

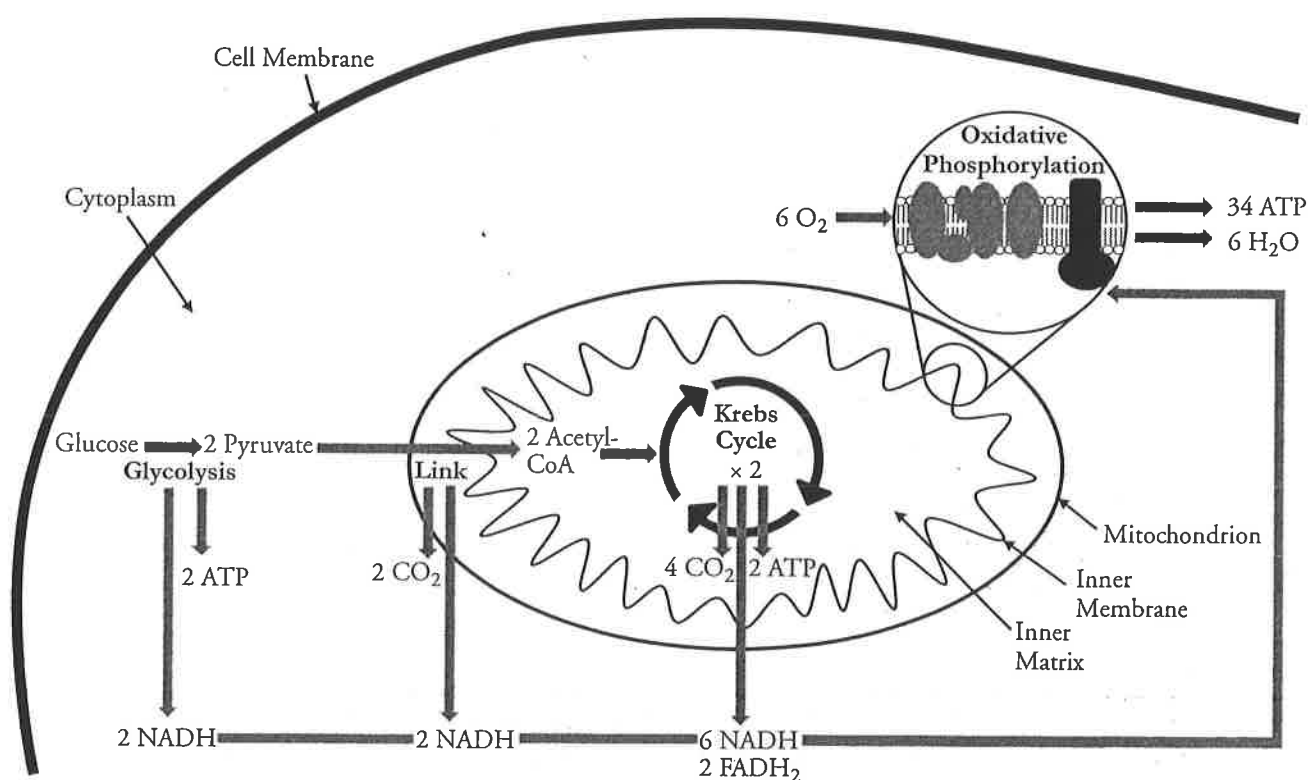
# Cellular Respiration—An Overview

What are the phases of cellular respiration?

## Why?

All cells need energy all the time, and their primary source of energy is ATP. The methods cells use to make ATP vary depending on the availability of oxygen and their biological make-up. In many cases the cells are in an oxygen-rich environment. For example, as you sit and read this sentence, you are breathing in oxygen, which is then carried throughout your body by red blood cells. But, some cells grow in environments without oxygen (yeast in wine-making or the bacteria that cause botulism in canned food), and occasionally animal cells must function without sufficient oxygen (as in running sprints). In this activity you will begin to look at the aerobic and anaerobic processes that are used by all organisms to produce ATP.

## Model 1 – Cellular Respiration



1. According to Model 1, what are the reactants of cellular respiration?  
*Glucose and oxygen.*
2. According to Model 1, what are the products of cellular respiration?  
*Carbon dioxide, water, and ATP (or energy).*

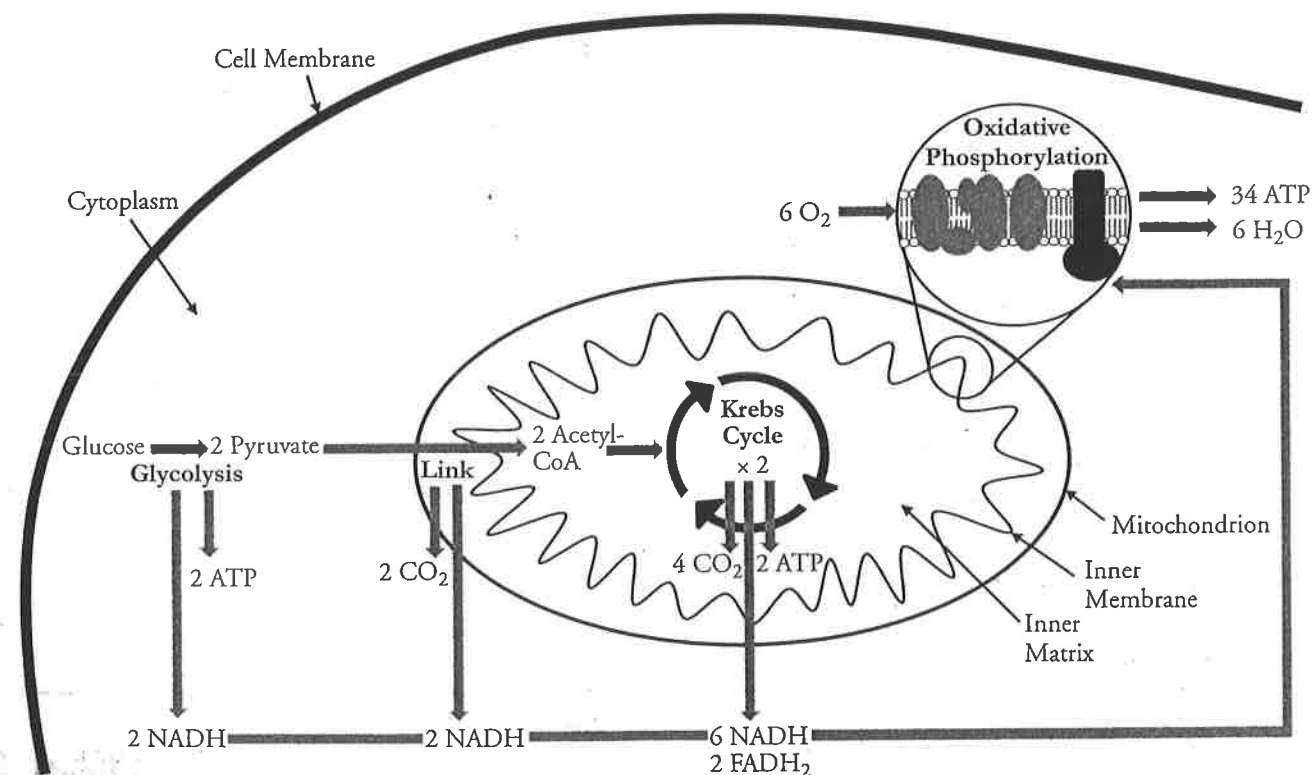
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3. Cellular respiration occurs in four phases: **glycolysis**, the **link reaction**, the **Krebs cycle**, and **oxidative phosphorylation**.
- Which phase of cellular respiration occurs in the cytoplasm of the cell?  
*Glycolysis.*
  - Which phases of cellular respiration occur in the mitochondria?  
*The link reaction, the Krebs cycle, and oxidative phosphorylation.*
  - Which of the four phases of cellular respiration require oxygen?  
*Oxidative phosphorylation.*
  - Which of the four phases of cellular respiration produce carbon dioxide?  
*The link reaction and the Krebs cycle.*
  - Which of the four phases of cellular respiration produce water?  
*Oxidative phosphorylation.*
4. The goal of cellular respiration is to provide the cell with energy in the form of ATP.
- Which of the four phases of cellular respiration result in the production of ATP?  
*Glycolysis, the Krebs cycle, and oxidative phosphorylation.*
  - How many ATPs (total) are produced for every glucose molecule that undergoes cellular respiration?  
*Each glucose molecule results in 38 ATPs being produced.*
  - What reactants of ATP must be available in the cell in order to produce ATP?  
*In order to make ATP, the cell must have ADP and  $P_i$  available.*
  - Brainstorm several cellular processes for which energy or ATP is necessary.  
*Answers will vary, but may include movement and muscle contraction, biochemical reactions, and growth and metabolism.*

## Read This!

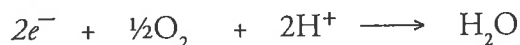
Glucose, or any carbon-based molecule, can be burned in oxygen (oxidized) to produce carbon dioxide and water. Combustion reactions release large amounts of energy. However, the energy release is uncontrolled. An organism would not be able to handle all that energy at once to do the work of the cell. Cellular respiration is essentially the same reaction as combustion, but the oxidation of glucose occurs in several controlled steps. The same amount of energy is ultimately released, but it is gradually released in small, controlled amounts. High potential energy molecules of ATP are produced while the carbon atoms are used to form various other molecules of lower potential energy. Each of these steps is catalyzed by an enzyme specific to that step. Model 1 illustrates the ideal circumstances for cellular respiration. In some situations, however, one glucose molecule may not result in 38 ATP molecules being produced.

5. Consider Model 1. Besides ATP, what other molecules appear to be high potential energy molecules (free energy carriers) during cellular respiration?

*NADH and  $FADH_2$ .*



## Model 2 – Electron Acceptor Molecules



6. Nicotinamide adenine dinucleotide ( $\text{NAD}^{+}$ ) and flavin adenine dinucleotide (FAD) are coenzymes used in cellular respiration to transport high potential energy electrons to the electron transport chain (a step in oxidative phosphorylation) in the mitochondria. At the conclusion of cellular respiration, oxygen is the final electron acceptor. The reactions in Model 2 show these electron acceptors in the process of picking up an electron.

- a. How many electrons are in a hydrogen ion ( $\text{H}^{+}$ )?

*Zero.*

- b. Is a hydrogen ion with its positive charge likely to be attracted to  $\text{NAD}^{+}$ , FAD or  $\text{O}_2$  without an input of free energy? Explain your reasoning.

*No, a positive hydrogen ion would only be attracted to a negatively charged particle.*

- c. Consider the charges in the first reaction in Model 2. Can two positive particles combine to form a neutral particle? Explain your reasoning.

*No, if two positive particles combine, the resulting particle would have a +2 charge.*



7. The reactions in Model 2 are missing very important particles—electrons.

- a. What is the charge on an electron?

*Electrons have a negative charge.*

- b. For each reaction in Model 2, predict the number of electrons that must be involved in the reaction to make the charges in the reaction balance.

*Two electrons are required to balance the +2 charge on the reactants side of the equation.*

- c. Add electrons to each reaction in Model 2 on either the reactant or product side of the equation to complete the reactions.

*See Model 2.*

## Read This!

Oxidation is a loss of electrons. Reduction is a gain of electrons. The two processes must go hand-in-hand. In other words, electrons cannot be added to something from thin air, they must have been taken off of something first.

8. Are the reactions in Model 2 oxidation or reduction reactions?

*Electrons are being gained, so the reactions are reduction.*

9. Which form of nicotinamide adenine dinucleotide is the “reduced” form,  $\text{NAD}^{+}$  or NADH? Explain your reasoning.

*NADH is the reduced form as it has the electrons that were gained in the process of reduction.*



10. According to Model 1, glucose undergoes the following changes during cellular respiration. In each step NADH or  $\text{FADH}_2$  is produced. Is glucose being oxidized or reduced during cellular respiration? Explain your reasoning.

Glucose  $\longrightarrow$  pyruvate  $\longrightarrow$  acetyl-CoA  $\longrightarrow$  carbon dioxide

*Glucose is oxidized during respiration because it gives its electrons to  $\text{NAD}^+$  or  $\text{FAD}$ .*

11. Historically, the term “oxidation” was derived from the combination of a substance with oxygen. Question 10 addressed which molecule is the “more oxidized form.” Validate your answer to Question 10 by comparing the ratio of carbon atoms to oxygen atoms in the chemical formulas of glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) versus carbon dioxide ( $\text{CO}_2$ ).

*Ratio in glucose  $\rightarrow$  1 carbon : 1 oxygen      Ratio in carbon dioxide  $\longrightarrow$  1 carbon : 2 oxygen*

*Carbon dioxide has more oxygen atoms per carbon, so it is the more oxidized form.*



12. Model 1 shows ten NADH molecules being produced during cellular respiration. What reactants must be available in the cell for these molecules to be produced?

*$\text{NAD}^+$  and  $\text{H}^+$  ions must be available to make NADH.*

13. The hydrogen ions and electrons that were carried by NADH and  $\text{FADH}_2$  are used in oxidative phosphorylation.

- a. What molecules are produced as the hydrogen ions and electrons are removed from NADH and  $\text{FADH}_2$ ?

*$\text{NAD}^+$  and  $\text{FAD}$  are produced.*

- b. Is the removal of hydrogen ions and electrons from NADH and  $\text{FADH}_2$  oxidation or reduction? Explain your reasoning.

*The loss of electrons is oxidation, so the conversion of NADH to  $\text{NAD}^+$  and  $\text{FADH}_2$  to  $\text{FAD}$  would be oxidation.*

- c. Predict what happens to those product molecules after they “drop off” their hydrogen ions and electrons.

*The  $\text{NAD}^+$  and  $\text{FAD}$  get reused in glycolysis, the link reaction, and the Krebs cycle.*

14. Cells can survive for short periods without oxygen. Only the glycolysis phase of cellular respiration occurs in those circumstances.

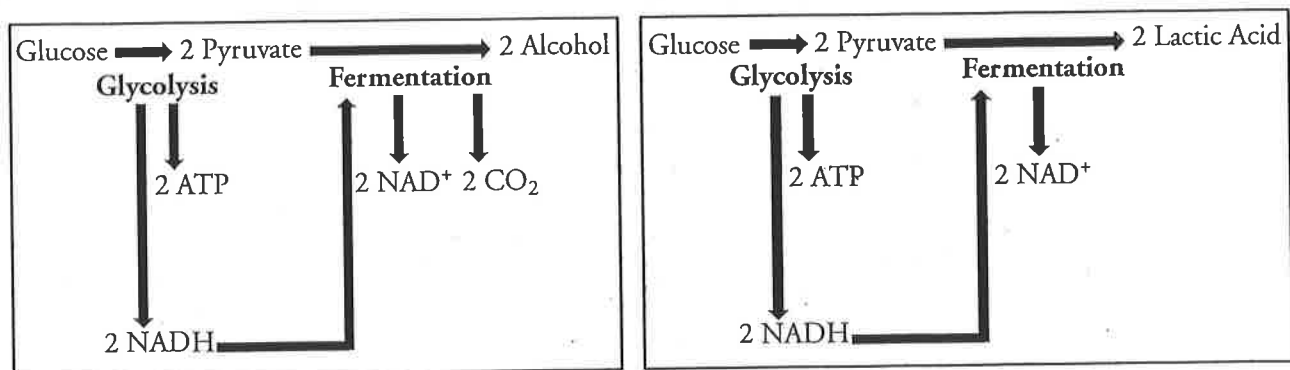
- a. Predict the number of ATP molecules that could be produced from one glucose molecule if oxygen were not available.

*Only 2 ATP molecules would be produced.*

- b. Since oxidative phosphorylation no longer occurs when oxygen is not available, predict what would eventually happen to the supply of  $\text{NAD}^+$  in the cell if only glycolysis were occurring?

*All of the  $\text{NAD}^+$  would be converted to NADH, which would not be recycled by oxidative phosphorylation, so eventually glycolysis would not be able to occur either.*

### Model 3 – Energy in Anaerobic Environments



15. Examine the two anaerobic processes in Model 3. Is oxygen used in either process?

*Oxygen is not used in either process.*

16. What is the definition of anaerobic?

*Without oxygen.*

17. Compare the energy output (in the form of ATP) for a single glucose molecule that undergoes glycolysis and fermentation to that of a glucose molecule undergoing cellular respiration.

*Glycolysis and fermentation make far fewer ATP from a glucose molecule. Glycolysis and fermentation make only 2 ATPs while full cellular respiration makes 38 ATPs.*

18. The efficiency of a cell is dependent on the cyclic nature of NAD<sup>+</sup> and NADH. Building NAD<sup>+</sup> molecules from raw materials each time one was needed would require a huge amount of free energy and resources. Even though the fermentation steps shown in Model 3 do not provide any ATP, they are critical to the energy production of the cell. Predict what would happen to the energy supply in a cell if fermentation did not happen under anaerobic conditions.

*If fermentation did not recycle the NADH in a cell, glycolysis would eventually cease because no NAD<sup>+</sup> would be available.*



## Extension Questions

19. The muscle “burn” that you feel when doing strenuous activity (sprints for example) is caused by a buildup of lactic acid in the muscle tissue of your body. Explain this phenomenon in the context of cellular respiration and fermentation.

*Under normal conditions, the muscle cells have adequate oxygen and cellular respiration occurs. Under strenuous conditions, not enough oxygen can get into the cell so the cell begins lactic acid fermentation instead.*

20. The evolution of photosynthesizing organisms on Earth and the development of an oxygen-rich environment led to a rapid diversification of life. Explain why there is an evolutionary advantage to an organism that requires oxygen to live compared to one that does not require oxygen.

*An organism that can metabolize glucose in an oxygen-rich environment can make far more ATPs per glucose molecule than an organism that uses anaerobic processes. This gives the organism requiring oxygen an advantage in survival.*

21. Under laboratory conditions muscle cells were broken up and separated into fractions of mitochondria and cytoplasm in an attempt to learn more about cellular respiration. Each fraction was incubated with glucose or pyruvate. Tests were carried out during incubation for the presence of either carbon dioxide or lactic acid. The results are shown below:

| Cell Fraction                        | CO <sub>2</sub> | Lactic Acid |
|--------------------------------------|-----------------|-------------|
| Mitochondria incubated with glucose  | Absent          | Absent      |
| Mitochondria incubated with pyruvate | Present         | Absent      |
| Cytoplasm incubated with glucose     | Absent          | Present     |
| Cytoplasm incubated with pyruvate    | Absent          | Present     |

- a. What does the presence of lactic acid in a sample indicate about what process is occurring in each cell fraction?

*Fermentation.*

- b. Explain why lactic acid was produced by the cytoplasm fraction incubated with glucose, but not the mitochondrial fraction.

*The cytoplasm is the site of glycolysis, which occurs in the presence of glucose. Once the pyruvate is formed in the cytoplasm from the breakdown of glucose, if there are no mitochondria to further process it through the link reaction and the Krebs cycle, then the pyruvate will be converted to lactic acid. The mitochondria cannot use glucose directly as they need pyruvate to enter Krebs, so no reaction would occur in the mitochondrial fraction.*

- c. Why was no carbon dioxide produced by either fraction incubated with glucose?

*The mitochondria cannot use glucose so there will be no reaction to produce CO<sub>2</sub>. In the cytoplasm fraction, the glucose was converted to pyruvate, but without mitochondria it cannot be converted to CO<sub>2</sub> (via the link reaction or the Krebs cycle) so no CO<sub>2</sub> is present.*

- d. Why did the cytoplasm fraction produce lactic acid in the presence of both glucose and pyruvate?

*Lactic acid is produced by fermentation, which begins with pyruvate. The pyruvic acid is produced by glycolysis in the cytoplasm, so either glucose or pyruvate would eventually produce lactic acid.*

- e. Why did the mitochondria produce carbon dioxide in the presence of pyruvate but not in the presence of glucose?

*When the mitochondria were incubated with pyruvate, the link reaction and the Krebs cycle took place and produced  $\text{CO}_2$  as a product. The mitochondria could not utilize the glucose as the starting material for the Krebs cycle, so no  $\text{CO}_2$  was produced.*