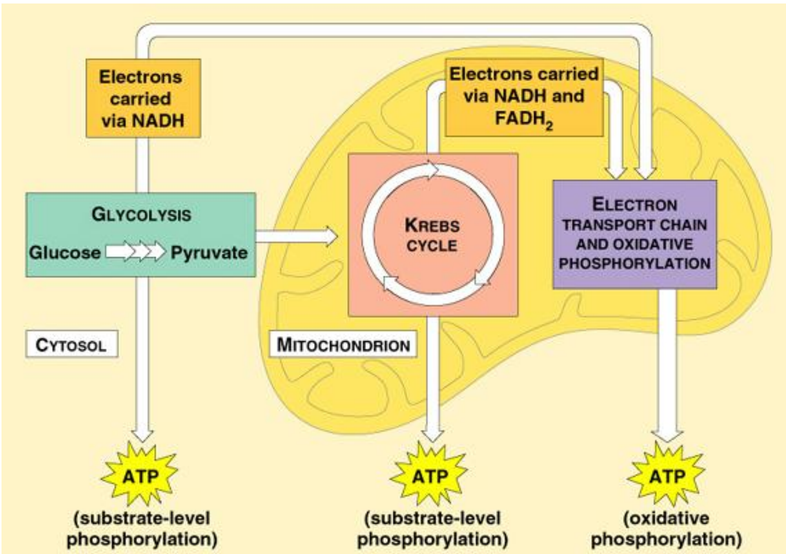
Cellular Respiration Tutorial and Practice Problems

The process by which your cells transfer the energy in organic compounds (glucose, starch, carbohydrates) to ATP, the byproduct of this reaction is water and carbon dioxide. It occurs in the cell's cytosol (cytoplasm) and the cell's mitochondria, the energy producer or "powerhouse" of the cell.

Cellular Respiration occurs in three stages

1. Glycolysis
2. Krebs Cycle
3. Electron Transport Chain (oxidative phosphorylation)



1. Glycolysis (anaerobic: does not require oxygen)

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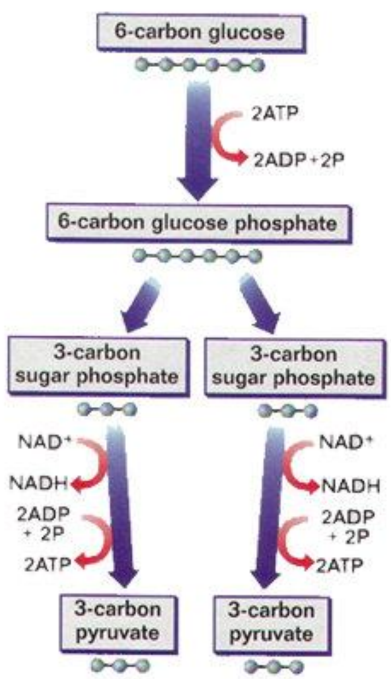
a. Occurs in the **cytoplasm (cytosol)**
b. Glycolysis has 10 steps, each step is catalyzed by a different enzyme
c. Glucose (6 carbons) is broken down into two **pyruvate** molecules (3 carbons each)
d. ATP consuming phase: **2** ATP are consumed
e. ATP producing phase: **4** ATP are produced
f. NET GAIN OF 2 ATP
g. NET GAIN OF 2 NADH
   - If O_2 is available, *each* NADH can be used to make **3** ATP in oxidative phosphorylation (Electron Transport)

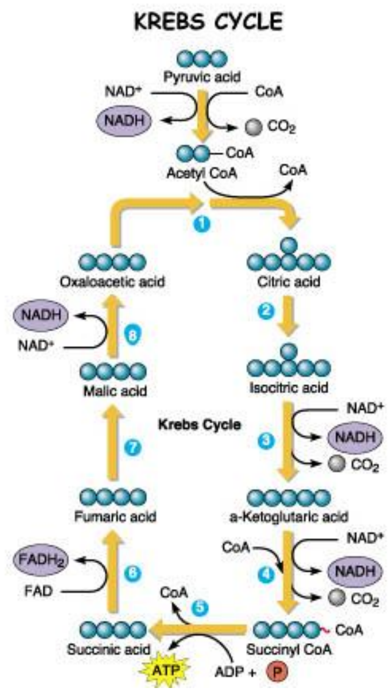


▶ Animation of Glycolysis

- **If you remember one thing about glycolysis, remember that starting with one molecule of glucose, $C_6H_{12}O_6$, glycolysis yields 2 molecules of the 3-carbon acid, pyruvate (i.e. pyruvic acid), 2 ATP, 2 NADH and does *not* require O_2**

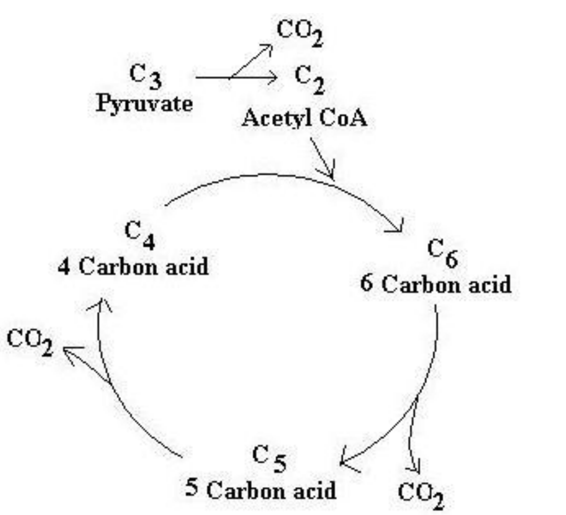
2. Krebs Cycle (also known as the CITRIC ACID CYCLE) (aerobic—requires oxygen!)

a. Occurs in the **matrix** of the mitochondria
b. The breakdown of glucose is completed and **CO_2** is produced
c. In the presence of **oxygen**, the two pyruvate molecules produced by glycolysis travel to the mitochondria
d. Krebs Cycle has 8 steps, each step is catalyzed by a different enzyme
e. Each turn of the Krebs cycle requires the input of one 2-carbon acetyl-CoA and two carbons are released as CO_2
   - One glucose molecule entering glycolysis results in the production of **2** pyruvate molecules which are converted to **2** molecules of acetyl-CoA,
   - Each turn of the Krebs cycle uses only **one** acetyl-coA, so it takes **two** complete turns of the Krebs cycle per glucose
f. The **NADH** and **$FADH_2$** created in the Krebs cycle are used by electron transport system to create large amounts of ____________
   - **3 ATP per NADH** and **2 ATP per $FADH_2$** that enter electron transport



▶ Animation of Krebs Cycle

- **If you remember one thing about the Krebs cycle, remember each pyruvate molecule yields 4 NADH, 1 $FADH_2$, 1 ATP and 3 CO_2 molecules**
- **Double this number, for each glucose molecule that enters glycolysis because the Krebs cycle makes 2 turns, one for each pyruvate**



A Simplified Version of the Krebs Cycle that only looks at what happens to the carbon atoms

3. The Electron Transport Chain (also known as oxidative phosphorylation)

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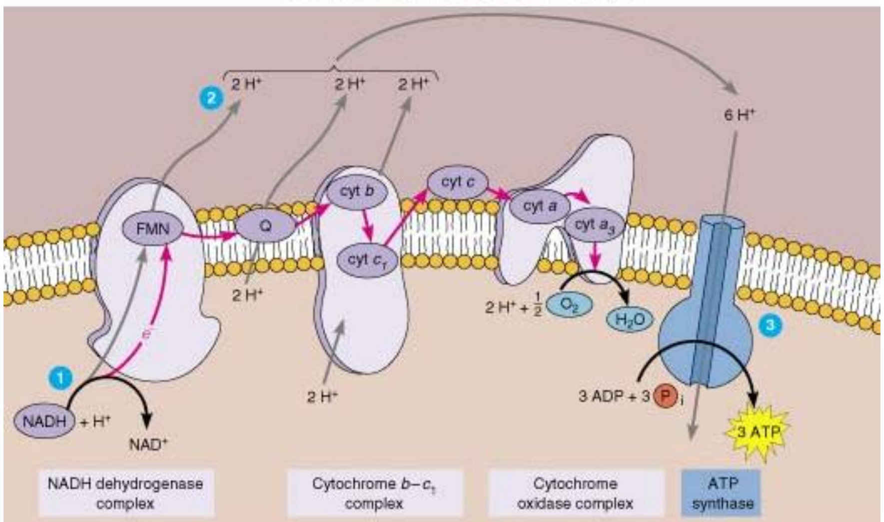
a. Produces the *chemiosmotic* energy that drives the synthesis of **ATP** in oxidative phosphorylation
b. The E.T.C consists of molecules (mostly proteins) that are embedded in the **inner membrane** of the mitochondria
c. Cofactors are attached to these proteins. The cofactors are alternately *reduced* and *oxidized* as they accept and donate **electrons**
d. The initial electron acceptor in the chain is a flavoprotein (FMN) and it accepts 2 electrons from NADH. The electrons are then passed down a series of carrier protein molecules to **oxygen gas, O_2**, which is the final electron acceptor. It is then combined with a two hydrogen ions, H^+, to form water. **E.T.C. will not function in the absence of oxygen .**
e. **NADH** and **$FADH_2$** both donate electrons to the chain
f. The electron transport chain doesn't make any ATP itself, instead these reactions are coupled to others to produce ATP, a process called ***CHEMIOSMOSIS***

ELECTRON TRANSPORT CHAIN

Intermembrane Space

Inner membrane of the mitochondrion



Mitochondrial Matrix

View both of these animations! They will totally help you understand!

▶Animation of Electron Transport Chain ▶Another Animation of Electron Transport Chain

The NET RESULTS of the Aerobic Respiration

1. **Each NADH produces 3 ATP**
   - Remember 8 NADH were created in the Krebs Cycle and 2 in Glycolysis
2. **Each $FADH_2$ produces 2 ATP** (since $FADH_2$ enters the ETC at a **lower** step)
   - Remember 2 $FADH_2$ were created in the Krebs Cycle per glucose
3. *Do the math*: 34 ATP produced in the ETC + 2 from glycolysis + 2 from Krebs = 38 total ATP from each glucose
4. However....In some cells 2 ATP are *used* to move NADH into the mitochondria from the cytoplasm. Therefore, a grand total of **36 ATP produced from each glucose molecule**

Anaerobic Respiration

In the absence of oxygen the ETC cannot function (remember that **oxygen, O_2,** is the final electron acceptor). Hence, under anaerobic conditions cells go through a process called **FERMENTATION**

Fermentation takes place under ***anaerobic conditions*** (no oxygen present). There are two types of fermentation, alcoholic fermentation and lactic acid fermentation.

Alcoholic Fermentation: occurs in yeasts, fungi and some bacteria.

Pyruvate (C_3) $\rightarrow$ Acetaldehyde (C_2) + CO_2

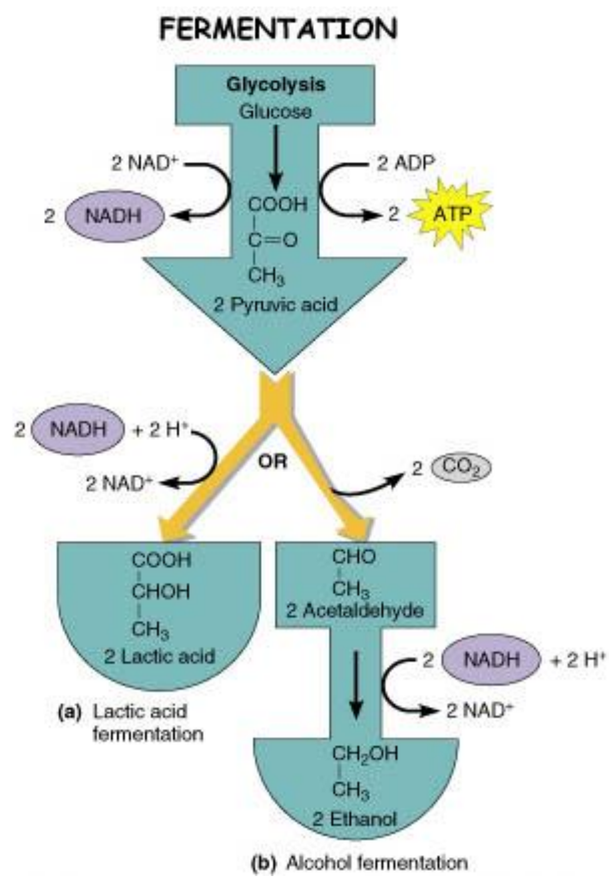
Acetaldehyde (C_2) + NADH $\rightarrow$ 2 Ethanol (C_2) + NAD^+

Lactic Acid Fermentation: occurs in some bacteria and oxygen deprived human muscle cells where lactate is produced as a waste product. Muscle cramps are caused by increased acidity caused by the lactate build up.

NADH + Pyruvate (C_3) $\rightarrow$ Lactic Acid (C_3) + NAD^+

Anaerobic Respiration

1. Glycolysis occurs, and pyruvate is produced. If pyruvate were to enter the Krebs cycle it would produce the H-carriers **NADH** and **$FADH_2$**, CO_2 and some ATP
2. The problem occurs in the ETC, because under anaerobic conditions there is no **oxygen** to be the final electron acceptor.
3. The ETC carrier proteins become saturated with electrons which prevent NADH from unloading the 2 electrons it carries—hence, **NAD^+** cannot be regenerated and NADH levels **increase**, while NAD^+ levels **decrease**.
4. The primary goal of fermentation is to regenerate **NAD^+** since it is required for Glycolysis to function. Fermentation does not generate any ATP: **Only 2 ATP per glucose are produced by *glycolysis*. Fermentation serves the sole purpose of regenerating NAD^+ to keep glycolysis functioning.**



(a) Lactic acid fermentation
(b) Alcohol fermentation

Cellular Respiration Self-Check Questions

Source: Animations of Glycolysis, Krebs Cycle and Electron Transport:
http://www.sumanasinc.com/webcontent/animations/content/cellularrespiration.html

1. **Where in the cell does glycolysis take place?**
   - ○ in the intermembrane space of the mitochondrion
   - ○ in the mitochondrial matrix
   - ○ in the cell membrane
   - ○ in the cytoplasm

2. **What is an outcome of glycolysis?**
   - ○ the breakdown of a pyruvate molecule into two smaller glucose molecules
   - ○ the breakdown of a glucose molecule into two smaller pyruvate molecules
   - ○ the breakdown of NADH into NAD^+ and high energy electrons
   - ○ the breakdown of glucose into molecules of carbon dioxide

3. **What is the difference between NAD^+ and NADH?**
   - ○ NAD^+ has lost a proton and has a positive charge.
   - ○ NADH has gained electrons and a proton.
   - ○ NAD^+ has gained a proton and has a positive charge.
   - ○ NADH has lost electrons but gained a proton.

4. **What is the function of NADH?**
   - ○ to provide energy for glycolysis
   - ○ to carry electrons from a glucose molecule to ATP
   - ○ to carry electrons from a glucose molecule to the electron transport chain
   - ○ to provide energy for the breakdown of a glucose molecule

5. **Why does the Krebs cycle only operate in the presence of oxygen?**
   - ○ Because oxygen must combine with carbon to form carbon dioxide
   - ○ Because oxygen allows the electron transport chain to receive electrons from NADH and $FADH_2$, recycling NAD^+ and FAD back to the Krebs cycle
   - ○ Because oxygen accepts the ATP from glycolysis so that it can be recycled
   - ◉ Because oxygen is added in the form of water to the Krebs cycle

6. **What would occur if NAD^+ were not regenerated for the Krebs cycle?**
   - ○ The further breakdown of pyruvate in the Krebs cycle would stop because there would be no place for the high energy electrons to go
   - ○ The pyruvate would be recycled back to glycolysis to form glucose again
   - ○ Oxygen would accept the high energy electrons and form water
   - ○ The cycle would continue until the NAD^+ was again available

7. **What is the function of the electrons carried to the chain by NADH and $FADH_2$?**
   - ○ to capture the energy from protons being pumped across the membrane
   - ○ to release the energy stored in ATP molecules from glycolysis and the Krebs cycle
   - ○ to provide the energy that pumps protons across the inner membrane of a mitochondrion
   - ○ to cycle back to the Krebs cycle to make more NAD^+ and FAD

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10. **What happens to the electron transport chain if oxygen is lacking?**
    - ○ More NADH would be formed.
    - ○ The electrons would be recycled back to NAD^+.
    - ○ The protons would be released as hydrogen gas.
    - ○ The proton gradient would disappear.

11. **What is the primary function of the electron transport chain?**

- ○ to create carbon dioxide and water
- ◉ to use available oxygen
- ○ to harvest the remaining energy available in a glucose molecule

12. **What is the overall purpose of cellular respiration?**

- ○ to breakdown glucose
- ○ to capture energy contained in the bonds of glucose in molecules of ATP
- ○ to make water and carbon dioxide
- ○ to convert the higher energy electrons into lower energy electrons to make ATP

13. **Where was the energy in the original glucose molecule?**

- ○ stored in the protons of a glucose molecule
- ○ stored in the oxygen atoms of a glucose molecule
- ○ stored in the bonds between the atoms of a glucose molecule
- ○ stored in the carbon atoms of a glucose molecule