5.9: Cellular Respiration

Bring on the S’mores!

This inviting campfire can be used for both heat and light. Heat and light are two forms of energy that are released when a fuel like wood is burned. The cells of living things also get energy by "burning." They “burn” glucose in the process called cellular respiration.

Figure \(\PageIndex{1}\): Burning logs that convert carbon in wood into carbon dioxide and a significant amount of thermal energy (Public domain; Jon Sullivan via Wikipedia)

Inside every cell of all living things, energy is needed to carry out life processes. Energy is required to break down and build up molecules and to transport many molecules across plasma membranes. All of life’s work needs energy. A lot of
energy is also simply lost to the environment as heat. The story of life is a story of energy flow — its capture, its change of form, its use for work, and its loss as heat. Energy, unlike matter, cannot be recycled, so organisms require a constant input of energy. Life runs on chemical energy. Where do living organisms get this chemical energy?

Where do organisms get energy from?

The chemical energy that organisms need comes from food. Food consists of organic molecules that store energy in their chemical bonds. Glucose is a simple carbohydrate with the chemical formula \(\text{C}_6\text{H}_{12}\text{O}_6\). It stores chemical energy in a concentrated, stable form. In your body, glucose is the form of energy that is carried in your blood and taken up by each of your trillions of cells. Cells do cellular respiration to extract energy from the bonds of glucose and other food molecules. Cells can store the extracted energy in the form of ATP (adenosine triphosphate).

What is ATP?

Let’s take a closer look at a molecule of ATP. Although it carries less energy than glucose, its structure is more complex. “A” in ATP refers to the majority of the molecule – adenosine – a combination of a nitrogenous base and a five-carbon sugar. “T” and “P” indicate the three phosphates, linked by bonds which hold the energy actually used by cells. Usually, only the outermost bond breaks to release or spend energy for cellular work.

An ATP molecule, shown in the figure below, is like a rechargeable battery: its energy can be used by the cell when it breaks apart into ADP (adenosine diphosphate) and phosphate, and then the “worn-out battery” ADP can be recharged using new energy to attach a new phosphate and rebuild ATP. The materials are recyclable, but recall that energy is not! ADP can be further reduced to AMP (adenosine monophosphate and phosphate, releasing additional energy. As with ADT “recharged” to ATP, AMP can be recharged to ADP.

How much energy does it cost to do your body’s work? A single cell uses about 10 million ATP molecules per second and recycles all of its ATP molecules about every 20-30 seconds.

![Chemical structure of ATP](https://bio.libretexts.org/Bookshelves/Human_Biology/Book%3A_Human_Biology_(Wakim_and_Grewal)/05%3A_Cells/5.09%…)
What Is Cellular Respiration?

Cellular respiration is the process by which living cells break down glucose molecules and release energy. The process is similar to burning, although it doesn’t produce light or intense heat as a campfire does. This is because cellular respiration releases the energy in glucose slowly, in many small steps. It uses the energy that is released to form molecules of ATP, the energy-carrying molecules that cells use to power biochemical processes. Cellular respiration involves many chemical reactions, but they can all be summed up with this chemical equation:

\[
\ce{C6H12O6 + 6O2 -> 6CO2 + 6H2O + Energy}\]

where the energy that is released is in chemical energy in ATP (vs. thermal energy as heat). The equation above shows that glucose (\(\ce{C6H12O6}\)) and oxygen (\(\ce{O_2}\)) react to form carbon dioxide (\(\ce{CO_2}\)) and water (\(\ce{H_2O}\)), releasing energy in the process. Because oxygen is required for cellular respiration, it is an aerobic process.

Cellular respiration occurs in the cells of all living things, both autotrophs and heterotrophs. All of them burn glucose to form ATP. The reactions of cellular respiration can be grouped into three stages: glycolysis, the Krebs cycle (also called the citric acid cycle), and electron transport. Figure \(\PageIndex{3}\) gives an overview of these three stages, which are also described in detail below.

Figure \(\PageIndex{3}\): Cellular respiration takes place in the stages shown here. The process begins with a molecule of glucose, which has six carbon atoms. What happens to each of these atoms of carbon? (CC BY 3.0; OpenStax College via Wikimedia.org)
Glycolysis

The first stage of cellular respiration is **glycolysis**. It takes place in the cytosol of the cytoplasm.

![Glycolysis Diagram](https://bio.libretexts.org/Bookshelves/Human_Biology/Book%3A_Human_Biology_(Wakim_and_Grewal)/05%3A_Cells/5.09%…)

**Figure \( \PageIndex{4} \):** In glycolysis, a glucose molecule is converted into two pyruvate molecules. (CC BY 3.0 via lumenlearning)

### Splitting Glucose

The word *glycolysis* means “glucose splitting,” which is exactly what happens in this stage. Enzymes split a molecule of glucose into two molecules of pyruvate (also known as pyruvic acid). This occurs in several steps, as shown in the following diagram.

### Results of Glycolysis

Energy is needed at the start of glycolysis to split the glucose molecule into two pyruvate molecules. These two molecules go on to stage II of cellular respiration. The energy to split glucose is provided by two molecules of ATP. As glycolysis proceeds, energy is released, and the energy is used to make four molecules of ATP. As a result, there is a net gain of two ATP molecules during glycolysis. During this stage, high-energy electrons are also transferred to molecules of NAD$^+$ to produce two molecules of NADH, another energy-carrying molecule. NADH is used in stage III of cellular respiration to make more ATP.
Citric Acid Cycle

In eukaryotic cells, the pyruvate molecules produced at the end of glycolysis are transported into mitochondria, which are sites of cellular respiration. If oxygen is available, aerobic respiration will go forward. In mitochondria, pyruvate will be transformed into a two-carbon acetyl group (by removing a molecule of carbon dioxide) that will be picked up by a carrier compound called coenzyme A (CoA), which is made from vitamin B₅. The resulting compound is called acetyl CoA. Acetyl CoA can be used in a variety of ways by the cell, but its major function is to deliver the acetyl group derived from pyruvate to the next pathway in glucose catabolism.

![Citric acid cycle diagram](image)

Figure \(\PageIndex{5}\): Pyruvate is converted into acetyl-CoA before entering the citric acid cycle. (CC BY 3.0 via lumenlearning)

Structure of the Mitochondrion

Before you read about the last two stages of cellular respiration, you need to review the structure of the mitochondrion, where these two stages take place. As you can see from Figure \(\PageIndex{6}\), a mitochondrion has an inner and outer membrane. The space between the inner and outer membrane is called the intermembrane space. The space enclosed by the inner membrane is called the matrix. The second stage of cellular respiration, the Krebs cycle, takes place in the matrix. The third stage, electron transport, takes place on the inner membrane.

![Mitochondrion structure diagram](image)

Figure \(\PageIndex{6}\): The structure of a mitochondrion is defined by an inner and outer membrane. (Public Domain; Mariana Ruiz Villarreal via Wikipedia)
The Krebs Cycle

Recall that glycolysis produces two molecules of pyruvate (pyruvic acid). These molecules enter the matrix of a mitochondrion, where they start the **Krebs cycle**. The reactions that occur next are shown in the following figure.

![Transformation of pyruvate into acetyl CoA](https://bio.libretexts.org/Bookshelves/Human_Biology/Book%3A_Human_Biology_(Wakim_and_Grewal)/05%3A_Cells/5.09%3A_Citric_Acid_Cycle/transform.png)

**The Krebs/citric acid cycle**

Before the Krebs cycle begins, pyruvic acid, which has three carbon atoms, is split apart and combined with an enzyme known as CoA, which stands for coenzyme A. The product of this reaction is a two-carbon molecule called acetyl-CoA. The third carbon from pyruvic acid combines with oxygen to form carbon dioxide, which is released as a waste product. High-energy electrons are also released and captured in NADH.

**Steps of the Krebs Cycle**

The Krebs cycle itself actually begins when acetyl-CoA combines with a four-carbon molecule called OAA (oxaloacetate). This produces citric acid, which has six carbon atoms. This is why the Krebs cycle is also called the citric
acid cycle. After citric acid forms, it goes through a series of reactions that release energy. The energy is captured in molecules of NADH, ATP, and FADH\(_2\) (another energy-carrying compound.) Carbon dioxide is also released as a waste product of these reactions. The final step of the Krebs cycle regenerates OAA, the molecule that began the Krebs cycle. This molecule is needed for the next turn through the cycle. Two turns are needed because glycolysis produces two pyruvic acid molecules when it splits glucose.

### Results of the Krebs Cycle

After the second turn through the Krebs cycle, the original glucose molecule has been broken down completely. All six of its carbon atoms have combined with oxygen to form carbon dioxide. The energy from its chemical bonds has been stored in a total of 16 energy-carrier molecules. These molecules are:

- 4 ATP (including 2 from glycolysis)
- 10 NADH (including 2 from glycolysis)
- 2 FADH\(_2\)

### Oxidative phosphorylation

Oxidative phosphorylation is the final stage of aerobic cellular respiration. There are two substages of oxidative phosphorylation, Electron transport chain and Chemiosmosis. In these stages, energy from NADH and FADH\(_2\), which result from the previous stages of cellular respiration, is transferred to ATP.

![Oxidative Phosphorylation: Electron Transport chain and Chemiosmosis](https://bio.libretexts.org/Bookshelves/Human_Biology/Book%3A_Human_Biology_(Wakim_and_Grewal)/05%3A_Cells/5.09%3A_Cell_Respiration/OxPhos_Figure.png)

Electron Transport Chain

During this stage, high-energy electrons are released from NADH and FADH\(_2\), and they move along electron-transport...
chains on the inner membrane of the mitochondrion. An electron-transport chain is a series of molecules that transfer electrons from molecule to molecule by chemical reactions. Some of the energy from the electrons is used to pump hydrogen ions (H\(^+\)) across the inner membrane, from the matrix into the intermembrane space. This ion transfer creates an electrochemical gradient that drives the synthesis of ATP.

### Chemiosmosis

The pumping of hydrogen ions across the inner membrane creates a greater concentration of the ions in the intermembrane space than in the matrix. This gradient causes the ions to flow back across the membrane into the matrix, where their concentration is lower. The ATP synthase acts as a channel protein, helping the hydrogen ions across the membrane. It also acts as an enzyme, forming ATP from ADP and inorganic phosphate in a process called oxidative phosphorylation. The flow of hydrogen ions through ATP synthase gives energy for ATP synthesis. After passing through the electron-transport chain, the "spent" electrons combine with oxygen to form water.

### How Much ATP?

You have seen how the three stages of aerobic respiration use the energy in glucose to make ATP. How much ATP is produced in all three stages combined? Glycolysis produces 2 ATP molecules, and the Krebs cycle produces 2 more. Electron transport begins with several molecules of NADH and FADH\(_2\) from the Krebs cycle and transfers their energy into as many as 32 more ATP molecules. A total of up to 36 molecules of ATP from just one molecule of glucose in the process of cellular respiration.

### Summary

- Cellular respiration is the aerobic process by which living cells break down glucose molecules, release energy, and form molecules of ATP. Overall, this three-stage process involves glucose and oxygen reacting to form carbon dioxide and water.
- The first stage of cellular respiration, called glycolysis, takes place in the cytoplasm. In this step, enzymes split a molecule of glucose into two molecules of pyruvate, which releases energy that is transferred to ATP.
- The organelle called a mitochondrion is the site of the other two stages of cellular respiration. The mitochondrion has an inner and outer membrane separated by an intermembrane space, and the inner membrane encloses a space called the matrix.
- The second stage of cellular respiration, called the Krebs cycle, takes place in the matrix of a mitochondrion. During this stage, two turns through the cycle result in all of the carbon atoms from the two pyruvate molecules forming carbon dioxide and the energy from their chemical bonds being stored in a total of 16 energy-carrying molecules (including 4 from glycolysis).
- The third and final stage of cellular respiration, called oxidative phosphorylation, takes place on the inner membrane of the mitochondrion. Electrons are transported from molecule to molecule down an electron-transport chain. Some of the energy from the electrons is used to pump hydrogen ions across the membrane, creating an electrochemical gradient that drives the synthesis of many more molecules of ATP.
- In all three stages of cellular respiration combined, as many as 36 molecules of ATP are produced from just one molecule of glucose.
Review

1. What is the purpose of cellular respiration? Provide a concise summary of the process.
2. Draw and explain the structure of ATP (Adenosine Tri-Phosphate).
4. Describe the structure of a mitochondrion.
5. Outline the steps of the Krebs cycle.
6. What happens during the electron transport stage of cellular respiration?
7. How many molecules of ATP can be produced from one molecule of glucose during all three stages of cellular respiration combined?
8. Do plants undergo cellular respiration? Why or why not?
9. Explain why the process of cellular respiration described in this section is considered aerobic.
10. Name three energy-carrying molecules involved in cellular respiration.
11. Energy is stored within chemical _________ within a glucose molecule.
12. True or False. During cellular respiration, NADH and ATP are used to make glucose.
13. True or False. ATP synthase acts as both an enzyme and a channel protein.
14. True or False. The carbons from glucose end up in ATP molecules at the end of cellular respiration.
15. Which stage of aerobic cellular respiration produces the most ATP?

Explore More

https://bio.libretexts.org/link?17025#Explore_More

Although this animation has no words, it illustrates the processes which occur inside a mitochondrion, including the production of ATP.
Watch the video below for a detailed overview of cellular respiration.