The big picture

? Guiding question(s)

- What are the roles of hydrogen and oxygen in the release of energy in cells?
- How is energy distributed and used inside cells?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

The game of football, or soccer, is loved the world over. The top players in the world are incredible athletes whose skill and hard work have allowed them to reach the highest levels of the sport. In a 90-minute football match, players might travel as far as 10 km or more plus compete for possession of the ball multiple times. The energy needed to do all of this is very high. Just where do top footballers get this energy? How are their bodies able to function at such a high level?

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Figure 1. Footballers need great coordination and lots of energy.

Credit: Lighthouse Films, Getty Images

Of course, we eat food and breathe in oxygen to gain energy and power our bodies, but just how do our bodies use that food and oxygen to make our muscles work and give energy to all of the other processes necessary to keep our bodies functioning? In this subtopic we will explore how the energy in our food is released within our cells for use by our bodies to do everything from contract our muscles to power our brains.

Prior learning

Before you study this subtopic make sure that you understand the following:

- Components of a nucleotide (see section A1.2.1—4 (/study/app/bio/sid-422-cid-755105/book/nucleic-acids-and-their-structure-id-43580/)).
- Eukaryote cell structure (see section A2.2.4—6 (/study/app/bio/sid-422-cid-755105/book/prokaryotic-and-eukaryotic-cells-id-43583/)).
- Adaptations of the mitochondrion (see section B2.2.4—6 (/study/app/bio/sid-422-cid-755105/book/structure-and-function-of-double-membranes-hl-id-44251/)).

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

ATP

Student view

C1.2.1: ATP as the molecule that distributes energy within cells C1.2.2: Life processes within cells that ATP supplies with energy

C1.2.3: Energy transfers during interconversions between ATP and ADP

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Learning outcomes

By the end of this section you should be able to:

- Explain what ATP is and how it functions as a cell's energy currency.
- Describe processes within cells that use ATP as an energy source.
- Describe the interconversions and energy changes between ATP and ADP.

Every living thing on Earth needs energy to carry out all the processes it needs to stay alive and function. From a tiny bacteria to a blue whale, all living things make use of the same molecule to provide energy for everything done within their cell(s). In this section we will learn more about this amazing molecule.

ATP distributes energy within cells

Adenosine triphosphate (ATP) is the molecule used in the cells of every living organism to transfer energy to where it is required. It is actually an RNA nucleotide made of three parts: the nitrogenous base adenine, the 5-carbon sugar ribose and a tail of three phosphate molecules (**Figure 1**).

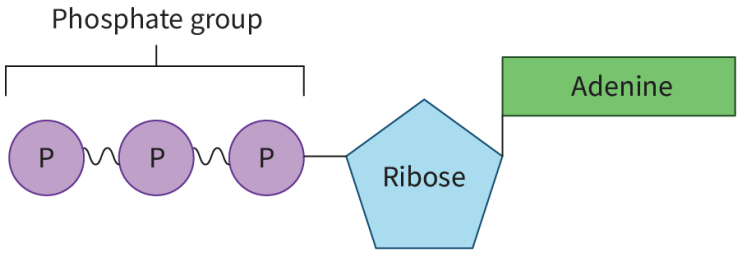

Figure 1. The structure of an ATP molecule.

More information for figure 1

The image is a diagram illustrating the structure of an ATP molecule. It consists of three main parts: a phosphate group, ribose, and adenine. The phosphate group contains three circles labeled 'P', each connected by a line, indicating the sequence of phosphate molecules. This group is noted as the 'Phosphate group' at the top. Next to the phosphate group is a pentagon labeled 'Ribose', representing the sugar component. The pentagon is colored blue. Finally, attached to the ribose is a green rectangle labeled 'Adenine', representing the nitrogenous base.

Student view
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Overview (/study/ap 422- cid- 755105/o

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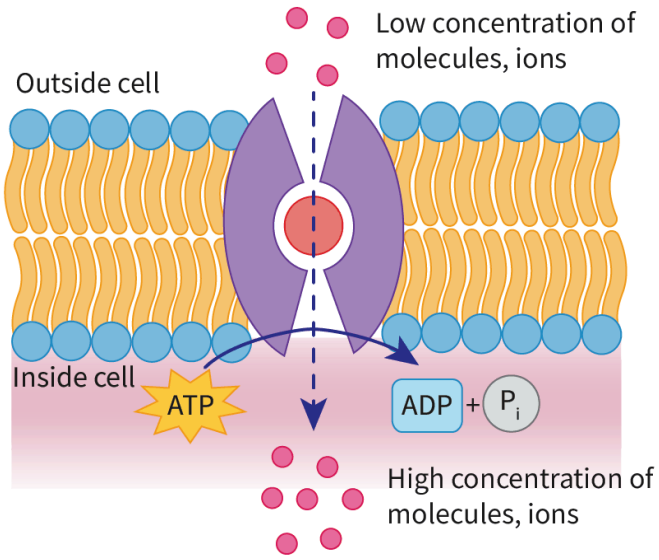
ATP is often referred to as the universal energy currency of cells as it is used very much like a currency, being exchanged for different biochemical processes such as the transport of substances, the contraction of muscles and the synthesis of large molecules.

Life processes within cells that ATP supplies with energy

ATP is used whenever a cellular process requires energy. The transport of molecules (see subtopic B2.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43205/)) across membranes can be a passive process, but when molecules need to be moved against their concentration gradient, active transport is required. For this process to occur transport proteins are needed and ATP is used. ATP binds to the transport protein, releasing the third phosphate, and energy is transferred to the transport protein allowing it to move the molecule across the membrane (**Figure 2**).

Making connections

Subtopic B2.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43205/) covers active transport. The transport proteins used in active transport use ATP to pump or carry substances across a membrane against its concentration gradient. Your understanding of membrane transport will aid in your understanding of many of the processes involved in cell respiration.



Student view

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Figure 2. Active transport of molecules across membranes uses ATP.

More information for figure 2

The image is a diagram showing the active transport of molecules across a cell membrane. It features a phospholipid bilayer with embedded protein channels. On the left side of the membrane is labeled 'Outside cell', and on the right side is labeled 'Inside cell'. There's a higher concentration of molecules and ions outside the cell, and a lower concentration inside.

The diagram highlights the process where molecules move from a low concentration area to a high concentration area inside the cell, against the concentration gradient. The transport occurs through the protein channel located in the cell membrane.

Energy for this process is provided by ATP (adenosine triphosphate). ATP is shown on the outside of the cell, breaking down into ADP (adenosine diphosphate) and an inorganic phosphate (Pi), releasing energy needed for the transport.

Arrows indicate the direction of movement of molecules through the protein channel from outside to inside the cell, driven by the energy released from the ATP. The diagram effectively demonstrates the role of cellular energy in transporting molecules through the cell membrane.

[Generated by AI]

The synthesis of macromolecules (anabolism) such as proteins and DNA also requires energy. Formation of the bonds in these molecules requires energy and the energy comes from ATP. Amino acids and nucleotides are not like LEGO bricks that fit together on their own; bonds need to be formed and that requires a source of energy. The enzymes that catalyse the reactions that form the bonds require ATP to function properly.

Another use for the energy from ATP is movement. This may involve the cell moving or the movement of components within the cell. Cell movement will involve the cytoskeleton of protein filaments. ATP is used to grow these filaments by providing the energy to bond fragments of the filaments together. The growth and contraction of these extensive networks of filaments produce changes in cell structure, which can lead to movement. When a phagocyte moves to engulf an invading bacterium, it is the movement of the cytoskeleton, using ATP that causes the membrane of the phagocyte to extend around the bacterium, leading to its destruction.

Student view

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Energy transfers during interconversions between ATP and ADP

Chemical energy is moved around a cell in a molecule of ATP. When the bond holding the third phosphate to the second in the phosphate tail is broken in a hydrolysis reaction, through the addition of a molecule of H_2O, an exergonic reaction occurs and energy is released. This energy is provided to a component of the cell that will carry out some form of work. This will change the ATP into ADP, adenosine diphosphate.

The generation of ATP involves adding the third phosphate to a molecule of ADP and removing a molecule of water in an endergonic reaction and temporarily storing the energy. This process of adding a phosphate to a molecule is known as phosphorylation. The energy stored during ATP synthesis and released during ATP hydrolysis is sufficient to carry out many tasks within a cell.

Try the drag and drop activity to help with your understanding of ATP and ADP interconversions.

Activity

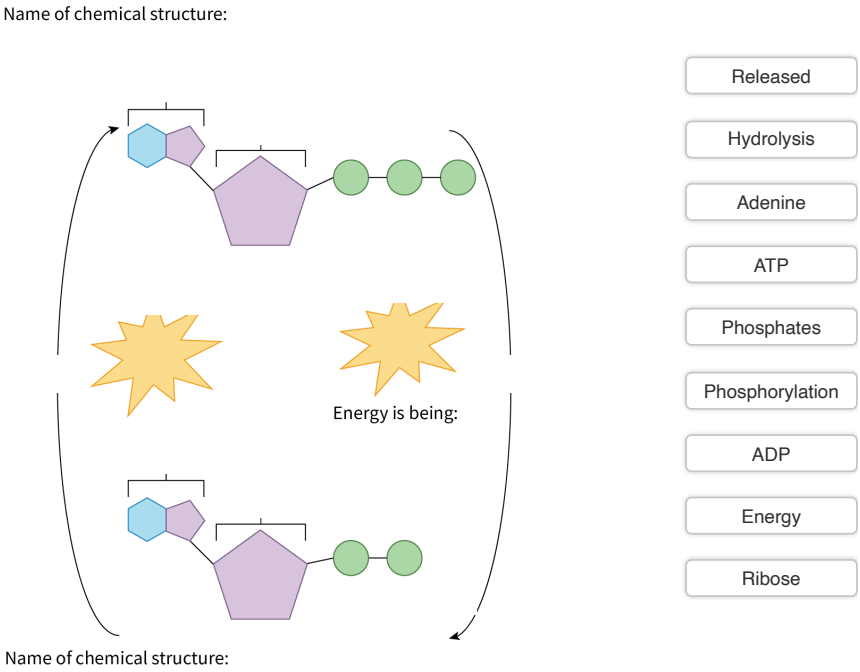
- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Individual activity

Complete the drag and drop activity in **Interactive 1** and answer the following questions.

1. What must be added to ATP to break the bond with the third phosphate?
2. What kind of a molecule is adenine?
3. How many carbons are in ribose?

Student view

Overview (/study/ap 422- cid- 755105/o



Check

4. **Interactive 1.** The interconversions between ATP and ADP.

More information for interactive 1

A drag and drop interactive illustrating two kinds of chemical reactions. One is the breakdown of ATP and the other is the formation of ATP.

At the top, there is a molecule. The molecule is divided into three parts. In the center, we have a purple pentagon with a drop box. The pentagon on its left side is connected to a pentagon, which is, in turn, connected to a hexagon on its left side with a drop box. The pentagon, on its right side, is connected to a chain of three green circles with a drop box. The caption at the top of the molecule reads: “Name of the chemical structure:”, with a drop box.

An arrow curves downwards from the ATP molecule on the right side pointing towards another molecule. In between the arrow, there is a drop box. In between the two molecules, on the left side, a nine-pointed orange star is depicted with a caption that reads: “Energy is being:”, with a drop box. Another drop box is provided at the top of the star.

At the bottom, there is another molecule. The molecule is divided into three parts. In the center, we have a purple pentagon with a drop box. The pentagon on its left side is connected to a pentagon, which is, in turn, connected to a hexagon on its left side with a drop box. The pentagon, on its right side, is connected to a chain of two green circles with a drop box. The caption at the bottom of the molecule reads: “Name of the chemical structure:”, with a drop box.

An arrow curves upwards to the molecule at the top. In between the arrow, there is a drop box. In between the two molecules, on the right side, a nine-pointed orange star is given with a drop box at its top.

To the right of the diagram, there is a vertical list of draggable labeled buttons. From top to bottom, they read: Released, Hydrolysis, Adenine, ATP, Phosphates, Phosphorylation, ADP,

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Energy, and Ribose.
Read below for the solution.
The first label at the very top is ATP or adenosine triphosphate.
The combined blue hexagon and purple pentagon structure is Adenine in both the structures.
The purple structure is Ribose in both structures.
The green circles are Phosphates in both structures.
The yellow stars are Energy.
The downward arrow on the right represents hydrolysis, and the energy is released here. The upward arrow on the left represents Phosphorylation.
The last label at the very bottom is ADP or Adenosine Diphosphate.

5 section questions

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

Understanding cell respiration

C1.2.4: Production of ATP using energy released from carbon compounds C1.2.5: Anaerobic and aerobic cell respiration in humans
C1.2.6: Variables affecting the rate of cell respiration

Learning outcomes

By the end of this section you should be able to:

- Describe cell respiration as the process that produces ATP using energy from carbon compounds and be able to distinguish between cell respiration and gas exchange.
- Distinguish between aerobic and anaerobic respiration.
- Describe the variables that affect the rate of cell respiration and be able to calculate the rate of respiration.

We know respiration is carried out by all living organisms. We know everything needs some form of nutrition to power their living processes. But how are these two really connected?

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Producing ATP using the energy released from carbon compounds

Cell respiration is the primary process that provides energy to cells. Organisms need to either produce or absorb molecules that can be used in cell respiration. Any molecule that can be broken down in respiration to release energy is known as a respiratory substrate.

Glucose is the main respiratory substrate used by most cells. When it is used up or absent cells will next turn to lipids and fatty acids as a source of energy. Cells may also use different sugars and other carbohydrates. When there are no carbohydrates or lipids available, cells will turn to proteins and their amino acids as a source of energy. This is usually a last resort as proteins serve other important functions within the cell.

Cell respiration is a complex series of metabolic pathways and cycles that break down these carbon compounds, releasing energy which is then used to produce the ATP molecules that power all other processes in the cell. Cell respiration must be clearly distinguished from gas exchange (respiration) in the alveoli of the lungs which is the movement of oxygen from the inhaled air into the blood and carbon dioxide from the blood into the air to be exhaled.

Comparing anaerobic and aerobic cell respiration

There are two main types of cell respiration that occur in human cells: aerobic and anaerobic. Aerobic respiration occurs in the presence of oxygen. It begins in the cytoplasm of the cell but most steps occur in the mitochondria. Aerobic respiration is able to use any of the respiratory substrates. The yield of ATP is relatively large from aerobic respiration with approximately 36–38 molecules of ATP produced. The waste products of aerobic respiration are carbon dioxide and water.

In comparison, anaerobic respiration occurs in the absence of oxygen. It occurs only in the cytoplasm of the cell. Only glucose and other carbohydrates can be used as respiratory substrates and a relatively small amount of ATP is the yield with only a net (overall) gain of two molecules. The waste product of anaerobic respiration in humans is lactate (lactic acid). **Table 1** outlines the major differences in humans.

Table 1. Aerobic versus anaerobic respiration in humans.

	Aerobic respiration in humans	Anaerobic respiration in humans
Oxygen	With oxygen	Without oxygen

Student view

	Aerobic respiration in humans	Anaerobic respiration in humans
Location	Cytoplasm and mitochondria	Cytoplasm only
Respiratory substrates	All	Carbohydrates only
ATP yield	High	Low
Waste products	Carbon dioxide and water	Lactate/lactic acid

The following are the word equations for aerobic and anaerobic respiration in humans.

Aerobic respiration:

$$\text{glucose} + \text{oxygen} \dashrightarrow \text{carbon dioxide} + \text{water} \ (+\text{ATP})$$

Anaerobic respiration:

$$\text{glucose} \dashrightarrow \text{lactate} \ (+\text{ATP})$$

Variables affecting the rate of cell respiration

There are several variables that affect the rate of cell respiration. These include temperature, pH, substrate concentration and oxygen concentration. As respiration is a series of enzyme-controlled reactions, the rate of respiration is affected by many of the same factors that affect any enzyme-controlled reaction.

The following outlines how you could investigate the effect of temperature on the rate of cell respiration.

A respirometer is a simple apparatus that can measure the rate of respiration. Aerobic cell respiration uses oxygen and produces carbon dioxide and water. We can measure the consumption of oxygen as an indication of the respiration rate.

The setup shown in **Figure 1** demonstrates a relatively simple way to measure the respiration rate of living organisms.

In Tube A, the organisms to be tested (such as insects or germinating seeds) are positioned, and the tap is closed. The organism starts respiring, consuming O_2 and producing CO_2 and H_2O. The alkaline solution at the bottom of Tube A will absorb the CO_2 which will decrease the volume of

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gas by an amount equivalent to the volume of oxygen absorbed. Tube B is the control where no O_2 is used or CO_2 produced because no living organism is present. The capillary connecting the two tubes is a manometer.

The reduction in oxygen in Tube A will reduce the pressure in Tube A and will move the coloured liquid in the manometer in the direction of Tube A. This provides an indirect measurement of the oxygen consumed, allowing the rate (amount of oxygen consumed per time unit) to be calculated.

Note: The use of animals in scientific experimentation has ethical implications. The IB has strict guidelines which must be adhered to in all laboratory procedures involving experimentation with animals. Remember, you should respect the IB animal experimentation policy.

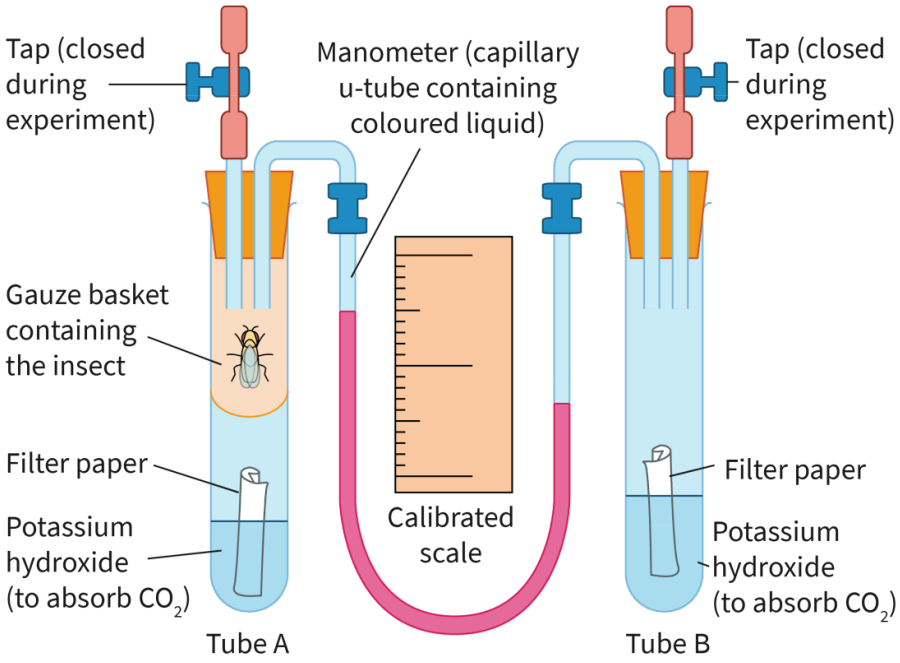

Figure 1. A respirometer used to measure the rate of cell respiration through the consumption of oxygen.

More information for figure 1

The image shows a diagram of a respirometer setup used to measure the rate of cell respiration. This setup consists of two main tubes, labeled Tube A and Tube B, each with distinct components. Tube A contains a gauze basket holding an insect, and both tubes have filter paper and potassium hydroxide to absorb carbon dioxide. The manometer, a U-shaped capillary tube containing colored liquid, is placed between these tubes and is marked with a calibrated scale to measure changes in pressure. Taps at the top of each tube are closed during the experiment. This setup allows the observation of oxygen consumption as the insect respires, indicated by changes in the manometer. The potassium hydroxide ensures accurate readings by absorbing the carbon dioxide produced by the insect.

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Student view

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Practical skills

- **Tool 3:** Mathematics — Applying general mathematics
- **Inquiry 2**: Collecting and processing data — Processing data

A few calculations will be necessary for the following activity.

- The first is calculating the volume of a cylinder (the inside of the manometer tube). For this the equation $V = \pi r^2 h$ should be used.
- The next is the calculation of a rate. For this you would divide the volume of gas consumed by the time taken to give a result in cm^3/min.
- The final calculation is for a mean rate. Add the rates together and divide by the number of trials.

Worked example 1

What is the volume of a cylinder with a diameter of 5 cm and a height of 10 cm?

$$V = \pi r^2 h$$

$$V = \pi \times \left(\frac{5}{2}\right)^2 \times 10$$

$$V = 196.35 \text{ cm}^3$$

Worked example 2

What is the rate of oxygen consumption if a volume of 50 cm^3 was consumed over 5 minutes?

$$\text{Rate} = \frac{\text{volume}}{\text{time}}$$

$$\text{Rate} = \frac{50 \text{ cm}^3}{5 \text{ min}}$$

Student view

$$\text{Rate} = 10\ \text{cm}^3/\text{min}$$

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Worked example 3

What is the mean rate of oxygen consumption for trials with the following rates: 12 cm^3/min, 14 cm^3/min, 15 cm^3/min, 13 cm^3/min, 15 cm^3/min?

$$\text{Mean} = \frac{\text{sum of values}}{\text{number of trials}}$$

$$\text{Mean} = \frac{(12 + 14 + 15 + 13 + 15)}{5}$$

$$\text{Mean} = 13.8\ \text{cm}^3/\text{min}$$

Try these calculations yourself in the activity below.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Providing a reasoned argument to support conclusions, Reflecting on the credibility of results
- **Time required to complete activity:** 30—40 minutes
- **Activity type:** Individual activity

The data in **Table 2** were collected from a practical investigation to determine the effect of temperature on the rate of cell respiration. Your task is to analyse and interpret the results.

Each trial was carried out over 3 minutes. The diameter of the manometer tubing is 1 mm.

You need to complete the following calculations:

1. Calculate the volume of oxygen consumed for each measurement.
2. Calculate the mean volume of oxygen consumed for each temperature.
3. Calculate the mean rate of oxygen consumption for each temperature.

Next, graph the mean rates of oxygen consumption against the temperatures. This can be done by hand on graph paper or using a spreadsheet tool such as Excel, Sheets or Numbers.

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Finally, describe and explain the results using the graph and specific data from it.

Table 2. Data from an investigation to determine the effect of temperature on the rate of respiration.

Temperature (°C)	Distance moved by coloured liquid (mm)				
	Trial 1	Trial 2	Trial 3	Trial 4	Tri
10	2	3	2	1	
20	3	5	4	6	
30	12	13	13	12	1
40	14	12	13	14	1
50	2	3	1	3	

5 section questions

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

Glycolysis (HL)

C1.2.7: Role of NAD (HL) C1.2.8: Conversion of glucose to pyruvate by stepwise reactions in glycolysis (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Explain the role of NAD as a hydrogen carrier in cell respiration.
- Describe the conversion of glucose to pyruvate by the process of glycolysis.

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Cell respiration is a very complex process. It is able to work efficiently due to some helpful molecules. In this section we will begin to break down this complex process and explore how one of these key molecules works.

The role of NAD

Nicotinamide adenine dinucleotide (NAD) is a key molecule in cell respiration (**Figure 1**). It functions as a coenzyme, a molecule that is required for an enzyme to carry out its function. In NAD's case, its ability to be reduced and oxidised allows it to perform the critical role of a hydrogen carrier.

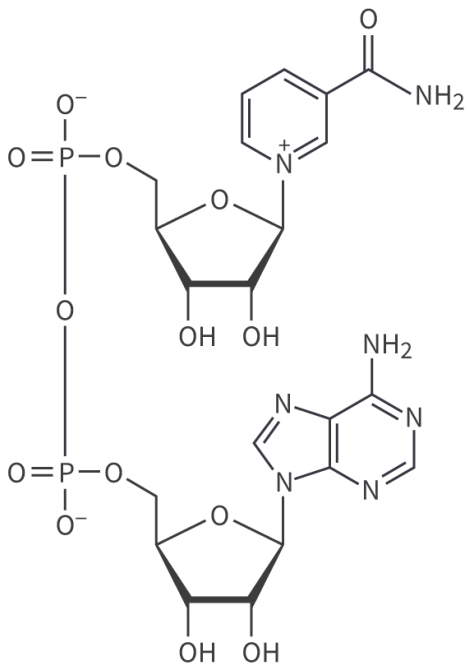

Figure 1. Nicotinamide adenine dinucleotide (NAD). You do not need to know this structure.

More information for figure 1

This image is a diagram showing the chemical structure of Nicotinamide adenine dinucleotide (NAD). It includes two nucleotides joined through their phosphate groups. One nucleotide contains an adenine base, while the other has nicotinamide. The phosphate groups are connected to a sugar ring (ribose), which links to either a purine or pyrimidine base. The structure illustrates the components and their arrangement, with rings representing the carbon components and lines showing the bonds among the atoms.

[Generated by AI]

Reduction-oxidation (redox) reactions are a class of chemical reactions where there is an exchange of electrons between two molecules. When electrons are lost from a molecule, atom or ion, it is oxidised. The molecule, atom or ion that accepted the electrons is reduced. This is important to note, whenever something is oxidised, the other substance is reduced.

Student view

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NAD is known as an oxidiser because it will oxidise other molecules, while becoming reduced itself, by accepting electrons. In cell respiration this will involve the transfer of hydrogen (containing electrons), and the molecule being oxidised is also dehydrogenated, meaning it has lost an atom of hydrogen. NAD will become reduced NAD, also known as NADH (**Figure 2**). This process plays a vital role in several steps of cell respiration where a substrate needs to be oxidised. It is also essential in that it carries electrons and hydrogen ions (protons) which will drive oxidative phosphorylation at the end of aerobic respiration, generating the majority of the ATP.

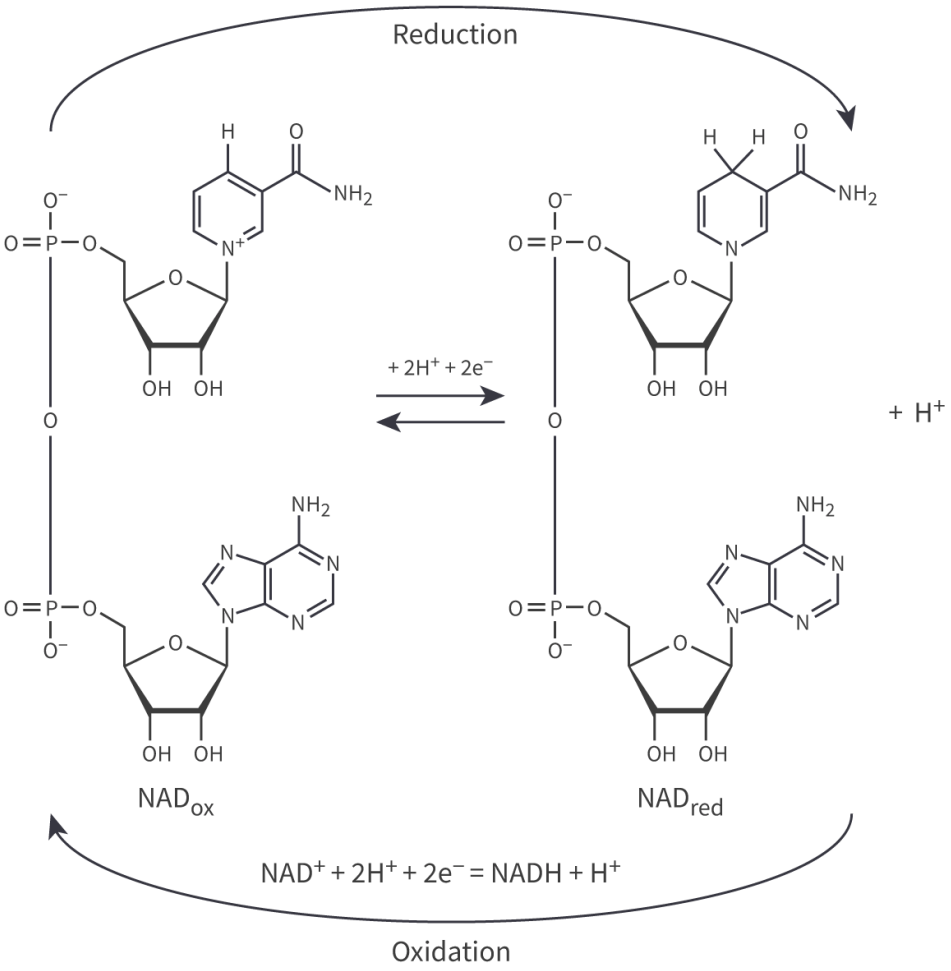

Figure 2. The interconversions of NAD and reduced NAD (also known as NADH) through redox reactions.

More information for figure 2

The diagram represents the chemical structure of NAD (nicotinamide adenine dinucleotide) and its reduced form NADH. At the top of the diagram, the term "Reduction" is displayed, while the bottom shows "Oxidation." On the left, the chemical structure labeled NAD_ox includes a pyridine ring with a positive charge and an attached adenine diphosphate group. On the right, an NAD_red structure includes a hydrogen atom added to the nicotinamide ring, indicating its reduced state.

An arrow between the structures indicates a reversible reaction with the text "+2H^+ + 2e^−," signifying the addition of protons and electrons during the reduction process. Below this, the equation shows "NAD^+ + 2H^+ + 2e^− = NADH + H^+."

Student view

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The diagram helps illustrate the role of NAD as an electron carrier in cellular respiration, as it accepts and donates electrons and protons during metabolic reactions.

[Generated by AI]

Glycolysis

The first step of cell respiration, regardless of it being aerobic or anaerobic, is glycolysis . This occurs in the cytoplasm of the cell and involves the splitting of a single molecule of glucose (a 6-carbon compound) into two molecules of pyruvate (a 3-carbon compound). Glycolysis is a complex sequence of reactions involving 10 steps and several key reactions (**Figure 3**). Each of the 10 steps is catalysed by its own enzyme.

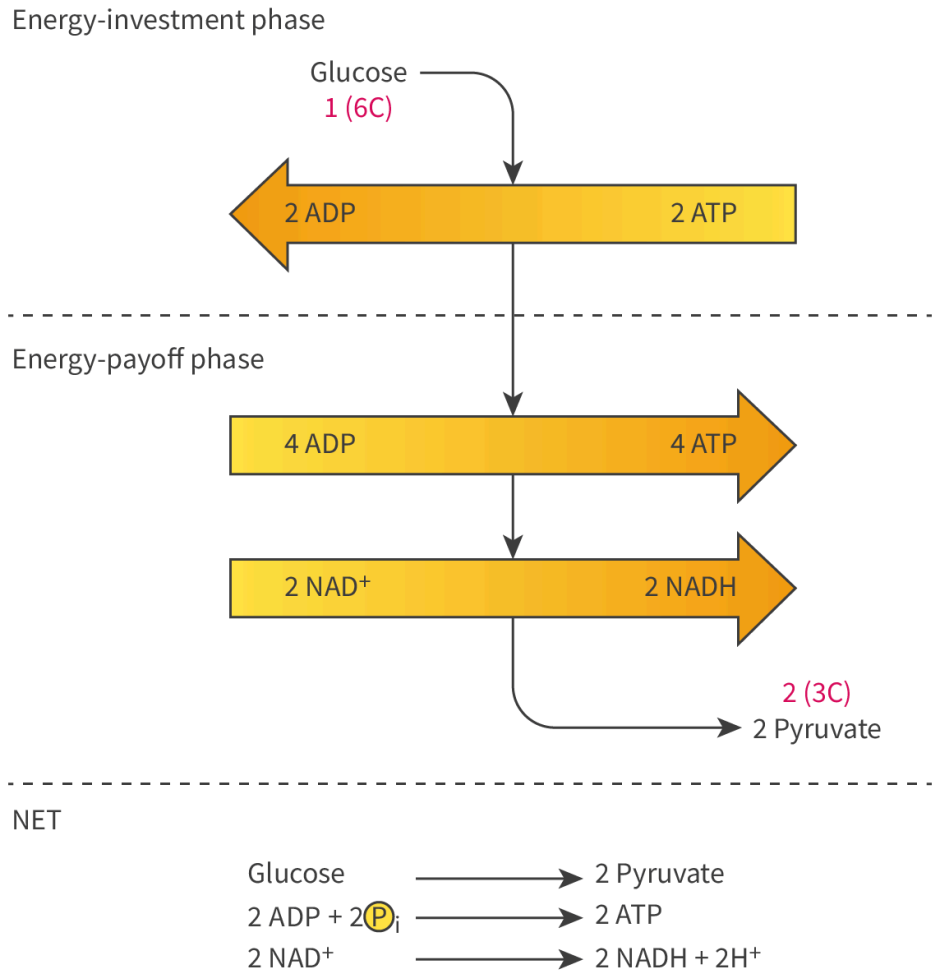

Figure 3. Summary of glycolysis. NADH = reduced NAD.

More information for figure 3

The image is a diagram showing the phases of glycolysis, broken into the energy-investment phase and energy-payoff phase. In the energy-investment phase, glucose (1, a 6-carbon compound) enters, reacting with 2 ADP to form 2 ATP. The process continues to the energy-payoff phase, which involves the conversion of 4 ADP into 4 ATP and 2 NAD+ into 2 NADH. This ultimately results in the production of 2 pyruvate molecules (2, a 3-carbon compound). A summary at the bottom indicates that glucose converts to 2 pyruvate, 2 ADP + 2 inorganic phosphate converts to 2 ATP, and 2 NAD+ converts to 2 NADH + 2 H+. Arrows indicate the flow of substances and reactions throughout the process.

Student view

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There are four main phases of glycolysis. The first is phosphorylation and involves the use of two molecules of ATP which phosphorylate the glucose molecule. This makes the glucose molecule more unstable. The second phase is known as lysis. The unstable, phosphorylated glucose molecule is split into two, forming two glyceraldehyde 3-phosphate (G3P) molecules.

The third phase of glycolysis involves the dehydrogenation and oxidation of each G3P molecule which reduces two molecules of NAD to reduced NAD. Finally, in the fourth stage, two ATP are generated by substrate-level phosphorylation from each G3P and the final product of pyruvate is formed. Substrate-level phosphorylation is the process of generating ATP using ADP and a phosphate taken from another molecule, the substrate. To summarise, glycolysis involves the investment of two ATP to produce four ATP, with a net yield of two ATP, and two molecules of NADH or reduced NAD are formed, along with the two molecules of pyruvate.

Study skills

Glycolysis is a complex process. You will likely come across extra details in other videos and resources. You are not required to know any of the intermediates formed during glycolysis or the enzymes involved. You should know that glycolysis involves phosphorylation, lysis, oxidation and ATP formation and that each step in the pathway is catalysed by a different enzyme.

Watch **Video 1** for an overview of glycolysis.

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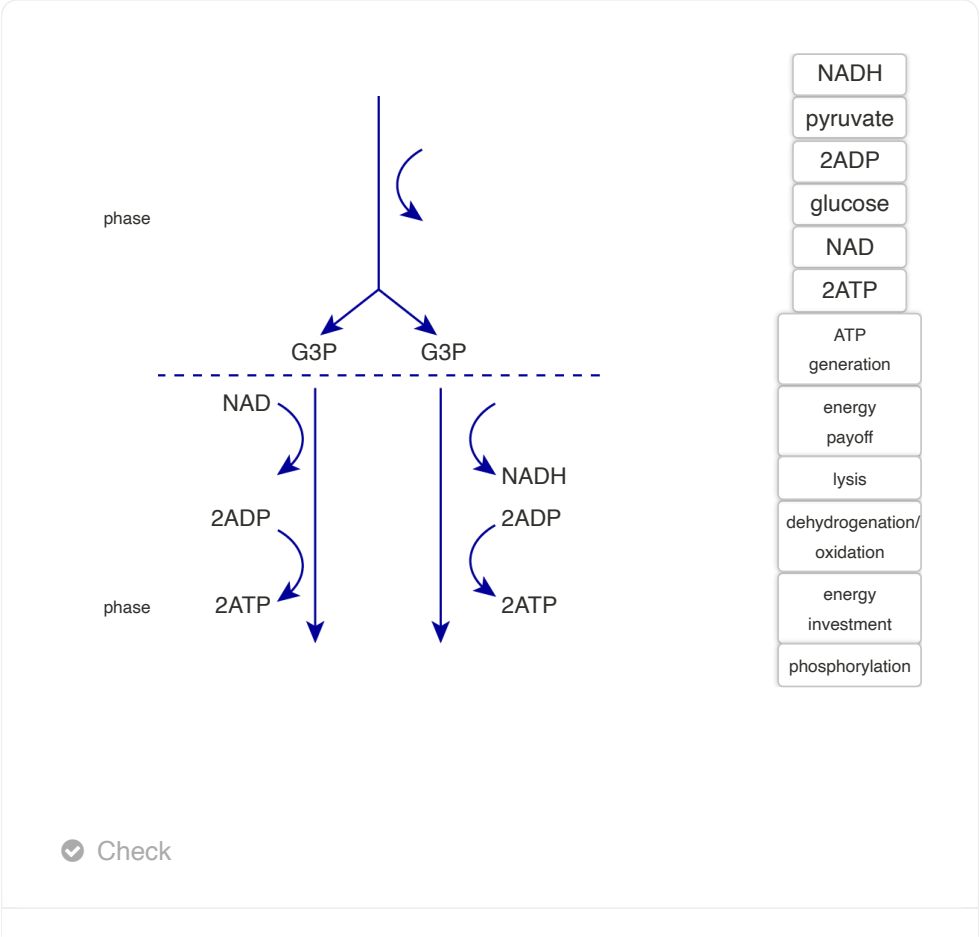
Video 1. A walkthrough of glycolysis.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Individual activity

Use the drag and drop activity in **Interactive 1** to demonstrate your understanding of glycolysis.



Interactive 1. Summary of glycolysis.

More information for interactive 1

This is a drag and drop interactive screen with a flowchart illustrating a glycolic process. It is divided into two main sections by a dashed horizontal line. This pathway illustrates the breakdown of glucose into two G3P molecules in an initial phase, followed by a second phase where each G3P is further processed, yielding ATP and NADH, and resulting in some final product.
Starting at the top, a box represents "glucose". A downward arrow leads from glucose to a

Student view

Overview (/study/ap 422-cid-755105/o

point where it splits into two downward arrows. Each of these arrows points to a box labeled "G3P".
This upper section, above the dashed line, is the energy investment phase.
Below the dashed line, each G3P molecule undergoes a series of transformations. On the left side, a downward curved arrow shows "NAD" going in and "NADH" coming out. Another downward curved arrow shows "2ADP" going in and "2ATP" coming out. A downward arrow then leads to a final box.
Similarly, on the right side below the dashed line, an upward curved arrow shows "NAD" going in and "NADH" coming out. Another upward curved arrow shows "2ADP" going in and "2ATP" coming out. A downward arrow also leads to a final box, positioned symmetrically to the one on the left.
This lower section, below the dashed line, is labeled as known as the energy payoff phase.
To the right of the flowchart, there is a vertical column of labeled boxes.
From top to bottom, they read: "NADH", "pyruvate", "2ADP", "glucose", "NAD", "2ATP", "ATP generation", "energy payoff", "lysis", "dehydrogenation/oxidation", "energy investment", and "phosphorylation". These labels represent the molecules, energy carriers, and processes involved in this metabolic pathway.
Read below for the answer.
The first gap above the text phase is the energy investment phase.
The pathway begins with glucose splitting into two G3P. This happens by spending 2ATP molecules which convert into 2ADP. This process is called phosphorylation. As the glucose molecule is split into two G3P molecules, this is called lysis.
Now moving below the purple dotted line. On the right side of the arrow, NAD is converted to NADH. This process is dehydrogenation/oxidation. And ATP generation takes place.
On the left side of the purple arrow, NAD is converted into NADH.
At the end, both these arrows lead to the generation of pyruvate molecules.
This phase is called the energy payoff phase.

5 section questions

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

Anaerobic respiration (HL)

C1.2.9: Conversion of pyruvate to lactate in anaerobic cell respiration (HL) C1.2.10: Anaerobic cell respiration in yeast (HL)

Higher level (HL)

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/understanding-cell-respiration-id-45980/print/) Assign

Learning outcomes

By the end of this section you should be able to:

Student view

Overview (/study/ap 422-cid-755105/o

- Describe anaerobic respiration as a means to regenerate NAD, producing lactate as a by-product.
- Describe anaerobic respiration in yeast and how we make use of it for brewing and baking.

Have you ever been doing some physical activity so intensely that you began to feel a burning sensation in your muscles? Have you ever baked bread or watched dough rise? Both of these experiences are much more similar than they first seem. We will explore the processes behind both of these in the following section.

Regenerating NAD in anaerobic cell respiration

Anaerobic respiration produces a lot less ATP than aerobic respiration. However, when oxygen is lacking or in short supply, anaerobic respiration is able to provide the cell with a source of ATP to allow key processes to function.

Glycolysis does not require oxygen to occur; however, in anaerobic conditions, after a short time the NAD of the cell would all be converted to reduced NAD and glycolysis would also stop. Anaerobic respiration allows for the regeneration of NAD so that glycolysis can continue and some ATP is still produced.

When there is no oxygen, glycolysis will continue to produce two pyruvate, a net gain of two ATP and two reduced NAD from each molecule of glucose. To regenerate the NAD needed to continue this, the cells in humans, other animals and some bacteria are able to convert the pyruvate into lactate by reducing the pyruvate with reduced NAD using an enzyme (**Figure 1**). This oxidises the reduced NAD back to NAD and allows it to take part in further glycolysis. This is known as lactic acid fermentation.

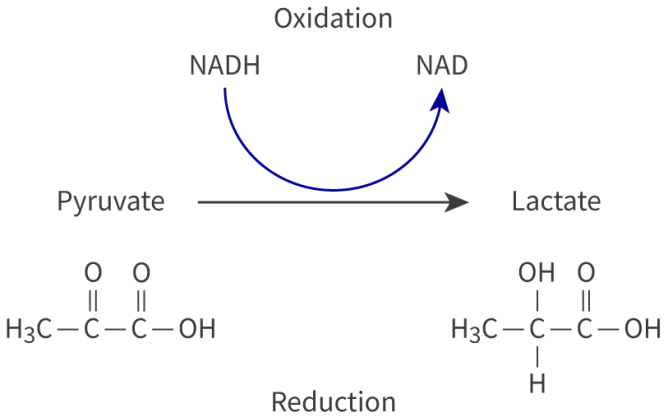


Figure 1. The reduction of pyruvate to lactate by reduced NAD (NADH).

More information for figure 1

Student view

Overview (/study/ap 422-cid-755105/o

The diagram illustrates the process of reducing pyruvate to lactate, facilitated by NADH. At the top, an arrow labeled 'Oxidation' points from NADH to NAD, indicating the transformation that occurs during this reaction. Below, an arrow labeled 'Reduction' leads from pyruvate to lactate. Chemical structures are depicted: on the left, pyruvate (H3C—C=O—C=O—OH); on the right, lactate (H3C—C—OH—C=O—OH), with an additional H atom bonded to the central carbon. This transformation is essential in anaerobic conditions to regenerate NAD from NADH, allowing glycolysis to continue by converting pyruvate into lactate, thus oxidizing NADH back to NAD.

[Generated by AI]

While this is not a good long-term solution for animals like us, due to our large energy requirements, anaerobic respiration does have the advantage of being much faster than aerobic respiration. It is therefore effective for generating a relatively large amount of ATP for short, intense exercises such as sprinting or weightlifting.

Anaerobic cell respiration in yeast

While most organisms will carry out glycolysis in the same way, the way in which they regenerate NAD when carrying out anaerobic respiration can differ. This will produce different products. When yeast respire anaerobically they regenerate their NAD through one of these different methods. This is a two-step process. First, they decarboxylate the pyruvate, releasing a molecule of carbon dioxide. This converts the pyruvate into ethanal. The ethanal is then reduced by the reduced NAD into ethanol, regenerating the NAD for glycolysis and the production of ATP to continue (**Figure 2**). Each step in this process uses its own enzyme to catalyse the reaction. As a result, anaerobic respiration in yeast produces two products: carbon dioxide and ethanol. This is known as alcohol fermentation.

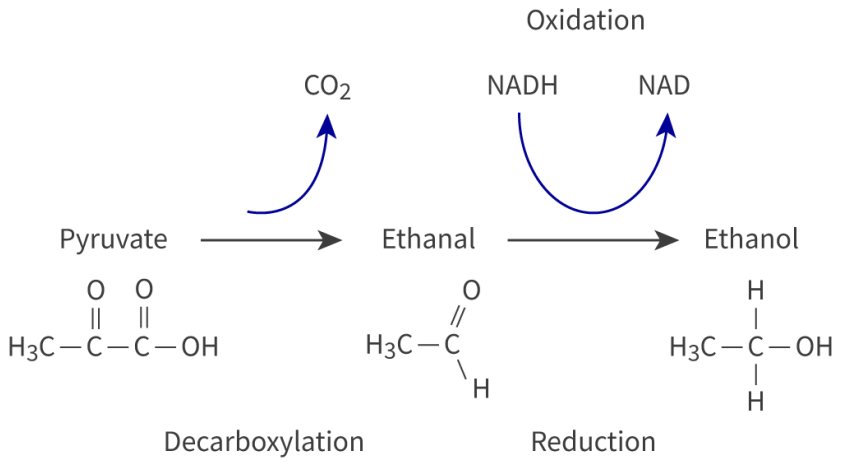


Figure 2. Ethanol fermentation in yeast. NADH = reduced NAD.

More information for figure 2

Student view

Overview (/study/ap 422-cid-755105/o

The diagram illustrates the process of ethanol fermentation in yeast. It shows a two-step chemical reaction. The first step is decarboxylation, where pyruvate (CH3-CO-COOH) is converted into ethanal (acetaldehyde), releasing carbon dioxide (CO2) in the process. This is visually represented with arrows indicating the release of CO2. In the second step, ethanal is reduced to ethanol (CH3-CH2-OH) using reduced NADH, which is oxidized to regenerate NAD+. Arrows and labels indicate these chemical transformations, with NADH and NAD features shown as part of the oxidation-reduction reaction. This sequence of reactions showcases the regeneration of NAD+ which ensures the continuation of glycolysis even under anaerobic conditions.

[Generated by AI]

Humans have made use of this process for centuries. When used in baking, yeast is added to the dough. The yeast feeds on the sugars in the dough and respires anaerobically as it uses up any available oxygen quickly. The carbon dioxide produced in the dough creates the bubbles that cause the dough to rise. Any ethanol produced evaporates away during the baking process.

In brewing, the yeast feeds on the sugars from the material being fermented. This would be barley for beers, grapes for wine, etc. Anaerobic conditions are maintained by fermenting in a sealed container or fermenter. The ethanol produced is the desired product of this fermentation process. The carbon dioxide may also be used to make some of these products carbonated.

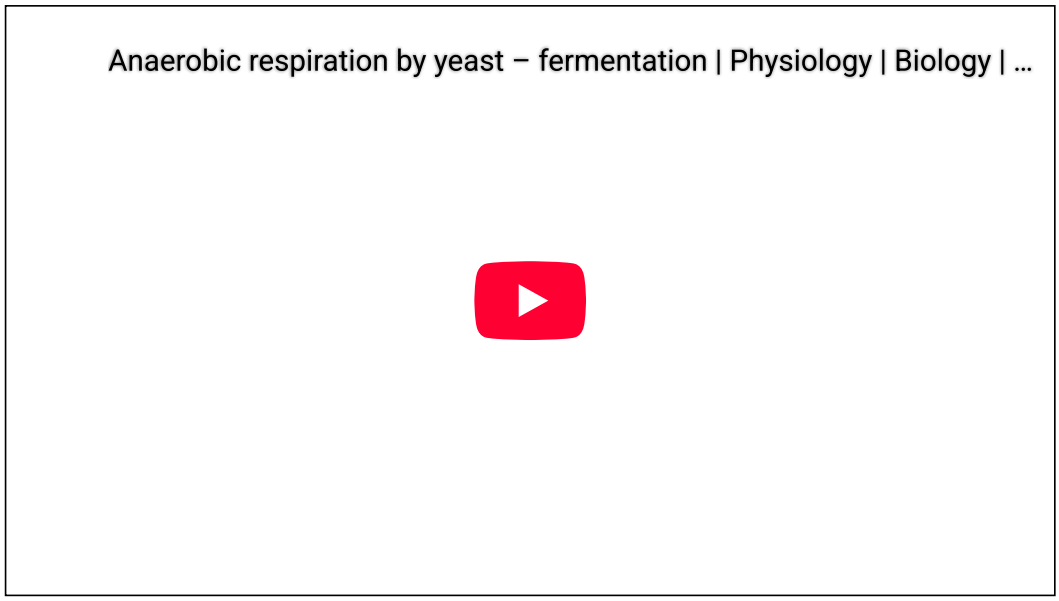
International Mindedness

Yeast is used for baking and/or brewing by many cultures and people across the world. The earliest records of yeast being used for baking date back to ancient Egypt and China. It is thought, however, that the use of yeast and other microorganisms for fermentation dates back even farther.

Watch **Video 1** for an outline of anaerobic respiration in yeast and its use in baking and brewing.

Student view

Overview (/study/ap 422-cid-755105/o



Video 1. Anaerobic respiration in yeast and its use in baking and brewing.

Try the activity to help with your understanding of anaerobic respiration.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:**
  - Communication skills —Using digital media for communicating information
  - Thinking skills — Designing procedures and models
- **Time required to complete activity:** 45—60 minutes
- **Activity type:** Pair activity

With a partner, produce a video or podcast outlining anaerobic respiration and its significance to humans both in terms of our own bodies and our use of fermentation by microorganisms such as yeast. Share your videos or podcasts with your class and give feedback on each other's work.

The media should include the following:

- The purpose of anaerobic respiration.
- An outline of anaerobic respiration in humans.
- An outline of anaerobic respiration in yeast.
- A discussion of the significance of fermentation to a selected culture.

Student view

5 section questions

Overview (/study/ap 422-cid-755105/o

Link reaction and Krebs cycle (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Describe the link reaction and the conversion of pyruvate to acetyl groups.
- Describe the Krebs cycle.

Once pyruvate has been produced in glycolysis and there is oxygen present, what happens next? What are the next steps in aerobic respiration?

The link reaction

For each molecule of glucose that is broken down in glycolysis, two pyruvates move into the matrix of the mitochondria via active transport. Once there, they are both oxidised/dehydrogenated and decarboxylated in what is known as the link reaction (**Figure 1**). As it involves both oxidation and decarboxylation it is called oxidative decarboxylation. This is carried out by enzymes that remove the CO_2 and transfer the hydrogen to NAD to make reduced NAD. The new products, two 2-carbon acetates, are then combined with the molecule coenzyme A to form two acetyl CoA molecules. This is also where metabolised lipids are broken down into 2-carbon acetyl groups to be transferred by coenzyme A to the Krebs cycle.

Student view

Overview (/study/ap 422-cid-755105/o

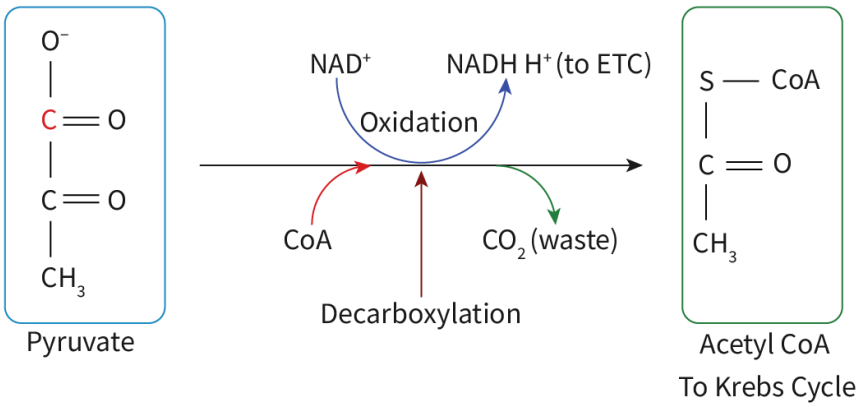


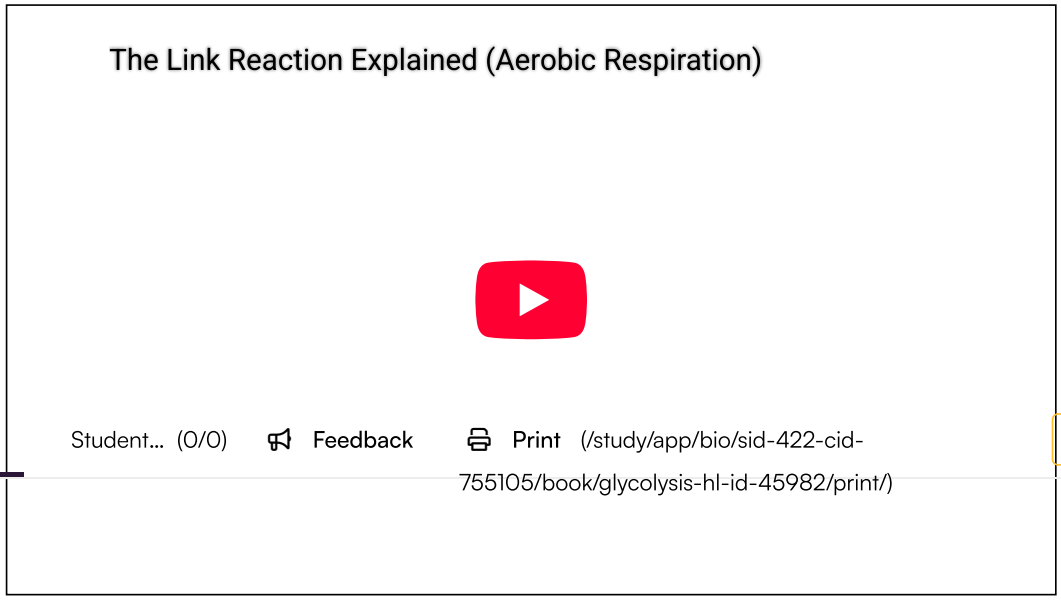
Figure 1. The link reaction. NADH = reduced NAD.

More information for figure 1

The diagram illustrates the link reaction in cellular metabolism. On the left, the diagram starts with a box labeled 'Pyruvate' containing a chemical structure of pyruvate: O^(-), C═O, C═O, and CH3. Arrows indicate the process steps. A red arrow labeled 'CoA' points towards the center, symbolizing the addition of coenzyme A. A blue arrow labeled 'NAD⁺' points upwards and curves around to label NADH H⁺ (to ETC), signifying oxidation. A brown upward arrow labeled 'Decarboxylation' indicates the removal of carbon dioxide. A green arrow labeled 'CO_2 (waste)' points downwards, showing CO_2 as a waste product. On the right, another box labeled 'Acetyl CoA' contains a different structure: S—CoA, C═O, CH3, indicating the formation of acetyl CoA, which then enters the Krebs cycle (as noted at the bottom).

[Generated by AI]

Watch **Video 1** for a summary of the link reaction.



Video 1. A walkthrough of the link reaction.

Student view

Overview (/study/ap 422- cid- 755105/o

At this stage of aerobic respiration (glycolysis + the link reaction) we now have the following net products:

- two ATP
- four reduced NAD (NADH)
- two acetyl CoA.

Krebs cycle

Still in the mitochondrial matrix, acetyl CoA now continues to the next step, which is the Krebs cycle (**Figure 2**). As a cycle, it is a series of enzyme-controlled reactions. The first is the binding of the acetate from the acetyl CoA with a 4-carbon compound called oxaloacetate. This releases coenzyme A to return to continue the link reaction and together, the acetate and oxaloacetate form a 6-carbon compound called citrate or citric acid. The Krebs cycle is also known as the citric acid cycle after this compound.

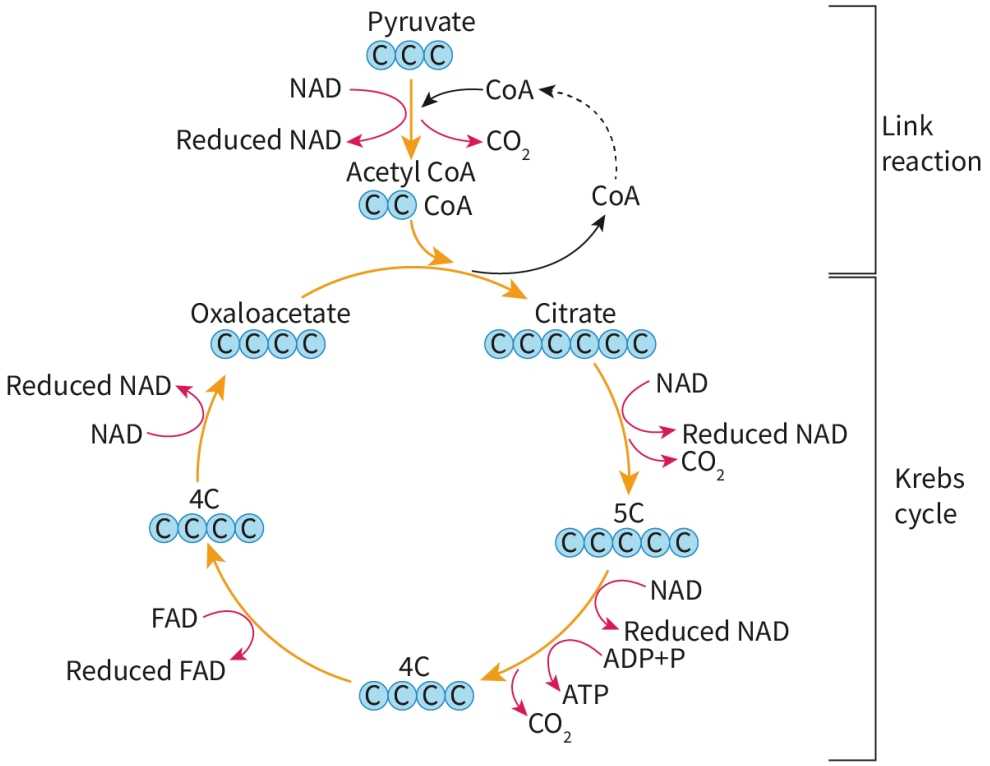


Figure 2. The Krebs cycle. Each molecule of glucose results in two turns around the Krebs cycle.

More information for figure 2

The image is a diagram illustrating the Krebs cycle, a series of enzyme-controlled chemical reactions important in cellular respiration.

1. **Beginning Stage:**

Student view

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2. Pyruvate enters the mitochondrial matrix where it combines with CoA, releasing CO2 and converting NAD to reduced NAD, forming acetyl CoA.
3. **Oxaloacetate and Citrate Formation**:
4. Acetyl CoA (2-carbon compound) combines with oxaloacetate (4-carbon compound) to form citrate (citric acid, 6-carbon compound), releasing CoA.
5. **Steps in the Cycle**:
6. The 6-carbon citrate undergoes oxidative decarboxylation, releasing CO2 and converting NAD to reduced NAD, forming a 5-carbon compound.
7. Further decarboxylation results in another CO2 release and formation of a 4-carbon compound while generating ATP from ADP and P.
8. FAD is converted to reduced FAD, and another NAD converts to reduced NAD as the cycle continues, eventually regenerating oxaloacetate.
9. **Energy Carriers**:
10. Throughout the cycle, energy carriers NAD and FAD are alternately reduced and oxidized, facilitating electron transport for ATP production.

The cycle depicted is a crucial part of aerobic respiration, emphasizing the interconversion of carbon compounds and the production of high-energy molecules like ATP, NADH, and FADH2.

[Generated by AI]

The next step involves oxidative decarboxylation as in the link reaction, removing a molecule of carbon dioxide and reducing a molecule of NAD to reduced NAD while oxidising and dehydrogenating the citrate. This changes the 6-carbon citrate into a 5-carbon compound.

In the next step of the cycle, another oxidative decarboxylation reaction takes place, reducing another NAD and releasing another carbon dioxide molecule. There is also one molecule of ATP generated in this step through substrate-level phosphorylation. The remaining carbon compound now has four carbons left. All six of the carbons from the original glucose molecule have now been released as six molecules of carbon dioxide.

However, to continue the cycle oxaloacetate must be regenerated, which requires further modification of the 4-carbon compound. This modification involves oxidation, reducing another molecule of NAD to reduced NAD and also reducing a new molecule, flavin adenine dinucleotide (FAD) (**Figure 3**) to reduced FAD (also called $FADH_2$). FAD functions similarly to NAD, as a hydrogen carrier. FAD is able to carry one more H^+ than NAD when it is reduced. Oxaloacetate is now available to bind with another acetate, continuing the cycle.

Student view

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/anaerobic-respiration-hl-id-45983/print/) Assign

Overview (/study/ap 422- cid- 755105/o

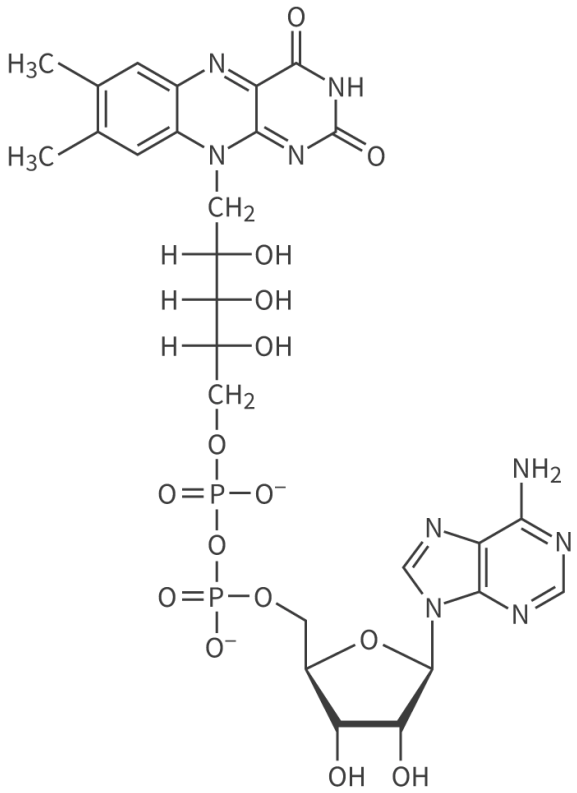


Figure 3. The structure of FAD (flavin adenine dinucleotide). You do not need to know this structure.

More information for figure 3

The image is a structural diagram of FAD (flavin adenine dinucleotide). It consists of two main parts: a riboflavin moiety and an adenine dinucleotide connected by a phosphate linkage. The riboflavin part features a tricyclic isoalloxazine ring system, which is shown at the top and includes several nitrogen and oxygen atoms, as well as two methyl groups attached to the middle ring. Below this, there is a ribitol sugar chain with hydroxyl groups attached to each of the carbon atoms. The chain is connected via a phosphate group to the adenine dinucleotide component, which is shown at the bottom of the diagram. This part displays an adenine ring attached to a ribose sugar, completing the FAD structure. The diagram displays all elements involved, including nitrogenous bases, phosphate groups, and hydroxyl groups, depicted with chemical symbols and bonds.

[Generated by AI]

The Krebs cycle completes the breakdown of the original glucose molecule and generates the majority of the reduced NAD and reduced FAD that will deliver the required electrons and hydrogen to the electron transport chain. This allows oxidative phosphorylation to be carried out, producing the majority of the ATP.

Study skills

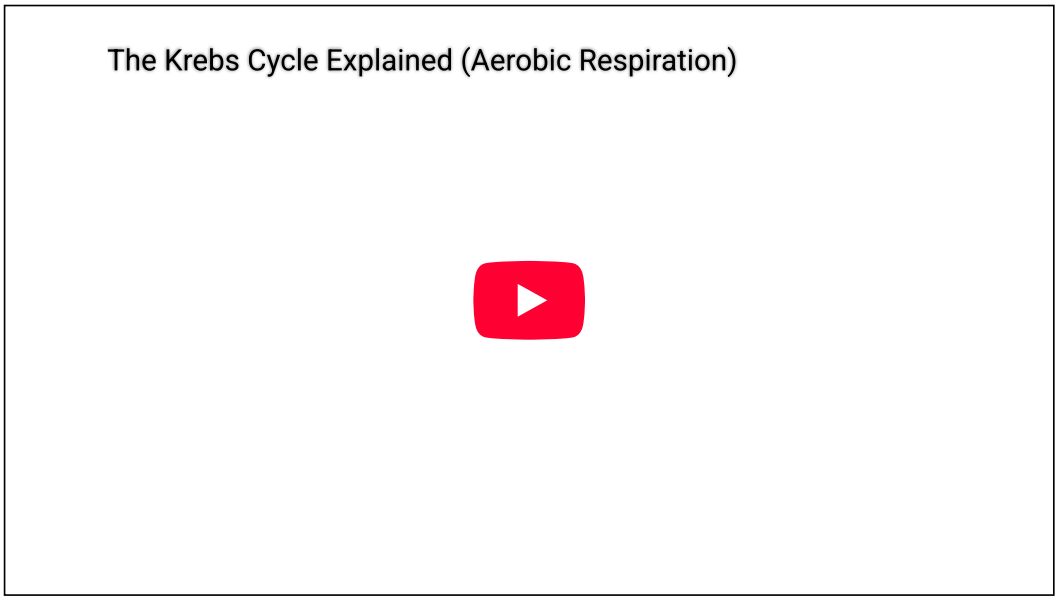
Remember that for each molecule of glucose that began in glycolysis, two pyruvate molecules were produced, which became two acetyl CoAs in the link

Student view

Overview (/study/ap 422-cid-755105/o

reaction and therefore went through two turns of the Krebs cycle.

Watch **Video 2** for a clear outline of the Krebs cycle.



Video 2. A walkthrough of the Krebs cycle.

Try the activity to help with your understanding of the link reaction and Krebs cycle.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Individual activity

Complete the drag and drop activity in **Interactive 1** and answer the following questions about the link reaction and the Krebs cycle.

1. What happens to the CO_2 given off in these two stages of aerobic respiration?
2. For one molecule of glucose, what are the total products produced up to the end of the Krebs cycle?
3. Why is it important to regenerate oxaloacetate?
4. Where does the coenzyme A go after dropping off the acetate in the Krebs cycle?

Student view

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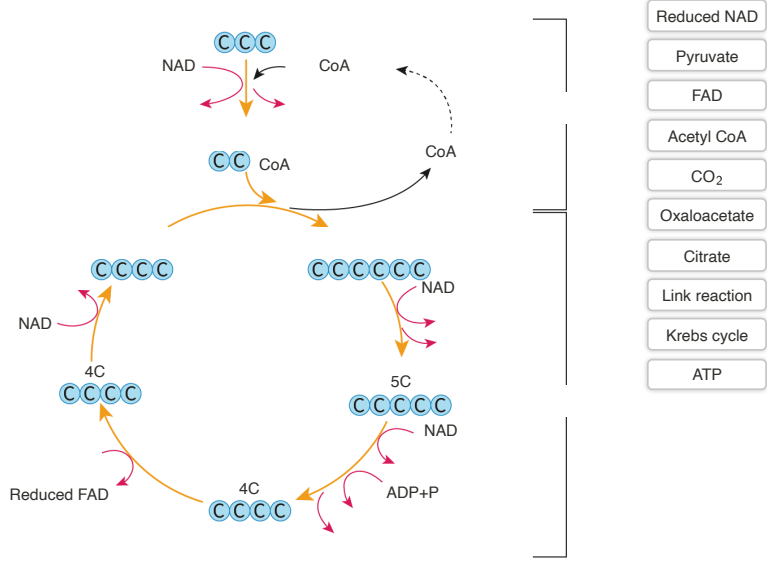

Check

5. **Interactive 1.** The Krebs Cycle.

More information for interactive 1

The interactive depicts two interconnected biochemical processes: the Link reaction and the Krebs cycle also known as the citric acid cycle.

At the top, a cluster of three connected light blue circles labeled "CCC" with a drop box on top is provided. The "CCC" cluster is then transformed into a cluster of two connected light blue circles labeled “CC” and is attached to "CoA". This transformation is indicated by a downward orange arrow that, in turn, points towards a drop box. A curved pink arrow on the left side of the orange arrow points from "NAD" towards a drop box. A black arrow on the right of the orange arrow shows an incoming molecule labeled "CoA". A pink arrow points towards a drop box that indicates a leaving molecule. An orange arrow from CC attached with CoA shows that this molecule is entering a new cycle. Before they enter into a new reaction, the CoA gets released, which is indicated by a curved solid black curve. This CoA is connected with another CoA with dotted lines indicating that this CoA joins the first reaction. This set of reactions is bracketed on the right side with a drop box.

A circular pathway is depicted below. It starts with the "CC CoA" molecule from the previous reaction entering and combining with a cluster of four connected light blue circles labeled "CCCC" to form a cluster of six connected light blue circles labeled "CCCCCC", indicated by an orange arrow.

Following the circular pathway clockwise from six connected “CCCCCC” blue circles, an orange arrow points to the 5C CCCCC molecule. A pink arrow on the right of the orange arrow points from "NAD" to a drop box. A second pink arrow below this points to a drop box that indicates a leaving molecule.

An orange arrow from "5C CCCCC" points towards the “4C CCCC” molecule. On the right side of the orange arrow, a pink arrow from "NAD" points to a drop box.

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Another pink arrow points from "ADP plus P" to a drop box. A third pink arrow points towards a drop box indicating a leaving molecule.
An orange arrow points from four connected light blue circles labeled "4C CCCC" to another “4C CCCC” molecule. A pink arrow on the left of the orange arrow starts from a drop box and points towards a "Reduced FAD" label.
Finally, an orange arrow from the "4C CCCC" cluster points towards a "CCCC" molecule. A pink arrow on the left of the orange arrow points from NAD to a drop box.
An orange arrow points from CCCC to CCCCCC indicating the repetition of the cyclic process.
The cyclic process is bracketed on the right side with a drop box.
There are 15 draggable options on the right side of the screen. The options from top to bottom read: Reduced NAD, Pyruvate, FAD, Acetyl CoA, CO_2, Oxaloacetate, Citrate, Link reaction, Krebs cycle, and ATP.
Read below for the solution.
The labels for each reaction within the brackets on the right side are Link reaction and Krebs cycle.
Link reaction starts with Pyruvate, which then releases CO_2. NAD is converted to Reduced NAD. Therefore, CO_2 is given on the right and reduced NAD on the left side of the orange arrow, respectively. Pyruvate is converted to Acetyl CoA, which is indicated in the bottom drop box of the Link reaction.
In the Krebs cycle, the 6-carbon compound is Citrate. And, now moving clockwise, NAD is converted to Reduced NAD, and CO_2 is released. Next, NAD converts to Reduced NAD, ADP plus P gives ATP, and CO_2 is released. Reduced FAD is formed from FAD. Finally, NAD is converted to Reduced NAD and finally forming the 4-carbon compound called Oxaloacetate. This completes the Krebs cycle.

5 section questions

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

Electron transport chain and chemiosmosis (HL)

C1.2.13: Electron transport chain in the mitochondrion (HL) C1.2.14: Generation of a proton gradient along the electron transport chain (HL)

C1.2.15: Chemiosmosis and the synthesis of ATP in the mitochondrion (HL)

Student view

Overview (/study/ap 422-cid-755105/o

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Explain how NAD transfers energy to the electron transport chain (ETC) for the pumping of protons across the inner mitochondrial membrane.
- Describe the establishment of a proton gradient across the inner membrane by the flow of electrons through the ETC.
- Describe the formation of ATP via chemiosmosis.

Now that our original glucose molecule has been completely broken down and we've released all six of the carbons in the form of carbon dioxide molecules, what is next? We still have only produced a small amount of ATP and a bunch of reduced NAD and reduced FAD. How will we use them to get more ATP?

The electron transport chain

Looking back at the previous stages of aerobic cell respiration, we have so far created four molecules of ATP (net of two from glycolysis and two from the Krebs cycle), ten molecules of reduced NAD (two from glycolysis, two from the link reaction and six from the Krebs cycle), and two molecules of reduced FAD (from the Krebs cycle). Along with these we have released six molecules of carbon dioxide, which will be exhaled through the lungs.

The next step involves the use of the ten reduced NAD and the two reduced FAD to generate many more molecules of ATP. For this we move from the matrix of the mitochondria to the inner mitochondrial membrane. Here we find a series of four membrane-bound protein complexes along with two electron carriers collectively called the electron transport chain (ETC) (**Figure 1**).

Student view

Overview (/study/ap 422- cid- 755105/o

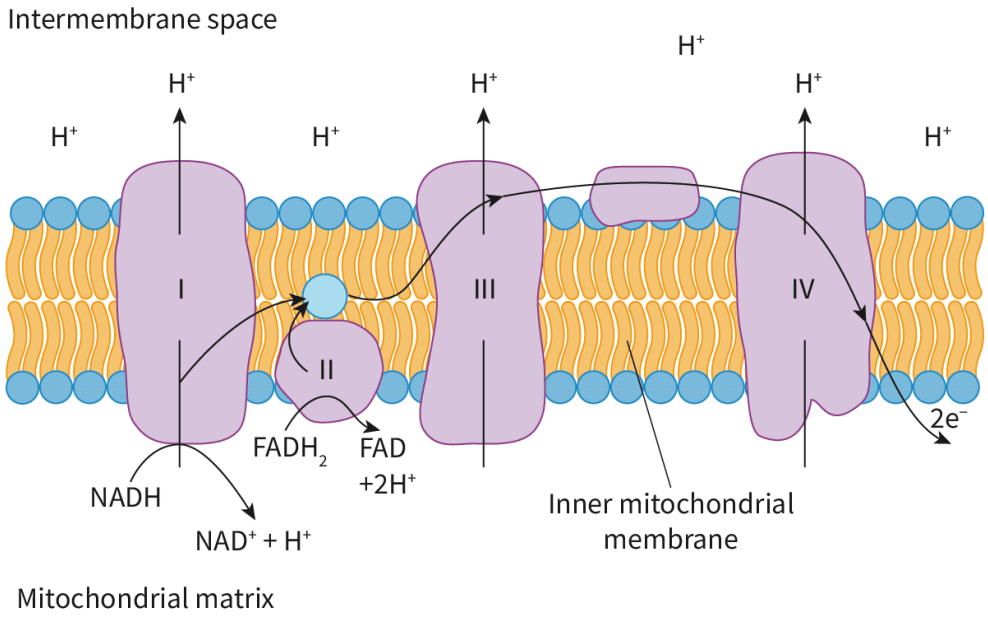

Figure 1. The electron transport chain on the inner mitochondrial membrane. NADH = reduced NAD; FADH = reduced FAD.

More information for figure 1

The diagram illustrates the electron transport chain (ETC) located on the inner mitochondrial membrane. It shows a series of four large protein complexes labeled I to IV, embedded within the membrane. The membrane itself is depicted as a double layer of phospholipids with small blue circles representing the hydrophilic heads.

To the left of the diagram, labels indicate the mitochondrial matrix, and to the right is the intermembrane space. The electron donors NADH and FADH2 are shown delivering electrons to Complexes I and II, respectively. Arrows indicate that NADH is oxidized to NAD+, releasing protons (H+) into the matrix, while FADH2 donates electrons and releases protons in a similar manner.

Electrons are transported between the complexes, with associated arrows showing movement from Complex I, to Complex II, onto Complex III, and finally to Complex IV. As electrons pass through these complexes, protons (H+) are pumped from the mitochondrial matrix across the membrane into the intermembrane space, as depicted by arrows pointing upward. The transfer of electrons and protons is intended to create a proton gradient across the membrane, essential for ATP synthesis.

Text labels indicate various components, such as NADH, NAD+, H+, FADH2, FAD, and electrons (2e-), providing a clear representation of the molecular participants in the electron transport chain.

[Generated by AI]

Reduced NAD delivers two electrons it has carried from glycolysis, the link reaction or the Krebs cycle, to the first protein complex in the ETC. These electrons power the pumping of hydrogen ions (H^+) or protons across the membrane from the matrix to the intermembrane space. The H^+ must be pumped across as the membrane is impermeable to them and they are moving against their concentration gradient. The

Student view

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electrons are transported along the ETC, pumping more H^+ as they go. Reduced FAD also delivers its two electrons to the ETC but does so at the second protein complex and therefore leads to fewer protons being pumped.

Making connections

Membrane transport, including active transport and diffusion, is covered in subtopic B2.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43205/). Diffusion is the net movement of particles from an area of high concentration to an area of low concentration. Active transport is the movement of particles from an area of low concentration to an area of high concentration across a partially permeable membrane. This process uses ATP to power transport proteins which move the particles against their concentration gradient.

Generating a proton gradient along the electron transport chain

The electrons from all ten reduced NAD and two reduced FAD will pump many H^+ across the inner membrane into the intermembrane space. As the space between the inner and outer membranes is small and narrow, and because the protons do not diffuse across membranes on their own, a high concentration of protons is established in the intermembrane space. This forms a proton gradient across the inner membrane with the high concentration on the intermembrane side and the low concentration on the matrix side of the membrane.

It is this gradient that is the key to the production of the remaining ATP. The H^+ want to move down their concentration gradient but as they cannot move across the membrane on their own they are blocked. You can think of the membrane as a dam and the H^+ as the water held behind it.

Chemiosmosis and the synthesis of ATP in the mitochondrion

The H^+ have one path to follow to move back across the inner membrane and down their concentration gradient. This is through a specialised protein channel called ATP synthase (**Figure 2**).

Student view

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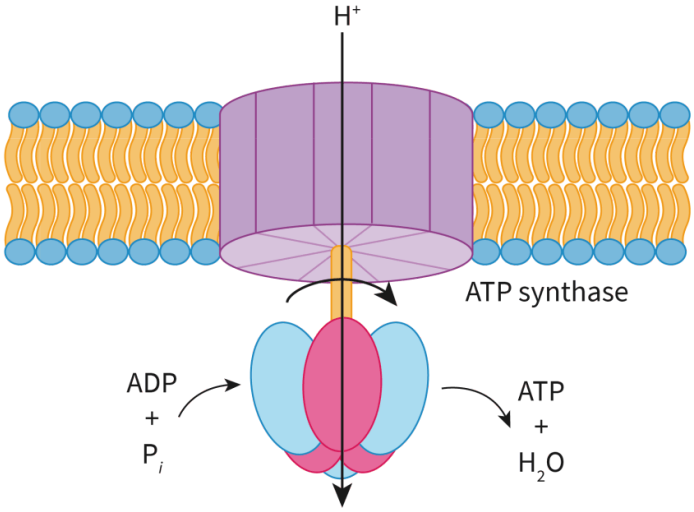


Figure 2. ATP synthase.

More information for figure 2

The image shows a schematic diagram of ATP synthase, which is embedded in a membrane. The membrane is depicted with a series of lipids forming a bilayer. An H+ (proton) is shown moving through the ATP synthase complex, which resembles a cylindrical rotor spanning the membrane. As protons move through, they cause a rotation represented by arrows in the diagram. This rotation drives the conversion of ADP and inorganic phosphate (Pi) into ATP and water (H2O). The conversion is illustrated with ADP and Pi entering as inputs and yielding ATP and H2O as outputs. The diagram highlights the flow of protons and the mechanical rotation necessary for ATP synthesis, emphasizing the enzyme's role in energy production through chemiosmosis and oxidative phosphorylation.

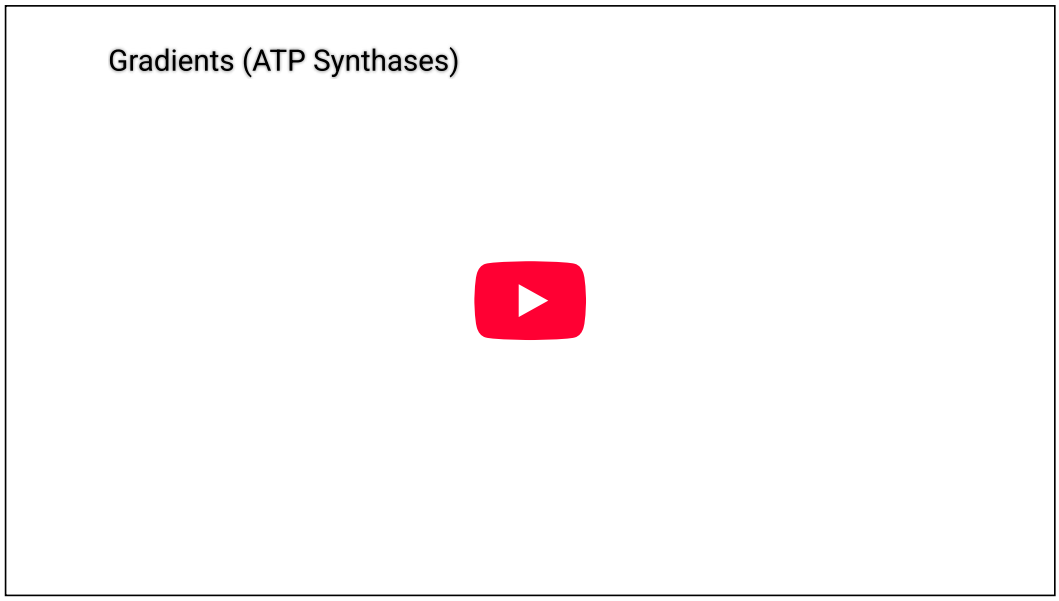
[Generated by AI]

This flow of protons, known as the proton motive force, generates the energy required to phosphorylate ADP using inorganic phosphate (Pi) to form ATP. This method of generating ATP is called oxidative phosphorylation. The ATP synthase has a structure on it that rotates like a turbine. As the H^+ flow through, it rotates and generates the ATP. Again this can be compared with a dam, allowing water through gates and across turbines, which spins those turbines and generates electricity. This flow of protons down their electrochemical gradient is called chemiosmosis. It is thought that three H^+ are used to phosphorylate each ADP to ATP but estimates range from two to four in most cases.

Watch **Video 1** to see a simulation of how ATP synthase generates ATP.

Student view

Overview (/study/ap 422-cid-755105/o



Video 1. A demonstration of how ATP synthase generates ATP through the flow of protons down their concentration gradient.

Nature of Science

Aspect: Falsification

Why does falsification of an established theory not always lead to the immediate acceptance of a new theory?

Until 1978, production of ATP by respiration was believed to be a direct consequence of the transfer of phosphate groups from molecules in the respiratory pathway to ADP. In 1961, Peter Mitchell proposed the chemiosmotic theory linking the mitochondrial membrane and electron transport to ATP synthesis. This was a paradigm shift, a radical departure from the previous theory and, as such, met considerable resistance. His theory was initially disregarded, as the previous theory seemed to explain the observed facts. This led to almost 20 years of 'Chemiosmotic Wars', eventually leading to the acceptance of his theory following new evidence. He received the Nobel Prize for his discovery 17 years after his original proposal. In his speech at the Nobel Banquet he said, 'Meanwhile, the originator of a theory may have a very lonely time, especially if his colleagues find his views of unfamiliar nature, and difficult to appreciate. The final outcome cannot be known, either to the originator of a new theory, or to his colleagues and critics, who are bent on falsifying it. Thus, the scientific innovator may feel all the more lonely and uncertain.'

Student view

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Table 1 summarises the different stages of cell respiration and the overall net yield of ATP. The totals are still estimates based on the best evidence available. While 38 ATP appears to be the theoretical maximum yield, new evidence suggests the actual yield is likely between 30 and 34 molecules of ATP due to the costs associated with the transport of molecules into and out of the mitochondria.

Table 1. Stages of cell respiration and the overall net yield of ATP.

Process	Location	Carriers formed (per glucose)	Net ATP yield (per glucose)
Glycolysis	Cytoplasm	2 reduced NAD	2 ATP via substrate-level phosphorylation
Link reaction	Mitochondrial matrix	2 reduced NAD	
Krebs cycle	Mitochondrial matrix	6 reduced NAD 2 reduced FAD	2 ATP via substrate-level phosphorylation
Electron transport chain	Across inner mitochondrial membrane and intermembrane space	3 ATP per reduced NAD 2 ATP per reduced FAD	30 ATP + 4 ATP via oxidative phosphorylation
ATP used for transport of molecules into and out of mitochondria			4—8 ATP
Total (approximate)			30—34 ATP

Watch **Video 2** for an overview of the electron transport chain and chemiosmosis.

Student view

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Video 2. A walkthrough of the electron transport chain and chemiosmosis.

Theory of Knowledge

Do the natural sciences rely on any assumptions that are themselves unprovable by science?

Try the activity to summarise your understanding of mitochondria and their adaptations for cell respiration.

Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:**
  - Social skills — Working collaboratively to achieve a common goal
  - Communication skills — Using digital media for communicating information
- **Time required to complete activity:** 30 minutes
- **Activity type:** Pair activity

In pairs, reflect back on subtopic B2.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43532/) or, if not yet covered, read this article about mitochondria (https://www.britannica.com/science/mitochondrion). Discuss how mitochondria are adapted for the efficient production of ATP through aerobic cell respiration. Then, design and produce an infographic on the mitochondria and how its structure is so important to the different processes involved in cell respiration.

This should bring together understandings and concepts from multiple sections of this course. Your completed infographics should be shared within your class and peer feedback given. A tool such as Padlet (http://padlet.com) would facilitate the sharing and feedback.

5 section questions

The role of oxygen and the cell respiration pathway (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Outline the role of oxygen as the final electron acceptor.
- Outline how carbohydrates and lipids are used differently in the cell respiration pathway.

We have now arrived at the end of our look at aerobic cell respiration, but we have yet to see oxygen. Oxygen is required for aerobic respiration so how has it not yet appeared? We also know that we can get energy from molecules other than glucose. Are they broken down in the same way?

Role of oxygen as terminal electron acceptor in aerobic cell respiration

Once the electrons have passed along the ETC, they need somewhere to go. This is where oxygen finally makes its appearance. Its role is as the terminal electron acceptor of the ETC (**Figure 1**). Each molecule of oxygen (O_2) splits and accepts four electrons and four protons (H^+) becoming two molecules of H_2O in the matrix of the mitochondrion. This allows all of the other processes of aerobic respiration to continue. When oxygen is not present to accept these electrons, more cannot join the ETC, which means NAD and FAD cannot be regenerated by oxidation and therefore there is no longer a supply of NAD and FAD to continue the link reaction and the Krebs cycle. It is almost as though there is a molecular traffic jam in the ETC. This also explains where water, one of the products in the cell respiration equation, comes from. Here it is again as a reminder.

$$\text{glucose} + \text{oxygen} \dashrightarrow \text{carbon dioxide} + \text{water} \ (+\text{ATP})$$

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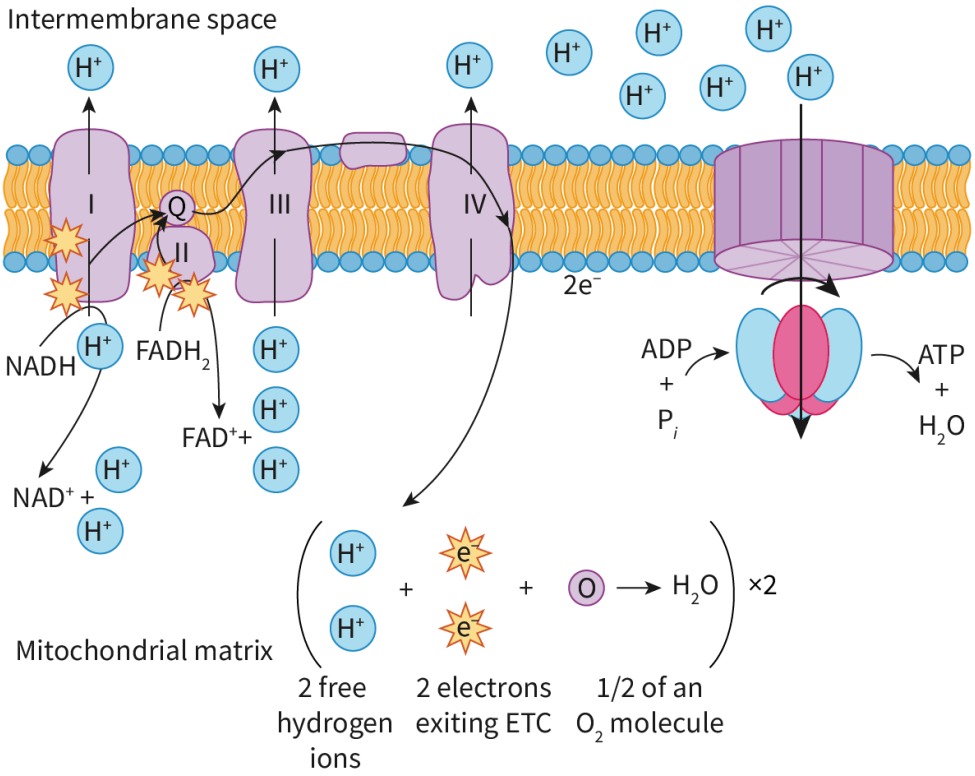

Figure 1. The ETC, ATP synthase and the role of oxygen as the terminal electron acceptor.

NADH = reduced NAD; FADH = reduced FAD.

More information for figure 1

The image is a diagram representing the electron transport chain (ETC) in the mitochondria. It shows the inner mitochondrial membrane with different complexes involved in the process. Key elements include:

1. **Intermembrane Space and Mitochondrial Matrix**: These areas are indicated to frame the location of the ETC.
2. **Complexes I-IV**: These are labeled with Roman numerals I, II, III, and IV. Each complex is shown facilitating the transfer of hydrogen ions (H^+) across the membrane into the intermembrane space.
3. **NADH and $FADH_2$**: These molecules are shown donating electrons to the electron transport chain, represented by arrows showing the flow of electrons through the complexes.
4. **Proton Gradient**: An accumulation of hydrogen ions (H^+) in the intermembrane space is illustrated, showing the creation of a proton gradient.
5. **ATP Synthase**: Depicted adjacent to the complexes, it uses the proton gradient to synthesize ATP from ADP and inorganic phosphate (Pi), releasing water (H_2O) as a byproduct.
6. **Oxygen as Terminal Electron Acceptor**: At the complex IV location, oxygen molecules are depicted accepting electrons accompanied by hydrogen ions to form water.

The diagram comprehensively illustrates the flow and conversion of energy within the mitochondrial inner membrane during cellular respiration.

[Generated by AI]

Student view

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Comparing lipids and carbohydrates as respiratory substrates

Up until now we have only been considering glucose as the respiratory substrate from which we extract the energy to generate ATP. However, we are aware that our cells are also capable of using other carbohydrates and lipids as respiratory substrates.

Different substrates are capable of generating different amounts of ATP. The main property that determines the energy content of a respiratory substrate is the amount of hydrogen available when the molecule is broken down. The more hydrogen, the more NAD can be reduced. The more reduced NAD produced, the more protons can be transported across the inner mitochondrial membrane, generating a greater proton motive force, and therefore more ATP. The disadvantage of this is that more oxygen is then required.

Lipids, which are composed of long chains of carbon with hydrogens, are capable of reducing more NAD than glucose and other carbohydrates.

The comparative energy content of the three main categories of respiratory substrates is given in **Table 1**.

Table 1. Energy content of respiratory substrates.

Respiratory substrate	Energy (kJ/g)
Carbohydrates	15.8
Lipids	39.4
Proteins	17.0

How carbohydrates and lipids are broken down and where they enter the phases of cell respiration also differs. Other carbohydrates like fructose and galactose are able to enter glycolysis although they need to be modified prior to entering the glycolysis pathway. This is often done by the liver. Lipids on the other hand, are unable to be broken down through glycolysis. Due to this, only carbohydrates can be used for anaerobic respiration.

When a lipid molecule is set to be respired, it is first broken down to its component glycerol and fatty acids. The glycerol is able to be used in glycolysis, while the fatty acids are broken down into acetyl groups and through the link reaction become units of acetyl CoA, ready to enter the Krebs cycle.

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These differences in energy content and availability at different stages of aerobic respiration are part of what makes our food choices so important.

International Mindedness

Diets, food choices and food availability are different all over the world. Your culture and where you live in the world will have a large influence on the type of diet you have. Having an understanding of how the food we eat is used to provide our cells with energy can have a positive influence on everyone.

Try the activity to summarise your learning on cell respiration.

Activity

- **IB learner profile attribute:** Reflective
- **Approaches to learning:** Thinking skills — Designing procedures and models
- **Time required to complete activity:** 15—20 minutes
- **Activity type:** Individual or pair activity

Working either individually or in pairs create a concept diagram outlining everything you've learned about cell respiration. This can be done on a large piece of blank paper or using a digital tool such as Coggle (https://coggle.it/) or some presentation software.

Try to make as many connections as you can and add as much detail and useful information as possible. To extend yourself even further, try to make connections to topics and concepts studied earlier in the course. Maybe think about the structure and function of the mitochondria, membrane transport, carbohydrates and lipids, enzymes and metabolism, and nucleic acids. Be prepared to share your concept diagram with your class. Being able to make these connections across the breadth of the IB Biology course is necessary to reach the highest grades.

The word lists below may serve as a starting point but they are not meant to provide all the terms you should be using.

SL word list

Aerobic respiration
Anaerobic respiration
ATP
Bonds
Carbon dioxide

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Cell respiration
Cytoplasm
Energy
Glucose
Hydrolysis
Lactate
Mitochondria
Oxygen
Phosphate
Phosphorylation
Respirometer
Water

HL word list (in addition to SL list)

ATP synthase
Chemiosmosis
Electron transport chain
Electrons
FAD
Fermentation
Glycolysis
Krebs cycle
Link reaction
Lysis
NAD
Oxidation
Oxidative phosphorylation
Protons
Pyruvate
Reduction
Substrate-level phosphorylation

5 section questions

Summary and key terms

Student view

- Adenosine triphosphate (ATP) is the universal energy currency of all cells. It provides the energy for most cellular processes. This includes transport, movement and anabolism. It releases energy when the bond holding the third phosphate is broken forming ADP,

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adenosine diphosphate. When ATP is formed from ADP plus a phosphate group, energy is stored.

- The primary way in which cells produce ATP is through cell respiration. This is the release of energy from respiratory substrates, primarily glucose to generate ATP. This is not to be confused with gas exchange which is the diffusion of oxygen into the blood and carbon dioxide out of the blood via the lungs.
- Cell respiration can be either aerobic or anaerobic. Aerobic respiration produces much more ATP, requires oxygen and produces carbon dioxide and water as waste products. Anaerobic respiration produces only a small amount of ATP, occurs in the absence of oxygen and produces the waste product of lactate in humans or ethanol and carbon dioxide in yeast.
- Several factors can affect the rate of respiration such as temperature, pH and substrate concentration. These can be investigated using a respirometer.

Higher level (HL)

- NAD plays a key role in cell respiration. It is a hydrogen carrier, transporting hydrogen and its electron from earlier phases of respiration to the electron transport chain. It accepts these hydrogens through redox reactions with substrates, oxidising the substrate and being reduced to reduced NAD (NADH).
- The reduced NAD, and reduced FAD molecules complete their roles as hydrogen carriers when they deliver their hydrogen to the electron transport chain on the inner membrane of the mitochondria. The hydrogens are split, with their electrons entering the ETC and the protons pumped across the membrane to the intermembrane space using the energy from the electrons. This establishes a proton gradient across the membrane. The protons diffuse back to the matrix through the ATP synthase complex. This creates a proton motive force used to generate ATP via chemiosmosis.
- Glycolysis is the first step in cell respiration. Molecules of glucose are split and turned into two molecules of pyruvate in a sequence of reactions involving phosphorylation, lysis, oxidation and ATP formation. Glycolysis produces two pyruvate, two ATP and two reduced NAD from each glucose.
- Without oxygen the NAD required to continue glycolysis and ATP production would quickly run out. To avoid this, lactate fermentation in humans and alcohol fermentation in yeast occurs. By converting pyruvate into lactate or ethanol the reduced NAD can be oxidised back to NAD, and return to the glycolysis pathway allowing it to continue. Humans make use of alcohol fermentation in yeast for both baking and brewing.
- The next step of aerobic respiration, following glycolysis is the link reaction. Each pyruvate goes through oxidative decarboxylation, releasing CO_2, reducing an NAD and forming acetate which binds to coenzyme A forming acetyl CoA. This can now enter the Krebs cycle where the acetate binds with oxaloacetate forming citrate. Through the cycle two further oxidative decarboxylations occur and further oxidation to form three reduced NAD, one reduced FAD and one ATP from each acetyl CoA. Two molecules of CO_2 are also released.

Student view

- The final electron acceptor in the ETC is oxygen. The oxygen binds with the electrons and protons forming water. Without this last step, all previous phases of aerobic respiration will stop, which is why oxygen is required.
- Carbohydrates and lipids can both be respiratory substrates. Lipids are actually more energy-dense due to their large amount of hydrogen that can be oxidated. However, the fatty acids of lipids only enter the respiration pathway at the link reaction. This means only carbohydrates are able to be used for anaerobic respiration.

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. The molecule known as the universal energy currency of cells is . When it undergoes , energy is released to carry out a cellular process.
2. Cell respiration can be either with oxygen, or without oxygen. When humans respire without oxygen they produce as a waste product; however, yeast produce and carbon dioxide.
3. The rate of respiration can be measured using a .

ATP | lactate | ethanol | respirometer | anaerobic | aerobic | hydrolysis

Check

Interactive 1. Cell Respiration Key Terms Review.

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Higher level (HL)

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. [HL] is an important hydrogen carrier in cell respiration. It is used in reactions, becoming reduced as it oxidises the substrates.
2. [HL] The first stage of cell respiration is , where glucose is first , then undergoes , before being and used to generate ATP, becoming two molecules of .
3. [HL] Anaerobic respiration may be either alcohol or lactic acid .
4. [HL] Following glycolysis in aerobic respiration is the . Pyruvate undergoes oxidative becoming .
5. [HL] The follows, generating more reduced NAD, ATP and .
6. [HL] All of the reduced NAD and FAD produced carry hydrogen to the chain, a series of protein complexes in the inner mitochondrial membrane, where are pumped across the membrane using the energy in the .
7. [HL] A proton is established and the protons flow back across the membrane through . This produces ATP in a process known as .

protons | Reduced NAD | lysis | redox | gradient | chemiosmosis | acetyl CoA | electrons | electron transport | oxidised | pyruvate | decarboxylation | phosphorylated | Krebs cycle | reduced FAD | ATP synthase | link reaction | fermentation | glycolysis

Check

Student view

Checklist

What you should know

After studying this subtopic you should be able to:

- Explain what ATP is and how it functions as a cell's energy currency.
- Describe processes within cells that use ATP as an energy source.
- Describe the interconversions and energy changes between ATP and ADP.
- Describe cell respiration as the process that produces ATP using energy from carbon compounds and be able to distinguish between cell respiration and gas exchange.
- Distinguish between aerobic and anaerobic respiration.
- Describe the variables that affect the rate of cell respiration and be able to calculate the rate of respiration.

Higher level (HL)

- Explain the role of NAD as a hydrogen carrier in cell respiration.
- Describe the conversion of glucose to pyruvate by the process of glycolysis.
- Describe anaerobic respiration as a means to regenerate NAD, producing lactate as a by-product.
- Describe anaerobic respiration in yeast and how we make use of it for brewing and baking.
- Describe the link reaction and the conversion of pyruvate to acetyl groups.
- Describe the Krebs cycle.
- Explain how NAD transfers energy to the electron transport chain (ETC) for the pumping of protons across the inner mitochondrial membrane.
- Describe the establishment of a proton gradient across the inner membrane by the flow of electrons through the ETC.
- Describe the formation of ATP via chemiosmosis.
- Outline the role of oxygen as the final electron acceptor.

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- Outline how carbohydrates and lipids are used differently in the cell respiration pathway.

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

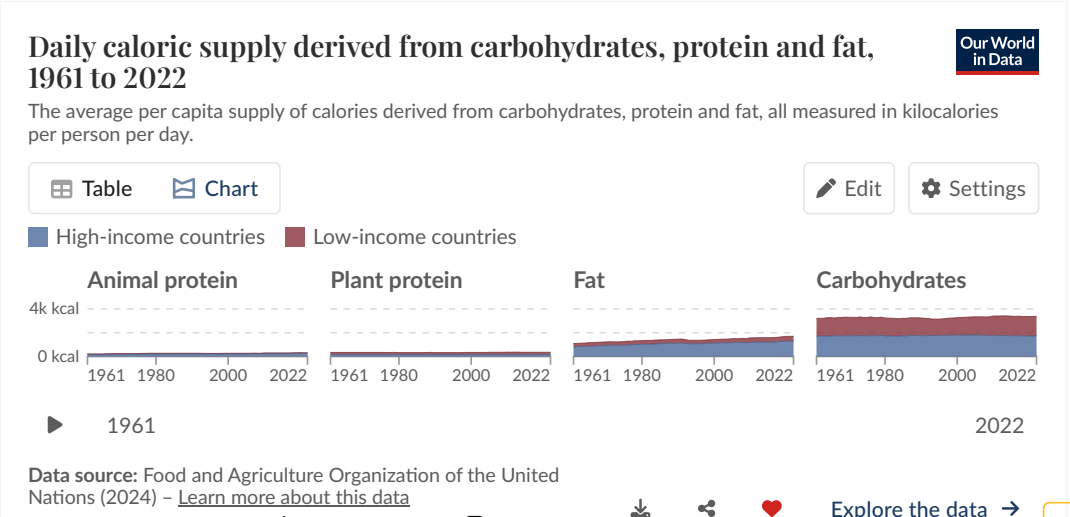
Investigation

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/the-role-of-oxygen-and-the-cell-respiration-pathway-hl-id-45984/print/) Assign

- **IB learner profile attribute:** Thinker
- **Approaches to learning:**
  - Research skills – Evaluating information sources for accuracy, bias, credibility and relevance
  - Thinking skills – Reflecting on the credibility of results
- **Time required to complete activity:** 45 minutes
- **Activity type:** Individual activity

Your task

Compare the diets of some different countries using the data in **Interactive 1**. Start with your own country, then compare with another country from a different part of the world or one at a different stage of economic development. Also have a look at the different food/dietary guidelines (https://www.fao.org/nutrition/education/food-dietary-guidelines/en/) that each country has produced.



Student view

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Overview (/study/ap 422- cid- 755105/o

Interactive 1. Daily caloric supply derived from carbohydrates, protein and fat, 1961 to 2020.

More information for interactive 1

An interactive area chart presents data on the daily caloric supply derived from carbohydrates, protein, and fat from 1961 to 2021. It displays the average per capita supply of calories in kilocalories per person per day, categorized into high-income and low-income countries. The four sections include animal protein, plant protein, fat, and carbohydrates. Both are represented by different shades. The interface allows users to toggle countries and regions on the right side. A timeline slider at the bottom enables selection of specific years. A time-lapse feature is available, allowing users to animate the supply over time.

This interactive highlights differences in dietary composition between high-income and low-income countries from 1961 to 2021. It shows that high-income countries have a greater caloric intake from fats and animal protein, while low-income countries rely more on carbohydrates and plant protein. The data suggests that economic development influences dietary diversity and access to nutrient-rich foods. Understanding these trends can help address nutritional disparities and guide policies for improving global food security and health outcomes.

The data is sourced from the Food and Agriculture Organization of the United Nations (2023). Hovering over any marked point on the graph reveals the supply for the corresponding year for U S and the world. Here is the table for each section, showing daily calorific supply derived from animal protein, plant protein, carbohydrates, and fat from 1961 to 2021.

Year	Animal Protein		Plant Protein		Fat		Carbohydrates	
	High Income	Low Income	High Income	Low Income	High Income	Low Income	High Income	Low Income
1961	178.16	39.10	176.93	168.93	276.06	818.91	1508.11	1714.86
1970	203.91	42.93	179.77	164.48	304.59	939.76	1559.38	1758.37
1980	225.38	48.12	170.15	160.87	313.32	1029.17	1515.97	1751.42
1990	237.91	45.14	172.81	166.88	353.95	1123.06	1516.55	1755.80
2000	243.80	35.01	174.68	171.01	295.67	1195.87	1495.87	1779.46
2010	267.68	41.72	200.48	169.51	380.77	1223.55	1691.74	1727.82
2021	284.96	43.68	195.29	167.59	410.98	1331.60	1653.37	1721.20

Section

Trend analysis

1. Identify any noticeable trends, such as increases, decreases or fluctuations in the consumption of each macronutrient.

Student view

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Discussion and interpretation

1. Analyse the trends observed in the graphs and compare them with known factors that may influence macronutrient consumption, such as cultural shifts, dietary guidelines or health awareness campaigns.
2. Discuss the potential implications of these trends on cellular respiration.
3. Consider the effects of variations in macronutrient consumption on energy production and utilisation within cells.
4. Discuss any potential consequences for human health and well-being.

Conclusion

1. Summarise the findings of the investigation, highlighting the trends observed in the consumption of carbohydrates, protein and fat over the 60-year period.
2. Reflect on the potential implications for cellular respiration and human health.
3. Suggest areas for further research or potential interventions to optimise macronutrient consumption patterns.

Prepare a 5–7 minute presentation for your class on what you have found in your research.

Creativity, activity, service

Strand: Service
Learning outcomes: Demonstrate engagement with issues of global significance

Social media has an incredible influence on hundreds of millions of young people across the globe. You could create a project to raise awareness, invite specialists for talks, school counsellor (well-being advisor) can set up a helpline for students/teens who need support to recognise the dangers of diet-related issues.

C1. Interaction and interdependence: Molecules / C1.2 Cell respiration

Reflection

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Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding question introduced in The big picture (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43538/).

- What are the roles of hydrogen and oxygen in the release of energy in cells?
- How is energy distributed and used inside cells?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

0/2000

Student view

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Submit

Rate subtopic C1.2 Cell respiration

Help us improve the content and user experience.

☆ ☆ ☆ ☆ ☆

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