How Cells Release Stored Energy

Course: BIO 101: Introduction to Biology

Chapter: 7

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What is Cellular Respiration?

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- The process in which organisms take molecules broken down from food and release the chemical energy stored in the chemical bonds of those molecules
- **Cellular respiration** is the process through which cells convert sugars into energy
- To create ATP and other forms of energy to power cellular reactions, cells require fuel and an electron acceptor which drives the chemical process of turning energy into a usable form

ATP – Adenosine Triphosphate

- **ATP** is considered by biologists to be the energy currency of life. It is the high-energy molecule that stores the energy we need to do just about everything we do
- The energy that is released from chemical bonds during cellular respiration is stored in molecules of ATP
- ATP is the energy currency of all biochemical processes

What types of organisms undergo cellular respiration?

- While only autotrophs perform photosynthesis

Heterotrophs

AND

Autotrophs

Undergo cellular respiration

What types of molecules are broken down?

Any food (organic) molecule, or nutrient, including carbohydrates, fats/lipids and proteins can be processed and broken down as a source of energy to produce ATP

What will the ATP be used for?

- ATP will release energy for cellular metabolic processes
- Examples:

  1) Active transport of molecules across the cell membrane

  2) Protein synthesis

  3) Muscle contractions

Cellular Respiration Simple Equation

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Cellular Respiration

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_20 + 6CO_2 + \textbf{energy}$$

(glucose + oxygen → water + carbon dioxide + energy)

vs

Photosynthesis

$$6\ H_2O + 6\ CO_2 \xrightarrow{\text{Light Energy}} C_6H_{12}O_6 + 6\ O_2$$

(water + carbon dioxide ----ENERGY---> glucose + oxygen)

Cellular Respiration and Photosynthesis

- Notice that the cellular respiration equation is the breakdown of those molecules made through photosynthesis and that it also uses the waste products of photosynthesis
- Notice that photosynthesis uses those products made by cellular respiration
- This is representative of a cycle

The Cellular Respiration Equation

AEROBIC CELLULAR RESPIRATION

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

Glucose	Oxygen		Carbon Dioxide	Water	Energy

Biochemical Pathway

- Cellular Respiration is a biochemical pathway just like photosynthesis in which each step (chemical reaction) of the process is dependent on the products of the previous step
- The cellular respiration equation represents many steps that have taken place

Cellular Respiration (Cont.)

- Overall, cellular respiration is a process that is **aerobic**
- Aerobic means that it requires the presence of oxygen
- Some steps within the process of cellular respiration do not require the presence of oxygen and are therefore **anaerobic**

Main Types of Energy-Releasing Pathways

Anaerobic pathways

- Evolved first
- Don't require **oxygen**
- Start with glycolysis in cytoplasm
- Completed in **cytoplasm**

Aerobic pathways

- Evolved later
- Require **oxygen**
- Start with glycolysis in cytoplasm
- Completed in **mitochondria**

Main Pathways Start with Glycolysis

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- Glycolysis occurs in cytoplasm
- Reactions are catalyzed by enzymes

Glucose $\longrightarrow$ **2 Pyruvate**

-C-C-C-C-C-C- -C-C-C- -C-C-C-

(six carbons) (three carbons)

Where does cellular respiration occur?

- Cellular respiration takes place in the <u>mitochondria</u> of the eukaryotic cell
- Recall that the mitochondria is considered to be the "powerhouse" of the cell because it produces the majority of a cell's ATP

Parts of the Mitochondria

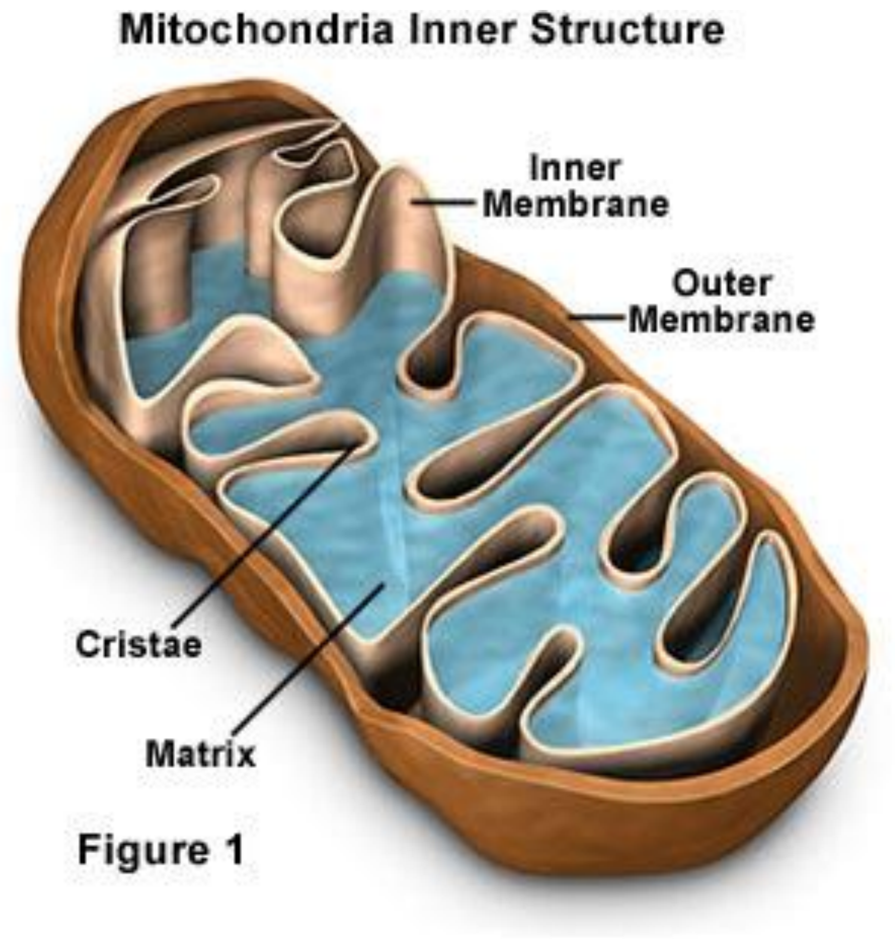


Figure 1

- Many similarities exist between the chloroplast and the mitochondria
- Mitochondria have a double membrane
- Mitochondria have their own DNA and only come from preexisting mitochondria

Parts of the Mitochondria

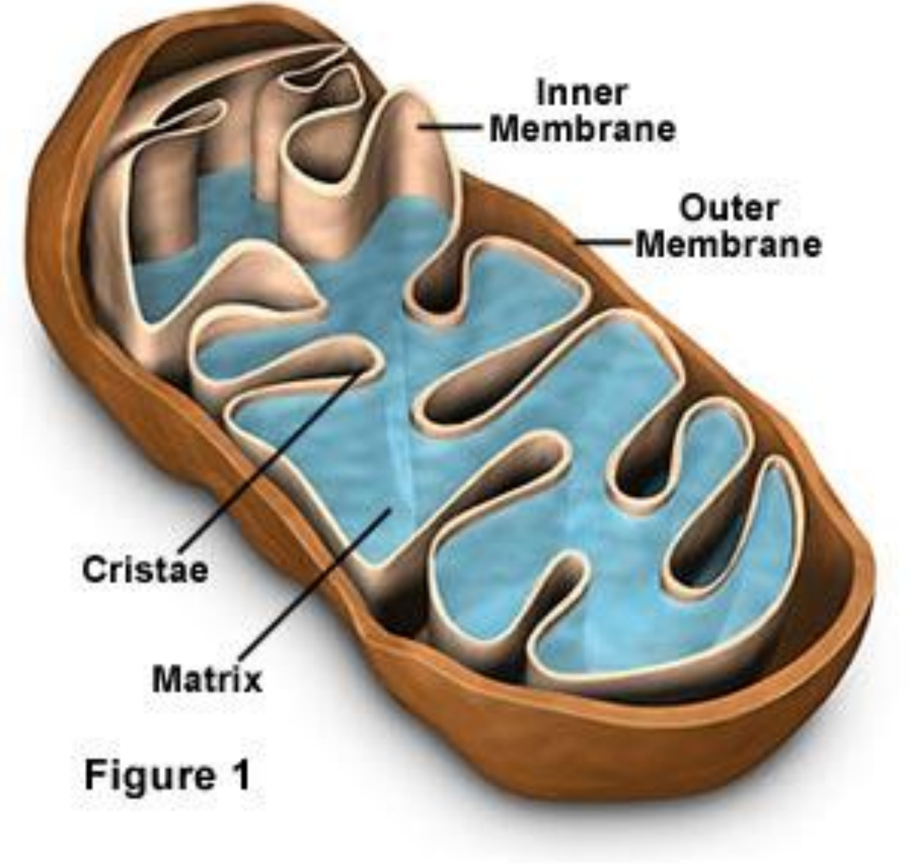


Figure 1

- Mitochondria have a smooth outer membrane
- Mitochondria have a folded inner-membrane called the cristae. A folded inner membrane allows more surface area for chemical reactions to occur
- Mitochondria have a center called the matrix

Glucose

For the sake of simplicity (as it is in photosynthesis), glucose is used as the example for cellular respiration. Remember that many different types of organic molecules are broken down through cellular respiration

Cellular Respiration

Cellular respiration breaks down into these major steps:

1. Glycolysis (anaerobic)

2. Krebs Cycle (aerobic)

3. Electron Transport Chain (aerobic)

Energy Carriers Found in Cellular Respiration

- **ATP**
- **NADH** (similar to NADPH in photosynthesis)
- **$FADH_2$**

Glycolysis

- Glycolysis is an anaerobic step in the cellular respiration pathway therefore it DOES NOT require oxygen
- Glycolysis takes place in the cytoplasm of the cell and is a series of reaction using enzymes
- Glycolysis is the break down of a molecule of glucose
- The products of glycolysis move to the mitochondria to make more ATP

What are the products of glycolysis?

- When a molecule of glucose is split, pyruvic acid, NADH and ATP are produced
- Glycolysis makes 4 molecules of ATP but it takes 2 molecules of ATP for the reaction to occur
- Therefore, Glycolysis yields a net of <u>2 ATP molecules</u>

What moves onto the next stage?

- Pyruvic acid is the main goal of glycolysis and these molecules will move on to the Krebs Cycle
- Pyruvic Acid $\longrightarrow$ Krebs Cycle
- NADH $\longrightarrow$ ETC
- ATP $\longrightarrow$ Usable Energy

What Happens After Glycolysis?

Glycolysis

If O_2 is not present

If O_2 is present

Fermentation

Anaerobic

Krebs Cycle

Aerobic Respiration

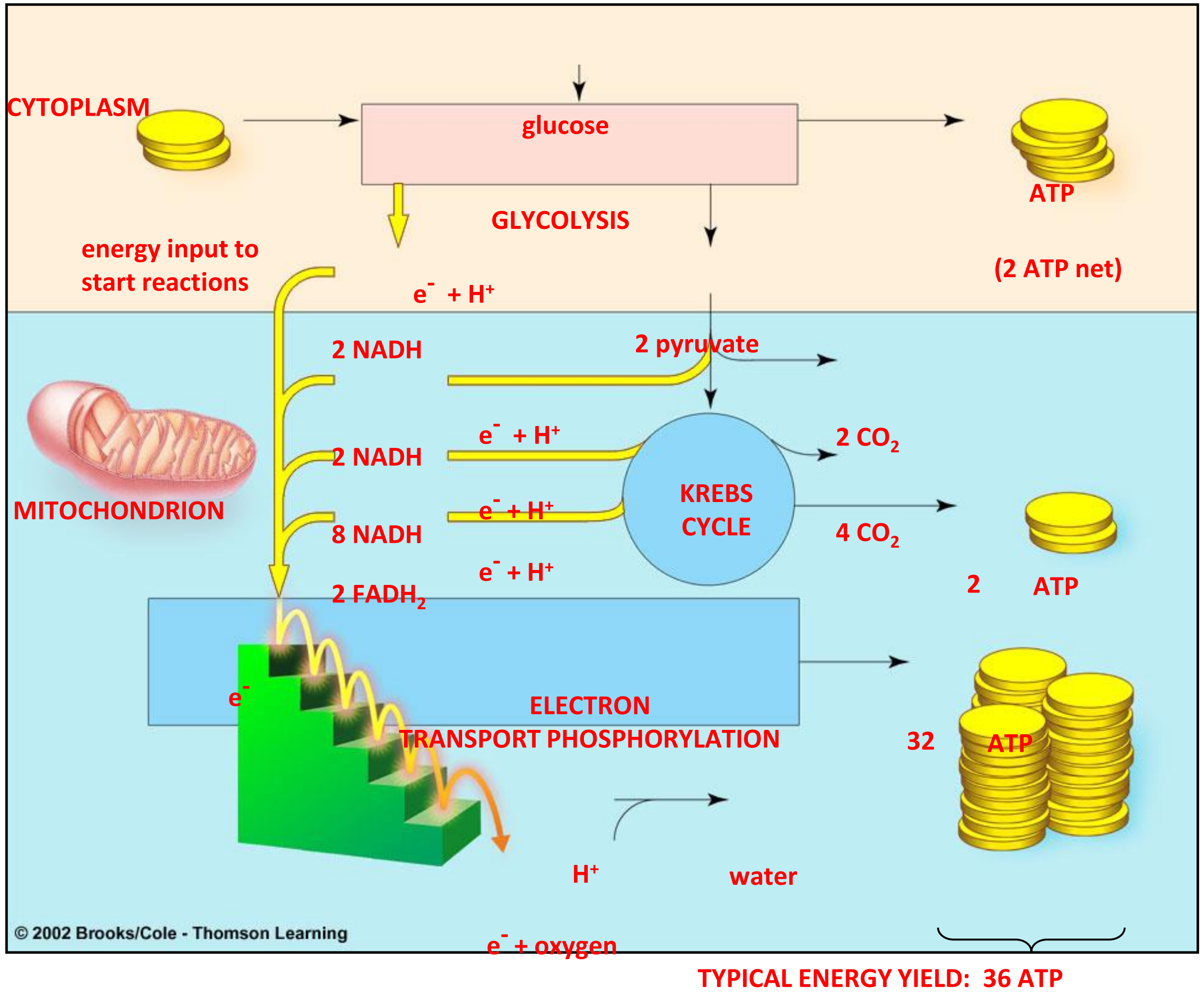
The Aerobic Pathway

Aerobic Respiration

Cellular Respiration

Four Steps:

1. Glycolysis
2. Pyruvate to Acetyl-CoA
3. The Krebs Cycle
4. ETC



Pre-Krebs Cycle (Acetyl-CoA)

- Before pyruvic acid enters the Krebs Cycle, it combines with an enzyme called Coenzyme A (CoA)
- This reaction produces a molecule of **Acetyl CoA**
- Acetyl CoA is a molecule produced by almost all nutrients (carbohydrate, protein, lipid metabolism) before entering the Krebs cycle

Pathway to the Krebs Cycle

Glycolysis

↓

Pyruvic Acid

↓

Acetyl CoA

↓

Krebs Cycle

The Krebs Cycle

- Named after Hans Krebs who won the Nobel Prize in 1953 for the pathway he discovered in cellular respiration

Hans Adolf Krebs (1900-1981)

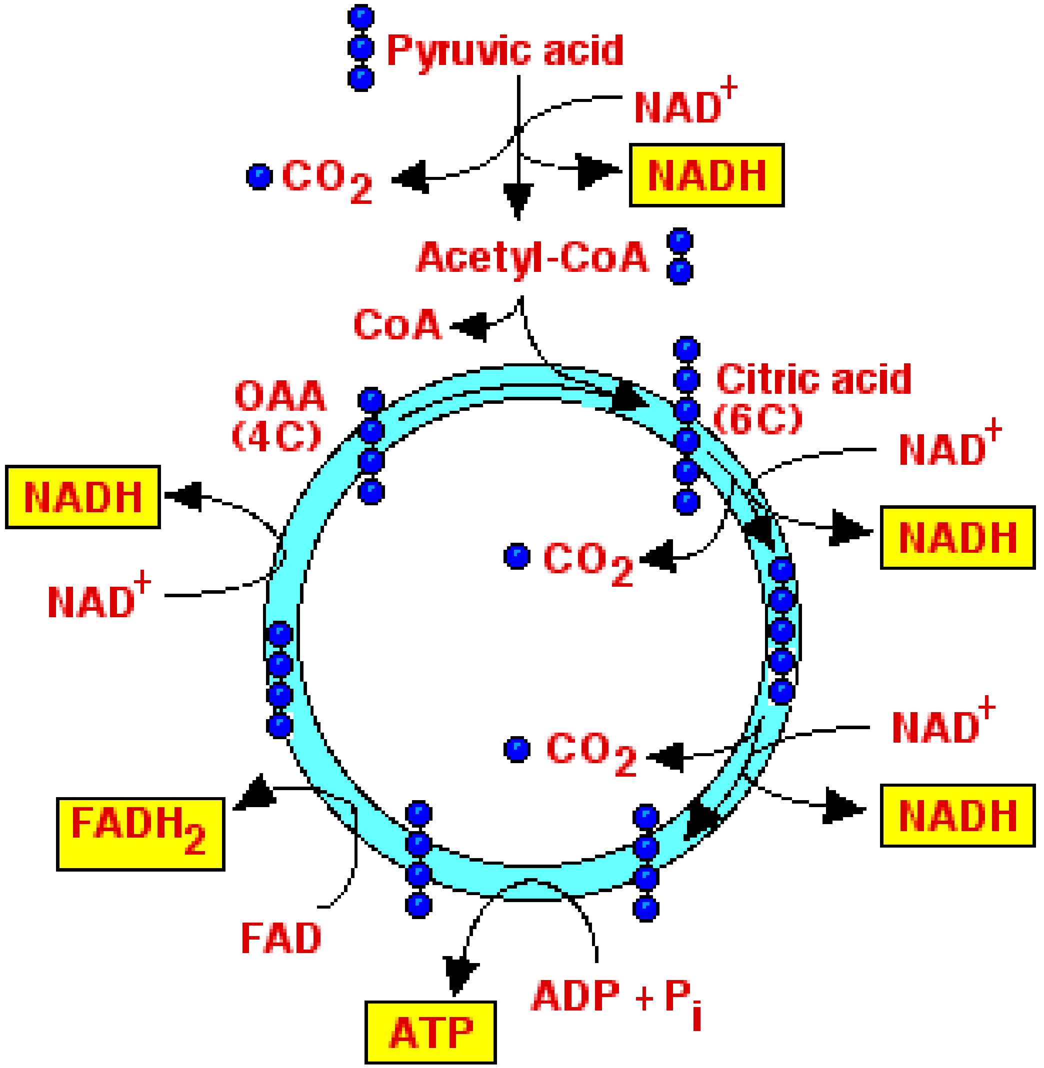
The Krebs Cycle

- Cyclical series of oxidation reactions that give off CO_2 and produce one ATP per cycle
- Requires Oxygen (aerobic)
- Turns twice per glucose molecule (produces 1 ATP per turn)
- Produces (2 X 1 ATP) = 2 ATP molecules
- Takes place in <u>matrix</u> of mitochondria

The Krebs Cycle

- Acetyl CoA (formed from Pyruvic Acid) combines with a four-carbon molecule to make a molecule of citric acid
- Citric acid is broken down in several steps providing the energy to make NADH, $FADH_2$, ATP

Krebs Cycle
(Citric Acid Cycle)



Krebs Cycle Reactant Summary

- Pyruvic Acid
- ADP
- NAD+
- FAD+

Krebs Cycle Product Summary

- 2 ATP → Usable energy
- NADH → Goes to ETC
- $FADH_2$ → Goes to ETC
- CO_2 → By product

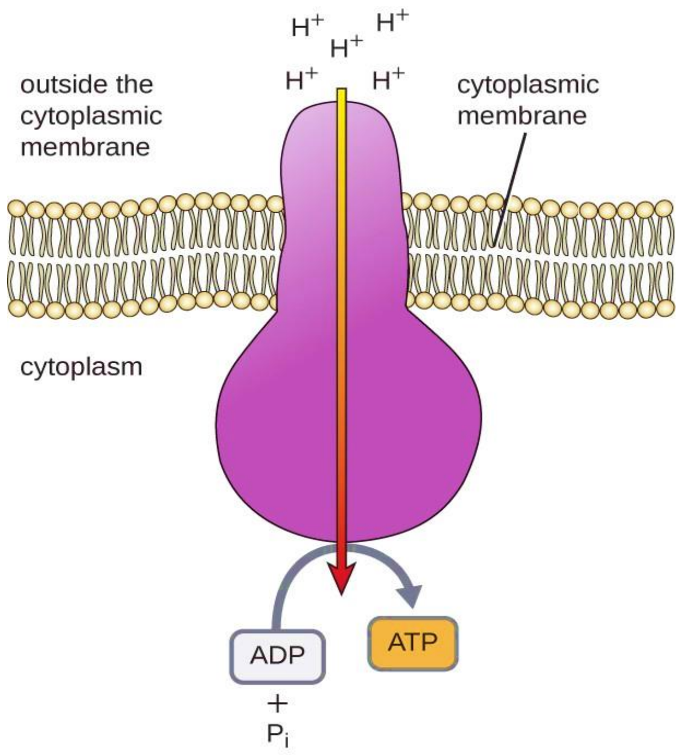
The Electron Transport Chain

- The ETC is a series of proteins located in the mitochondrial membrane
- It uses high energy electrons from the NADH and $FADH_2$ provided by the Krebs Cycle to move H+(protons) across the concentration gradient
- These protons pass back down the concentration gradient through ATP synthase to form ATP
- Very much like the ETC in the light reactions of photosynthesis

ETC

• Oxygen is used as the final electron acceptor at the end of the ETC

• Oxygen receives electrons and hydrogen ions (H+) and produces a molecule of water

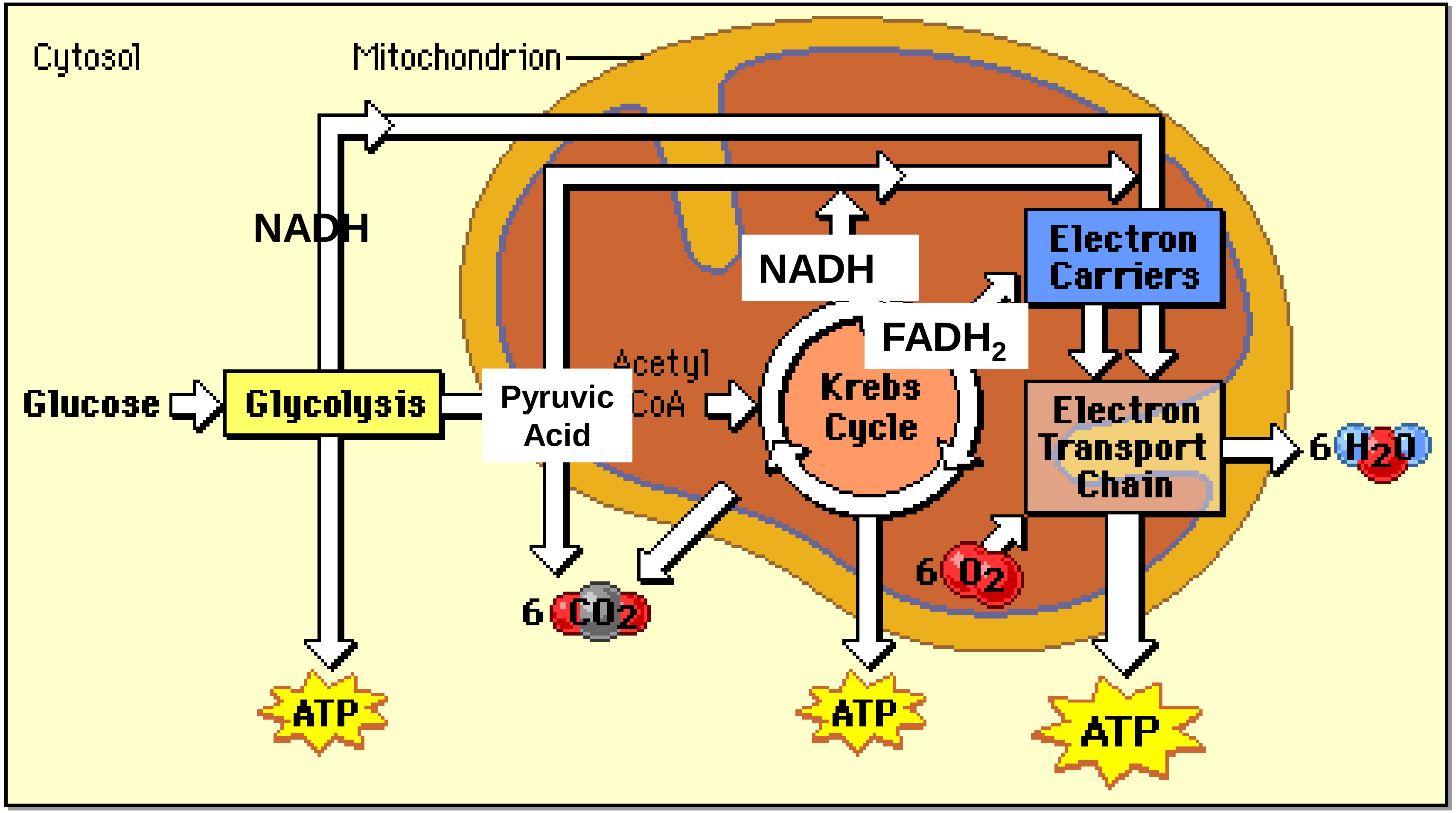


ATP synthase

ETC Product Summary

- 34 ATP $\longrightarrow$ Usable energy
- H_2O $\longrightarrow$ By product

Overview of Aerobic Respiration



Cellular Respiration ATP Tally

1. Glycolysis = 2 ATP
2. Krebs Cycle = 2 ATP
3. ETC = 32 to 34 ATP

Grand Total = 36 – 38 ATP

The Anaerobic Pathway

Evolution and Respiration

- It is thought that the most ancient type of respiration is anaerobic. Since there was little to no oxygen present when the first eukaryotic cells evolved through endosymbiosis, they could only undergo anaerobic respiration or something similar to fermentation
- This was not a problem, however, since those first cells were unicellular. Producing only 2 ATP at a time was enough to keep the single cell running

Evolution and Respiration (Cont.)

- As multicellular eukaryotic organisms began to appear on Earth, the larger and more complex organisms needed to produce more energy
- Through natural selection, organisms with more mitochondria that could undergo aerobic respiration survived and reproduced, passing on these favorable adaptations to their offspring
- The more ancient versions could no longer keep up with the demand for ATP in the more complex organism and went extinct

What happens to the products of Glycolysis when O_2 is not present?

Fermentation

- The processes that many organisms undergo when enough oxygen is NOT present
- The anaerobic processes are known as fermentation
- Most anaerobic processes start out the same way as aerobic respiration, but they stop partway through the pathway because the oxygen is not available for it to finish the aerobic respiration process, or they join with another molecule that is not oxygen as the final electron acceptor
- They use pyruvate as an electron acceptor

Fermentation (Cont.)

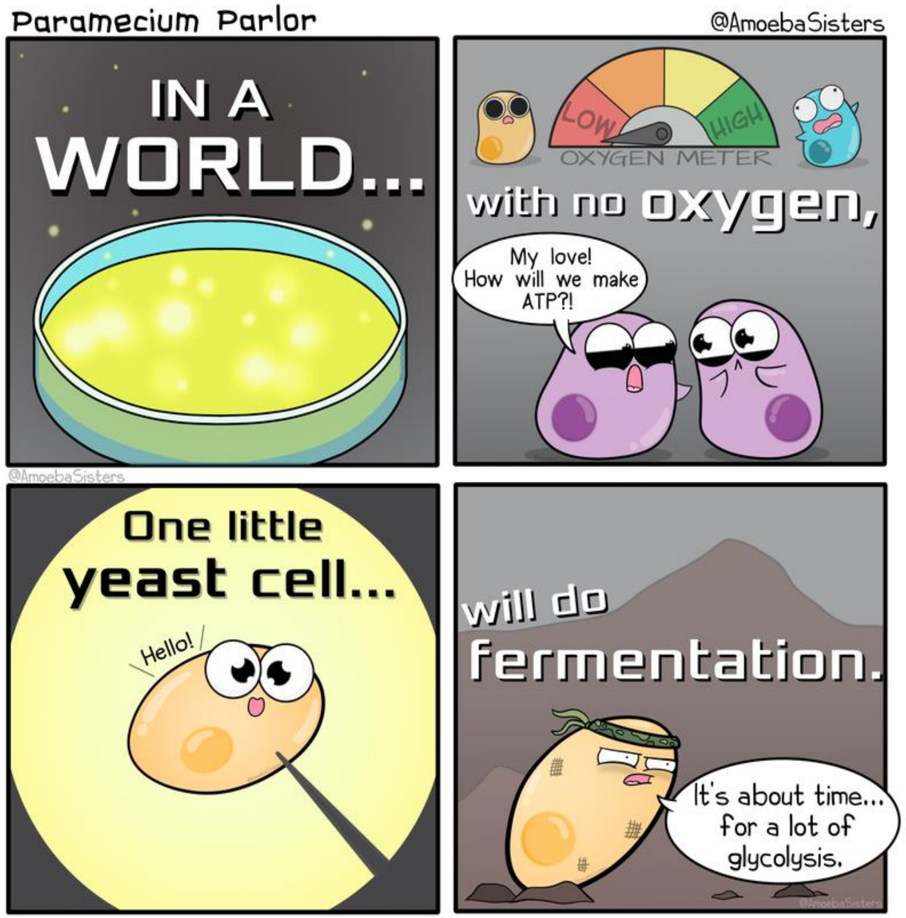
- If oxygen is not present, the products of glycolysis (pyruvic acid and NADH) will enter an alternative process called <u>**fermentation**</u>
- Fermentation provides enough ATP and recycles NADH into NAD+ so that glycolysis may continue until more oxygen becomes available
- Fermentation makes many fewer ATP and also releases byproducts either lactic acid or alcohol

Fermentation (Cont.)

- Breathing provides enough oxygen for your body to carry out normal activities
- When you are conducting a high level of activity, breathing doesn't supply enough air for your cell's activities
- Muscles produce lactic acid and The lactic acid can even cause cramping and soreness in the muscles

Where does fermentation occur?

- Cytoplasm of the cell



<u>Two types of fermentation:</u>

- Lactic Acid = Humans (muscle cells)
- Alcoholic = Yeasts (bread making)

Comparison b/w aerobic respiration & photosynthesis

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Aerobic Respiration

- **Reactants**
  - Sugar
  - Oxygen
- **Products**
  - Carbon dioxide
  - Water

Photosynthesis

- **Reactants**
  - Carbon dioxide
  - Water
- **Products**
  - Sugar
  - Oxygen

Comparison b/w aerobic respiration & photosynthesis (Cont.)

AEROBIC CELLULAR RESPIRATION

$$C_6H_{12}O + 6O_2 \longrightarrow 6CO_2 + 6H_2O + ATP$$

Glucose, Oxygen → Carbon Dioxide, Water, Energy

$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Carbon dioxide + Water → Sugar + Oxygen

Overall reaction of photosynthesis

Advantages of Anaerobic Respiration

1. One advantage of anaerobic respiration is: it lets organisms live in places where there is little or no oxygen. Such places include deep water, soil, and the digestive tracts of animals such as humans, some bacteria live in the human digestive tract

2. Another advantage of anaerobic respiration is its **speed**. It produces ATP very quickly. For example, it lets your muscles get the energy they need for short bursts of intense activity. Aerobic respiration, on the other hand, produces ATP more slowly

Aerobic Respiration vs Anaerobic Respiration

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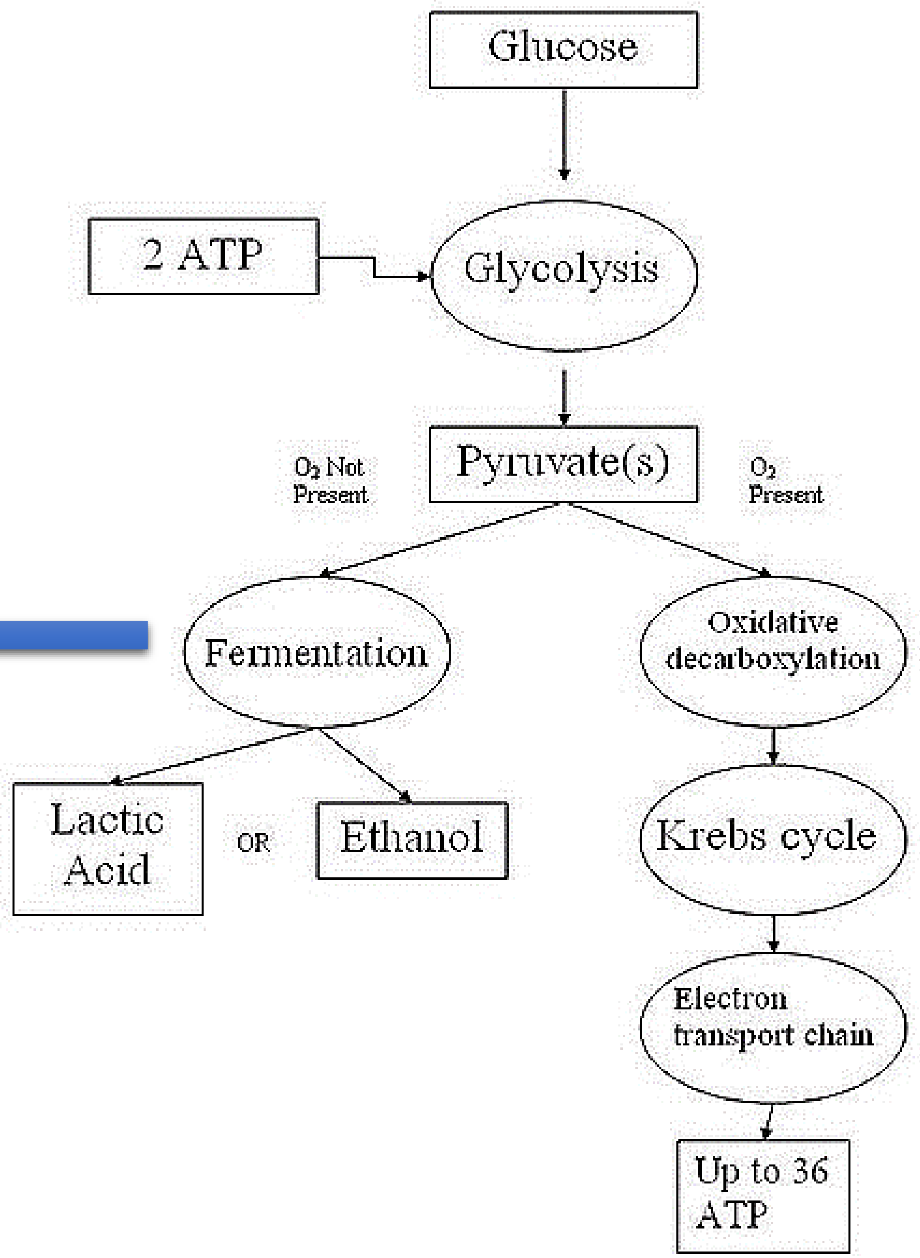
- Aerobic respiration produces much more ATP than anaerobic respiration
- Anaerobic respiration occurs more quickly than aerobic respiration

Which is better?

- Aerobic respiration is much more efficient at making ATP than anaerobic processes like fermentation. Without oxygen, the Krebs Cycle and the Electron Transport Chain in cellular respiration will not work any longer
- This forces the cell to undergo the much less efficient fermentation. While aerobic respiration can produce up to 38 ATP, the different types of fermentation can only have a net gain of 2 ATP

Overview of Cellular Respiration

- **2 ATP** produced in Glycolysis
- **CO2** is released
- NADH lose H+ to become **NAD+**
- **Ethanol/ lactic acid** is produced
- **No ATP** is made in alcoholic or lactic acid fermentation
- The purpose of fermentation is to make **NAD+** → helps restart **Glycolysis**
- **Net gain of 2 ATP**



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