The big picture

? Guiding question(s)

- In what ways do enzymes interact with other molecules?
- What are the interdependent components of metabolism?

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.

Have you ever heard of PETase – the plastic-eating enzyme? It is naturally produced by a bacterium called *Ideonella sakaiensis* and has the ability to catalyse the breakdown of PET (polyethylene terephthalate) into its monomers (**Figure 1**) in as little as 24 hours!

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

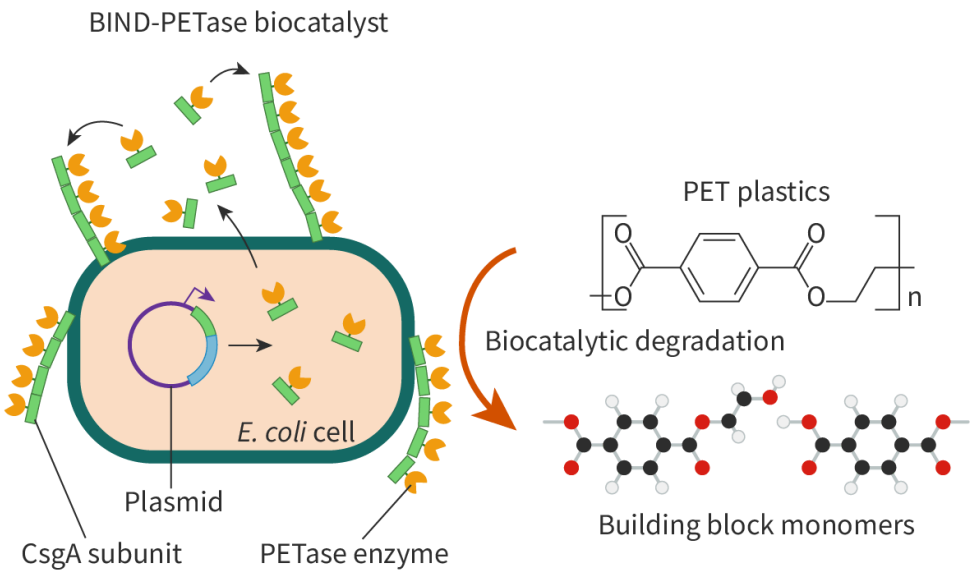

Figure 1. PETase — the plastic-eating enzyme.

More information for figure 1

The diagram shows the mechanism of PETase, a biocatalyst involved in degrading PET plastics. At the center, there is an illustration of an E. coli cell, labeled as such, showing a plasmid within. Surrounding the cell's inner wall are PETase enzymes, depicted by icons with a distinct green and yellow color, performing their function. The outer membrane has CsgA subunits with similar shapes. These components illustrate the process of biocatalytic degradation.

To the right of the cell, there is a structural formula of PET plastics, symbolized by repeated benzene rings with ester linkages, and labeled “PET plastics.” An arrow points from the cell to this structure, labeled “Biocatalytic degradation.” Below this, the breakdown product is depicted as building block monomers, represented by molecular structures with black, red, and white spheres, indicating carbon, oxygen, and hydrogen atoms, respectively.

[Generated by AI]

PET is a plastic polymer commonly used for packaging, but it poses a significant environmental problem as it makes up around 12% of global waste. PET is very durable and takes over 500 years to biodegrade naturally, contributing to the plastic pollution in our oceans and landfills. However, the discovery of PETase provides a ray of hope in the fight against plastic pollution.

Enzymes are molecules that catalyse chemical reactions and increase their rate of occurrence. How exactly do enzymes perform this function?

Student view

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International Mindedness

When it comes to plastic pollution, it is essential to consider the global impact of our actions. The plastic we use and dispose of in one part of the world can end up polluting another. The problem of plastic waste requires coordinated action from individuals, businesses, governments and international organisations to reduce plastic usage, promote recycling and prevent plastic waste from entering the environment.

Prior learning

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

- Definitions of the terms metabolism, monomer, polymer, protein structure, function and effect of temperature and pH on the structure of proteins subtopic B1.2 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43531/).
- Metabolism as one of the functions of life subtopic A2.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43253/).

Practical skills

Once you have completed this subtopic, you can gain application of skills by going to Practical 3: Investigating the activity of enzymes (/study/app/bio/sid-422-cid-755105/book/investigating-the-activity-of-enzymes-id-46694/).

C1. Interaction and interdependence: Molecules / C1.1 Enzymes and metabolism

Enzymes as catalysts

C1.1.1: Enzymes as catalysts C1.1.2: Role of enzymes in metabolism C1.1.3: Anabolic and catabolic reactions C1.1.4: Enzymes as globular proteins with an active site

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/enzymes-as-catalysts-id-46232/print/) Assign

Learning outcomes

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

- Define metabolism.
- Distinguish between anabolism and catabolism and give examples.

Student view

- Describe the structure and role of enzymes.

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

Metabolism

In 1995, Wolfenden reported that without a particular enzyme, creating the building blocks of DNA and RNA would take 78 million years. Knowing how long reactions would take without enzymes allows us to appreciate the role of enzymes in living organisms.

Metabolism is the complex network of interdependent and interacting chemical reactions occurring in living organisms. The metabolic processes in a cell consist of anabolic and catabolic reactions (**Figure 1**).

- Anabolism is the synthesis of complex molecules from simpler molecules; it is a process that requires the input of energy. Anabolism includes the formation of macromolecules from monomers by condensation reactions. For instance, protein and starch are made from amino acids and glucose units, respectively.
- Catabolism is the breakdown of complex molecules into simpler molecules and includes the hydrolysis of macromolecules into monomers. The breakdown of sugars (including glycolysis) or fats to release energy are examples of catabolic reactions. Catabolism is a process during which energy is released.

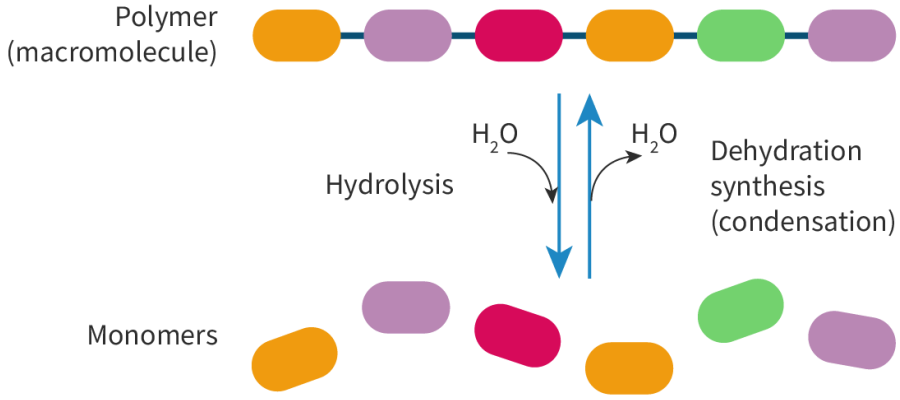


Figure 1. Metabolic reactions.

More information for figure 1

The diagram illustrates the metabolic reactions of polymers and monomers. At the top, there is a chain labeled as "Polymer (macromolecule)," composed of different colored oval shapes connected together. Below the polymer, there are separate oval shapes of the same colors, labeled as "Monomers." Between the polymer and the monomers, there are two arrows showing the direction of reactions. The first arrow pointing downwards is labeled "Hydrolysis," indicating that the

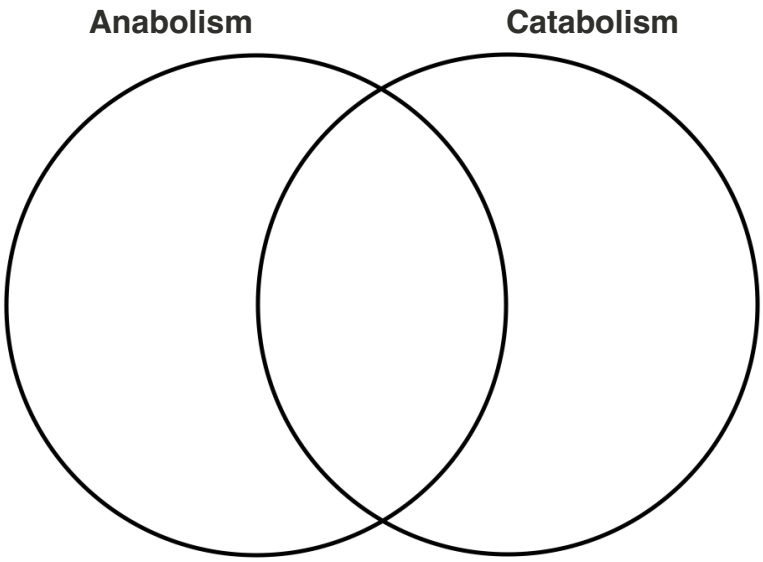
Student view

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

polymer breaks down into monomers with the addition of water (H2O). The second arrow pointing upwards is labeled "Dehydration synthesis (condensation)," showing that monomers join together to form a polymer by removing a molecule of water (H2O).

[Generated by AI]

Complete the Venn diagram in **Interactive 1** to compare anabolism and catabolism.



1 Energy is released
2 Condensation reactions
3 Breakdown of complex into simpler molecules
4 Breakdown of fats to release energy
5 Synthesis of complex from simpler molecules
6 Hydrolysis reactions
7 amino acids → protein; glucose → starch
8 Metabolic reactions catalysed by enzymes
9 Requires input of energy
10 Breakdown of sugars (including glycolysis)

Check

Student view

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Interactive 1. Compare and contrast anabolic and catabolic reactions. [Keep in mind that many catabolic reactions actually require energy to start.]

More information for interactive 1

In this interactive Venn diagram, learners explore the similarities and differences between **anabolism** and **catabolism**, two key types of metabolic pathways. On screen, there are two overlapping circles—**Anabolism** on the left and **Catabolism** on the right—representing how these processes contrast and connect.

Learners are provided with 10 draggable labeled statements, each describing a step or characteristic of metabolic reactions.

1 Energy is released

2 Condensation reactions

3 Breakdown of complex into simpler molecules

4 Breakdown of fats to release energy

5 Synthesis of complex from simpler molecules

6 Hydrolysis reactions

7 amino acids → protein; glucose → starch

8 Metabolic reactions catalysed by enzymes

9 Requires input of energy

10 Breakdown of sugars (including glycolysis)

By analyzing each statement, they must correctly place it in the appropriate section of the diagram: under **Anabolism**, **Catabolism**, or the **shared (overlapping)** region if the characteristic applies to both.

Read below for answers

For anabolism, we have options 2, 5, 7 and 9

For the overlapping region we have option 8

For the Catabolism, we have 1, 3, 4, 6 and 10

Structure and function of enzymes

A catalyst is a substance that increases the rate of chemical reactions but is not changed or used up in the reaction. Catalysts can catalyse chemical reactions over and over without being consumed, and are only needed in small amounts. Enzymes are biological catalysts that speed up metabolic reactions found in all living organisms, including simple organisms such as bacteria. Unlike non-biological catalysts, enzymes are specific and because of enzyme specificity, many different enzymes are required by living organisms. Hence, control over metabolism can be exerted through these enzymes. For example, if a cell produces an enzyme it can catalyse a specific reaction to take place; cells can control the rate of metabolic reactions by producing more or less of the enzyme.

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Enzymes are complex globular proteins with a specific area composed of a few amino acids where the catalytic reaction takes place; this is called the active site. However, it is not only the amino acids that are found in the active site that are important for catalysis. Interactions between amino acids within the overall three-dimensional structure of the enzyme ensure that the active site has the necessary properties for catalysis. The active site is the result of the folding of the polypeptide chain(s). This folding creates the 3D shape that forms the active site, where the substrate interacts with the enzyme (**Figure 2**).

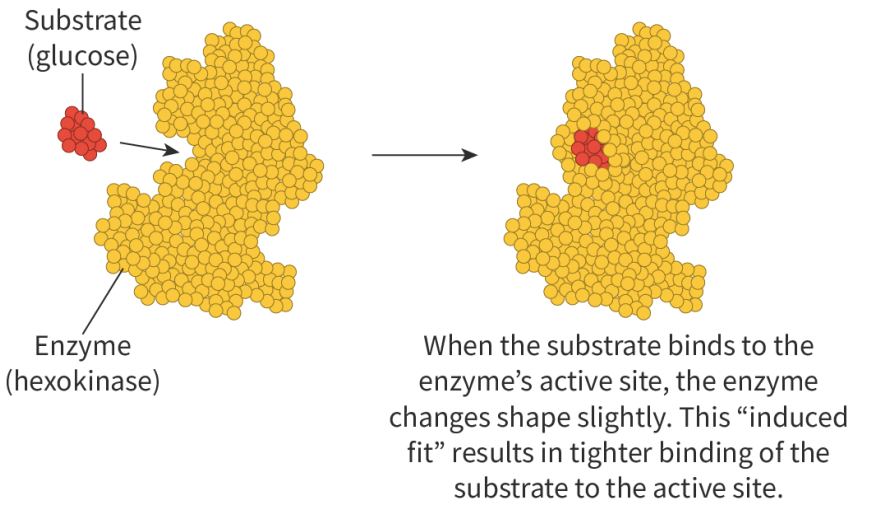


Figure 2. A substrate entering the active site of an enzyme.

More information for figure 2

The diagram illustrates the process of a substrate binding to the active site of an enzyme, specifically hexokinase. On the left side, a loose fitting complex of yellow, circular representations, indicates the enzyme, with a red circular cluster representing the glucose substrate approaching. An arrow points to the right side of the image, showing a similar structure, but with the substrate tightly bound within the enzyme, causing a slight shape change known as "induced fit." This structural modification results in a tighter binding of the substrate to the active site of the enzyme. The diagram also contains labels for the substrate (glucose) and enzyme (hexokinase), and an explanatory text detailing the changes in enzyme shape when the substrate binds.

[Generated by AI]

Making connections

The three-dimensional structure and the function of a protein is a consequence of the interaction between the amino acids in a polypeptide chain (see subtopic B1.2

Student view

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

(/study/app/bio/sid-422-cid-755105/book/big-picture-id-43531/)).

Enzymes catalyse metabolic reactions by binding to a substrate or substrates; this binding takes place at the active site. Chemical and physical properties of the active site match the substrate(s), which allows specific binding to occur.

Watch **Video 1** to learn more about enzymes.

Video 1. Enzymes.

Enzymes can be found in all living organisms, from bacteria to plants to animals. Some enzymes are used by multiple species, while others are unique to a specific organism. Catalase is an enzyme that is used by nearly all organisms exposed to oxygen. Catalase catalyses the breakdown of hydrogen peroxide to water and oxygen.

Practical skills

- **Tool 1:** Experimental techniques — Measuring variables
- **Tool 2:** Technology — Applying technology to collect data

Simulations help you conduct experiments in non-laboratory set-ups, enhance your experimental techniques in a virtual environment and provide rich learning experiences.

Student view

Try the following activity to learn more about catalase.

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

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Experimenting with new strategies for learning
- **Time required to complete activity:** 20 minutes
- **Activity type**: Pair activity

Catalase is an enzyme produced by most living organisms including some bacteria. This enzyme protects bacteria from hydrogen peroxide (H_2O_2), which can damage and kill bacterial cells. Catalase converts hydrogen peroxide into liquid water (H_2O) and oxygen gas (O_2). As a result, if catalase is present and in the presence of hydrogen peroxide, the rapid production of oxygen gas (O_2) can be observed by forming bubbles.

Chemical reaction catalysed by catalase:

$$2H_2O_2 \xrightarrow{\text{Catalase}} 2H_2O + O_2$$

The simulation Catalase Test (msu.edu) (https://learn.chm.msu.edu/vibl/vibl/Catalase/catalase_HTML5Canvas.html) can be used to distinguish catalase-positive bacteria from catalase-negative bacteria.

1. View the menu of the simulation.
2. Read the description of the activity.
3. View the steps of the experiment.
4. Press start.

Answer the following questions:

1. State the name of the substrate and the product(s) in the above chemical reaction.
2. State the independent variable and three controlled variables in the experiment.
3. Outline how the qualitative data collected could support a valid conclusion.
4. Suggest a method for measuring the generation of oxygen gas.
5. Outline the evidence of awareness of safety and environmental implications in the experiment.
6. Summarise the outcome, support with data and explain using correct scientific reasoning.

Student view

The mechanism of enzymes

C1.1.5: Induced-fit binding between substrate and active site C1.1.6: Substrate-active site collisions in enzyme catalysis

C1.1.7: Active site structure, specificity and denaturation

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/the-mechanism-of-enzymes-id-46233/print/) Assign

Learning outcomes

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

- Describe the mechanism of enzyme catalysis.
- Describe the role of molecular motion and substrate—active site collisions in enzyme catalysis.
- Explain the relationship between the structure of the active site, enzyme—substrate specificity and denaturation.

One of the fastest enzymes is acetylcholinesterase, which is found in the synapses of nerves and muscle fibres. It breaks down acetylcholine to choline and an acetate group. Acetylcholinesterase can catalyse up to 3×10^7 molecules of acetylcholine per minute!

The role of molecular collisions

Enzyme and substrate reactions usually take place in a watery environment, where the enzymes and substrate mix and bump into each other. These collisions allow the substrate to bind to the active site on the enzyme so that the reaction can proceed. An enzyme's active site is where specific substrates can attach. The active site and the substrate should collide in the correct orientation and with enough energy for the reaction to start.

The following equation shows this:

$$E + S \dashrightarrow ES \dashrightarrow EP \dashrightarrow E + P$$

(E: Enzyme; S: Substrate; P: Product)

Although molecular motion and collisions between the substrate and the active site are needed to catalyse the chemical reaction, there are some exceptions:

- Sometimes substrate molecules are immobilised when required. In this case the enzyme has to move in relation to the substrate. Examples of this are the enzymes that catalyse the formation of the peptide bond between amino acids.
- Sometimes enzymes can be immobilised by being embedded in membranes when required. In this case the enzyme cannot move and the substrate has to move. Many industrial enzymes are made immobile to increase their stability and reusability.

Watch **Video 1** to learn more about the collision theory.

Video 1. Collision theory.

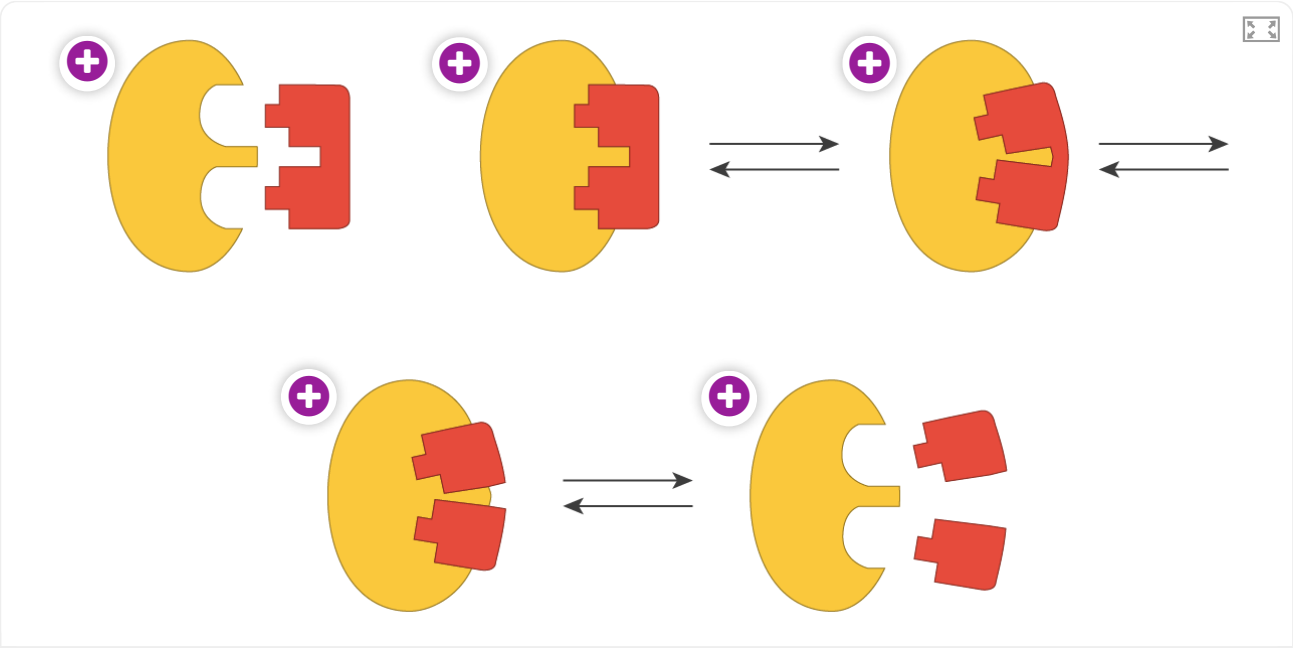
The induced fit model

The reaction that converts the substrate into products occurs at the active site of the enzyme.

- When the substrate binds with the active site, it triggers a change in the three-dimensional shape of the enzyme that allows a tighter fit (**Interactive 1**). This is called an induced fit and is possible because of the flexibility of the protein molecules that make up the enzyme; one enzyme can bind to one substrate.
- When the enzyme and substrate(s) fit together tightly, the enzyme induces the weakening of bonds within the molecules of the substrate(s), thus reducing the activation energy needed for the reaction; the reaction could be anabolic or catabolic. Activation energy will be discussed in more detail later in this subtopic.

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

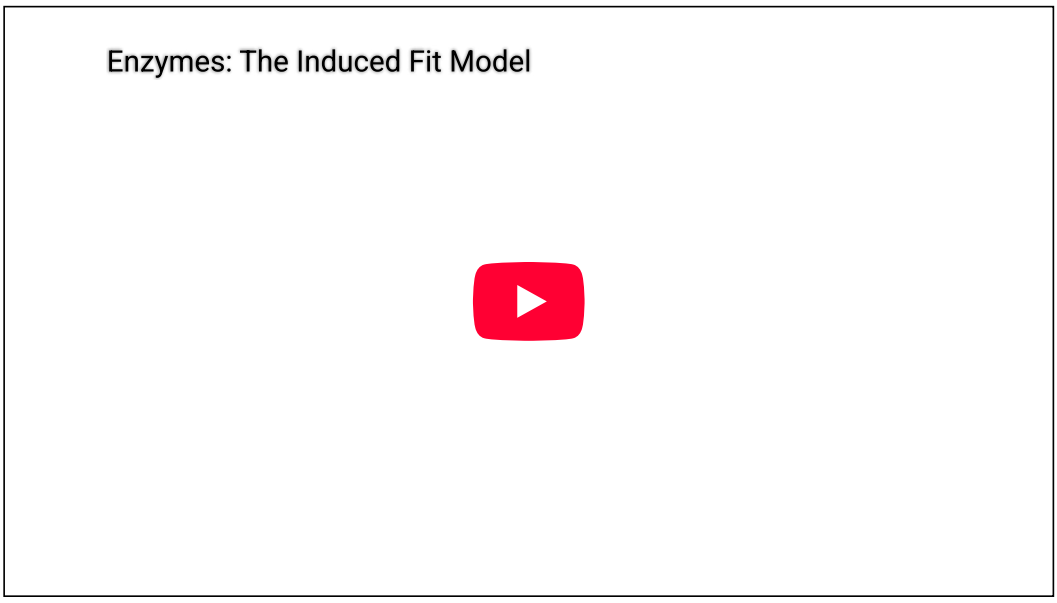
- When the enzyme-catalysed reaction is completed, the substrate(s) is converted to products and the product (s) are released from the enzyme.
- The enzyme's active site goes back to its original shape and is now empty, and can bind another substrate (**Interactive 1**).



Interactive 1. The Induced Fit Model.

More information for interactive 1

Watch **Video 2** to learn more about the induced fit model.

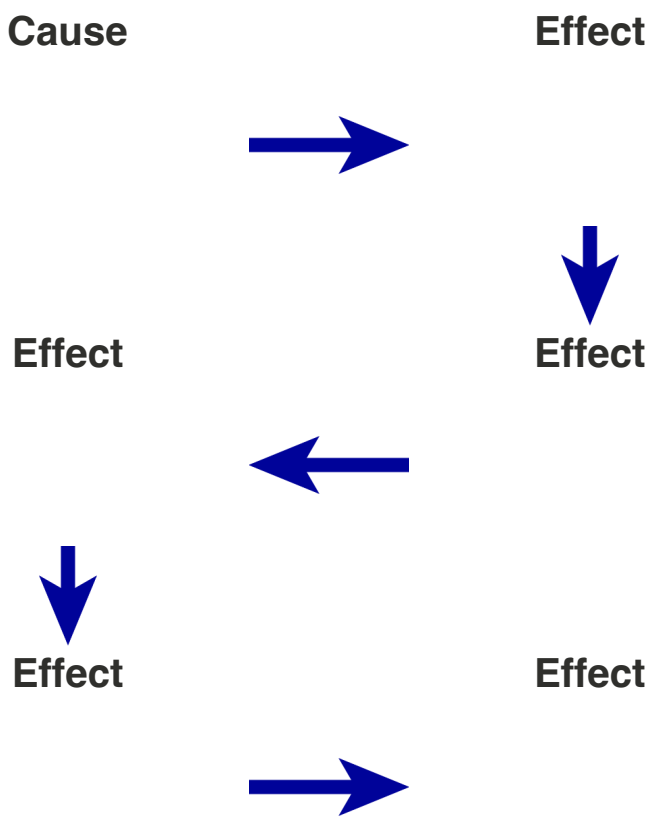


Video 2. The induced fit model.

Student view

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

Complete the concept diagram in **Interactive 2** to organise the steps involved in enzyme catalysis according to the induced fit model.



The enzyme induces the weakening of the bonds within the molecules of the substrate(s).	The substrate enters the active site and binds to it.	The product(s) are released from the enzyme.
The active site goes back to its original shape and is available to bind to other substrate(s).	The substrate changes into product(s).	The substrate triggers a change in the three-dimensional shape of the enzyme that allows a tighter fit.

Check

Interactive 2. The induced fit model cause and effect concept diagram.

More information for interactive 2

Theory of Knowledge

How can it be that scientific knowledge changes over time?

Student view

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

In science, a theory is an explanation that has been tested and verified using scientific investigations. Theories represent our best explanations for natural phenomena and are the result of systematic observation, experimentation and analysis. Theories are not mere speculations but are supported by substantial evidence. They undergo critical evaluation, peer review and refinement, allowing them to evolve and adapt as new information emerges.

There are two theories that explain the mechanism of enzymes; the induced fit theory has replaced the lock and key theory. According to the lock and key hypothesis, the enzyme functions as a lock while the substrate functions as a key. There is a perfect matching between both components. The induced fit model suggests that a substrate is capable of inducing a change of the active site that will enable the enzyme to perform its catalytic function. The active site can slightly change its shape to fit a substrate.

Enzyme—substrate specificity

Enzymes exhibit specificity due to the matching chemical and physical properties between the substrate and the active site. However, the level of enzyme–substrate specificity can vary. Certain enzymes are capable of binding to a single substrate exclusively, while others can bind to a range of similar substrates.

Enzymes are proteins, and can be denatured. Denaturation can be caused by extreme pH, heat and the presence of heavy metals. Denaturation is usually an irreversible change to a protein, meaning that it can no longer function. For instance, soluble proteins become insoluble or precipitate out after being denatured, as is the case when you boil or fry an egg.

Denaturation destroys the tertiary or quaternary conformation of a protein. In some cases, when the temperature is high enough or the pH is extreme, the secondary structure of a protein can be altered. When there is only a minor temperature increase or change in pH, it is possible that the denaturation is still reversible and the protein can fold back to its original and functional conformation.

Put your newly acquired knowledge into action by undertaking the following activity which involves lactase, an enzyme responsible for breaking down lactose, a type of sugar found in mammalian milk.

Student view

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

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Lactose is a naturally occurring disaccharide present in mammalian milk and dairy products such as cheese and yoghurt. It consists of two monosaccharides: glucose and galactose. Lactase belongs to the beta-galactosidase family that can break down lactose into monosaccharides. It is produced by cells in the lining of the small intestine and is immobilised in the intestinal epithelial cells (**Figure 2**).

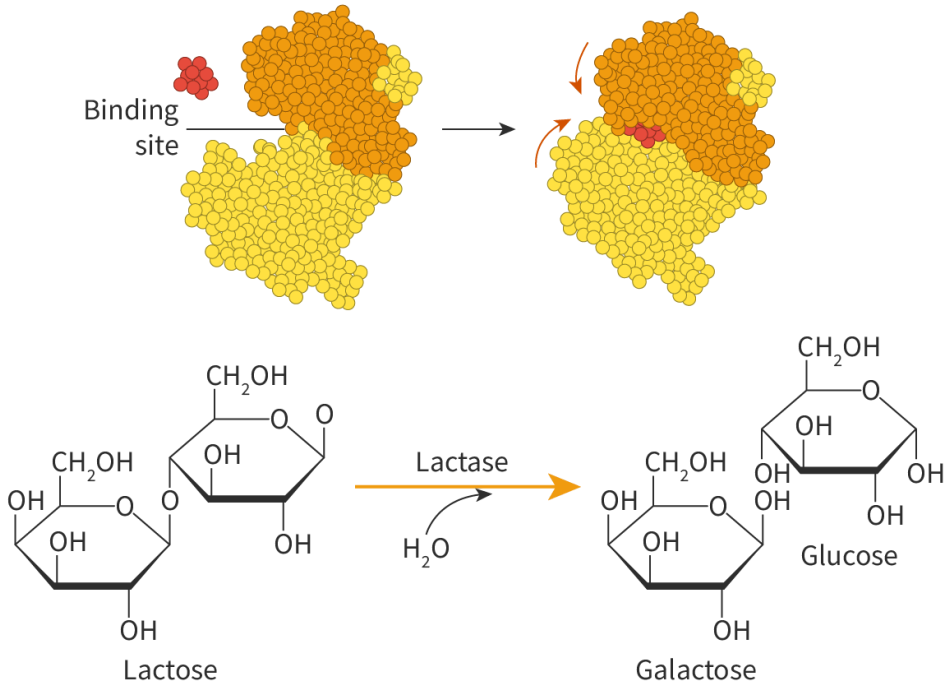


Figure 1. Lactose is broken down into glucose and galactose by lactase.

More information for figure 1

The image is a diagram illustrating how the enzyme lactase breaks down lactose into glucose and galactose. At the top of the diagram, there is a representation of lactase with labeled binding sites, depicted as a clustering of yellow and orange spheres. An arrow indicates the movement or interaction at the binding site. Below this, chemical structures are shown: lactose on the left, with its two linked hexagonal rings labeled with chemical groups (e.g., CH2OH, OH), and on the right, the split result into glucose and galactose, each retaining one of the hexagonal rings. An arrow labeled 'Lactase' and 'H2O' points from the lactose structure to the separated glucose and galactose structures, indicating the enzymatic action and involvement of water in the breakdown process.

[Generated by AI]

Student view

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

1. State whether the above reaction is anabolic or catabolic, Justify your answer.
2. State the name of the substrate(s), enzyme and product(s).
3. Explain the induced fit model by referring to the example in **Figure 1**.
4. Outline the effect of lactase immobilisation in relation to molecular motion and collisions.
5. Describe the consequence of exposing lactase to extreme temperature on the enzyme specificity.
6. A study investigated the relative activity of free beta-galactosidase against immobilised beta-galactosidase. Interpret the study data as given in **Figure 2** and compare the relative activity of both enzymes.

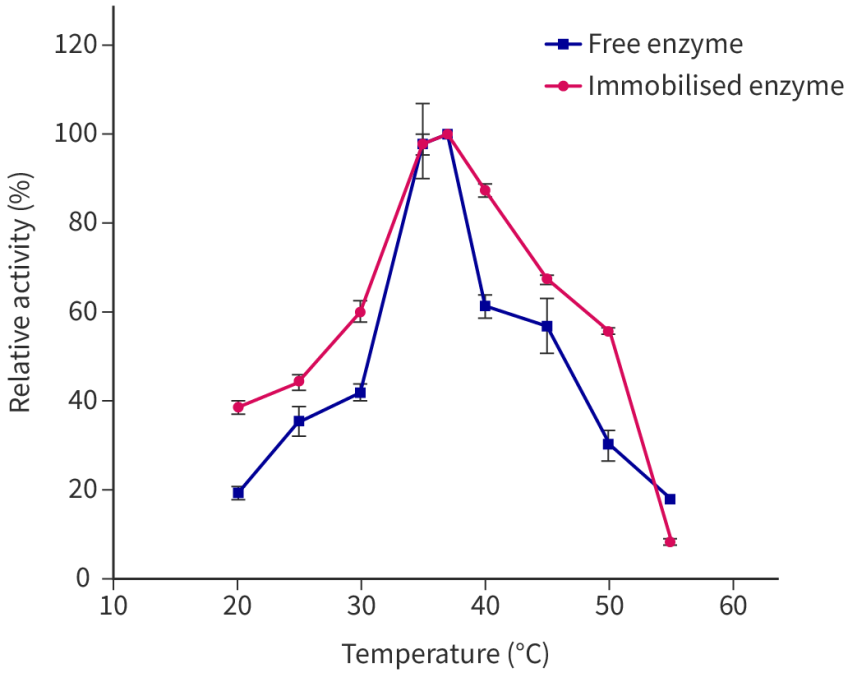


Figure 2. The effect of temperature on activity of free and immobilised beta-galactosidase.

More information for figure 2

The image is a line graph comparing the relative activity of free and immobilised beta-galactosidase enzymes against temperature. The X-axis represents temperature in degrees Celsius, ranging from 10°C to 60°C. The Y-axis represents relative activity in percentage, ranging from 0% to 120%.

Two lines are plotted: one in blue for 'Free enzyme' and another in red for 'Immobilised enzyme'. Both lines start at lower activity levels around 20°C, increase and peak at different temperatures, and then decrease. The blue line peaks at around 40°C reaching slightly above 100% activity, while the red line peaks slightly earlier at around 35°C and reaches slightly below 100% activity. Both enzymes demonstrate a drop in activity beyond their peak temperatures, with the red line declining more sharply.

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Student view

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

5 section questions

C1. Interaction and interdependence: Molecules / C1.1 Enzymes and metabolism

Thermodynamics of enzymes

C1.1.8: Factors affecting the rate of enzyme activity C1.1.9: Measurements in enzyme-catalysed reactions

C1.1.10: Effect of enzymes on activation energy

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/thermodynamics-of-enzymes-id-44899/print/) Assign

Learning outcomes

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

- Explain the effect of enzymes on the activation energy.
- Explain the effect of temperature, pH, substrate concentration on enzyme activity.
- Determine reaction rate through experimentation and secondary data.

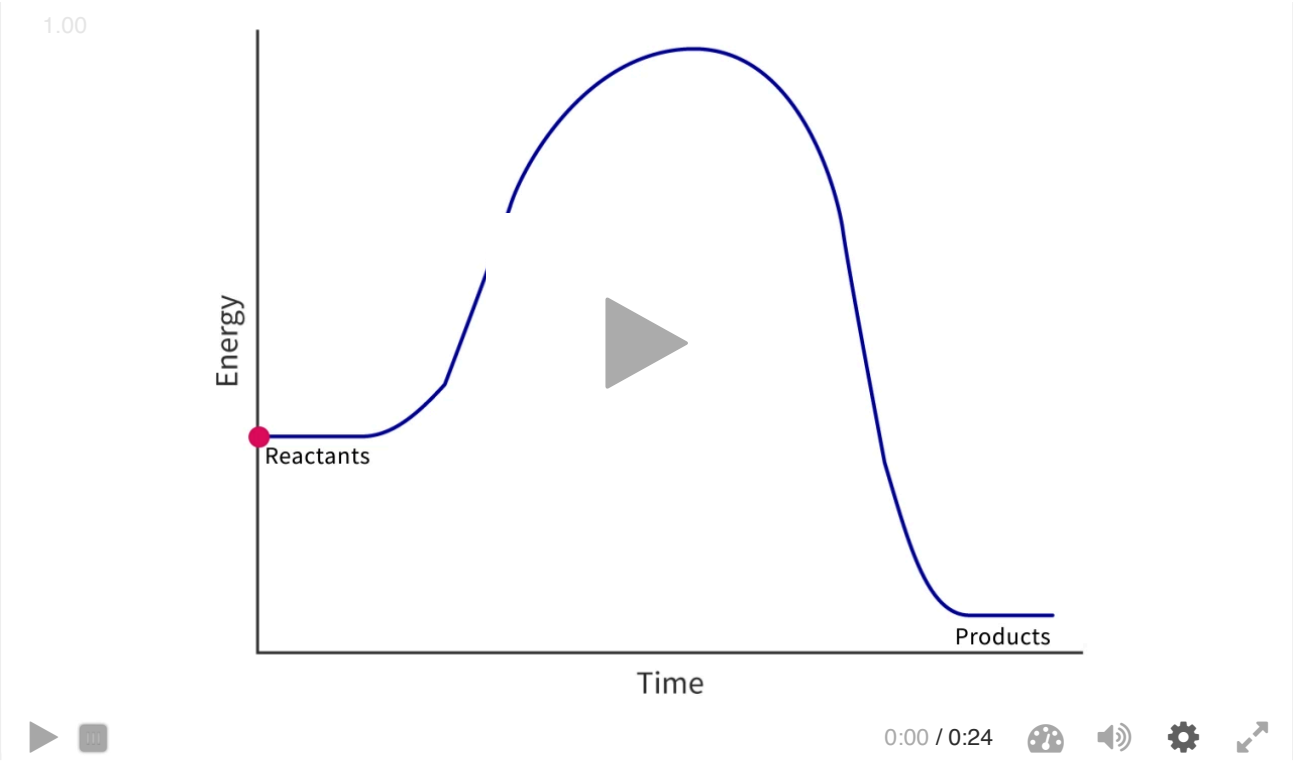
Thermodynamics of enzymes

Imagine that you have to jump over a rope. It is rather high and you could jump it, but with great effort. A teacher (enzyme) lowers the rope, and now jumping over it becomes a lot easier and quicker. How do enzymes facilitate reactions, making them easier and quicker? In this section you will learn more about how enzymes work and the factors that affect enzyme activity.

Chemical reactions take place in more than one step; in order for the substrate to be converted to products it should pass through a transition state. The activation energy is the minimum amount of energy needed to reach the transition state in which the bonds in the substrate(s) are broken and then the reaction continues to form the products (**Interactive 1)**.

Student view

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



Interactive 1. Catalyzed Chemical Reactions.

More information for interactive 1

The interactive is a graph representing an energy diagram showing reactants, transition state (peak representing activation energy), and products over time. It illustrates the minimum energy required (activation energy) to break substrate bonds and form products. Labels include energy levels, reactants, products, and a progression time frame.

Clicking on the play button triggers a time-lapse animation, dynamically revealing labels and curves. Labels appear sequentially to explain each stage (e.g. activation energy, enthalpy, and catalyst). The vertical axis (energy) shows energy changes during the reaction and the horizontal axis (Time) represents the progression of the reaction.

The reaction begins with reactant molecules at a higher energy and the resulting products have lower energy. A label reads “activation energy: bonds are broken” highlighting the energy barrier required to initiate the reaction. The curve rises to a peak representing the transition state where reactant bonds are broken before forming products. This peak signifies the uncatalyzed pathway’s high activation energy, the minimum energy needed for the reaction to proceed.

After the transition state, the curve descends to a lower energy level, representing the products. A label reads “enthalpy”, explaining that enthalpy change is independent of activation energy, and if products are lower, enthalpy is negative. A new label appears and reads “Now add a catalyst.” Catalysed Pathway is introduced next. A second lower curve is introduced, representing the catalyzed pathway. The catalyst reduces the activation energy (lower peak), making the reaction faster and more efficient. A label clarifies “Now add a catalyst. Activation energy for the catalyzed pathway is less than the uncatalyzed pathway”. A second, lower curve appears, showing the catalyzed pathway with reduced activation energy.

The final stage of the interactive is a comparison of the “uncatalyzed pathway” and “catalyzed pathway”. It provides a comparative energy profile for uncatalyzed (higher activation energy) and catalyzed (lower activation energy) reaction pathways.

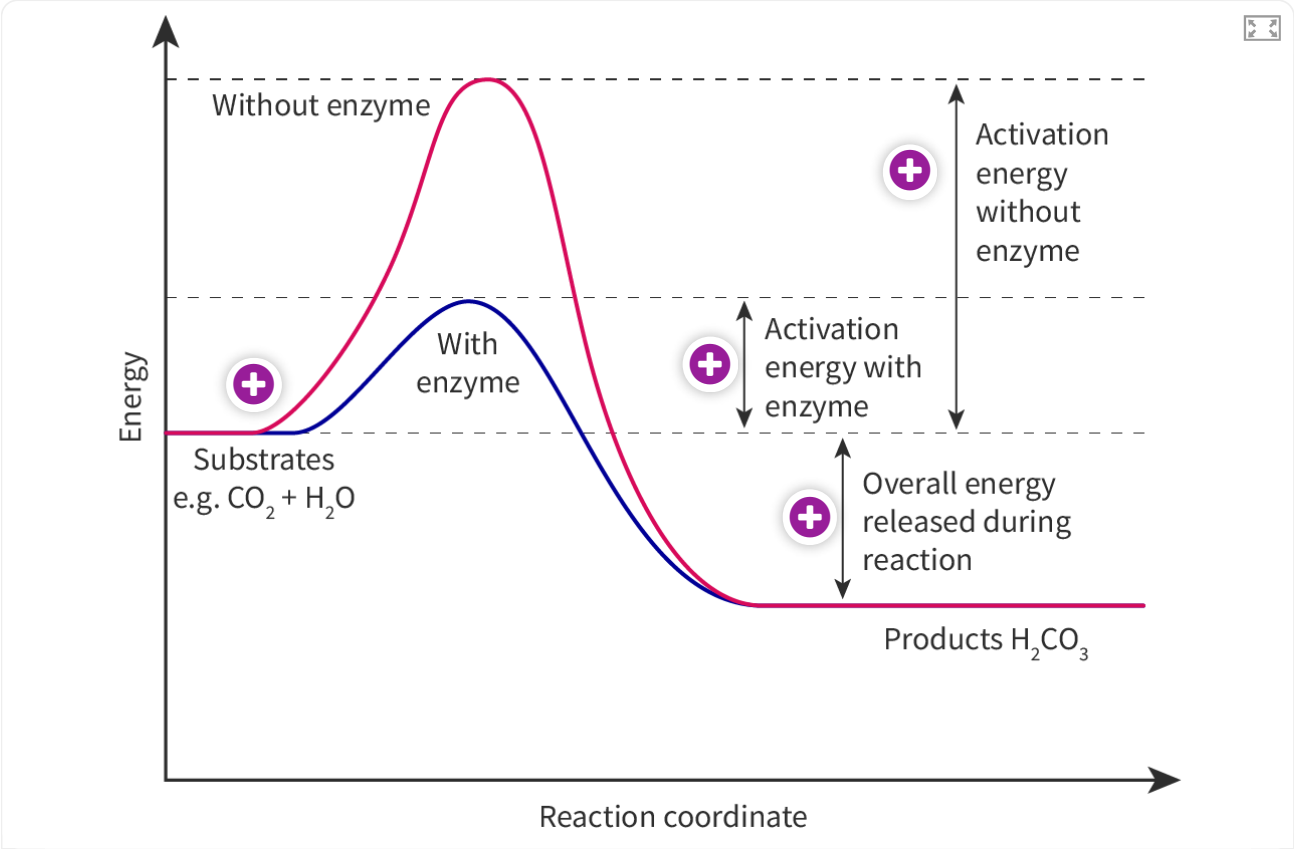
It demonstrates how catalysts accelerate reactions without altering thermodynamics. It emphasizes the role of transition states and activation energy in reaction kinetics.

Student view

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

Interactive 2 shows the same reaction both catalysed and uncatalysed by an enzyme; note the following:

- The initial energy of the substrate(s) is the same in both reactions (catalysed and uncatalysed).
- The energy of the product(s) is the same in both reactions (catalysed and uncatalysed).
- The overall energy released during the reaction is the same in both reactions (catalysed and uncatalysed). Note that the reaction shown in the diagram is exothermic as there is a release of energy.
- The activation energy needed to reach the transition state is lower in the catalysed reaction compared with the uncatalysed reaction. This is due to binding of the substrate to the active site, which helps to weaken the bonds in the substrate(s) therefore increasing the reaction rate.



Interactive 2. How an Enzyme Lowers the Activation Energy of a Reaction.

More information for interactive 2

The interactive graph illustrates the difference between an uncatalyzed reaction and an enzyme-catalyzed reaction while focusing on energy changes during the process. The vertical axis represents the energy levels of the molecules involved and the horizontal axis represents the reaction coordinate and shows the progress of the reaction from substrates to products.

Student view

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

The uncatalyzed reaction, labeled “without enzyme”, is represented by a red curve. This pathway has a high energy barrier (activation energy without enzyme). Substrates (e.g. $CO_2 + H_2O$) require a large amount of energy to reach the transition state. The reaction is slower due to the large energy requirement.

The catalyzed reaction, titled “with the enzyme”, is represented by a blue curve. This pathway shows a lower energy barrier. The enzyme reduces the activation energy by binding to the substrates at its active site, weakening bonds and speeding up the reaction. The “overall energy released” remains identical. The final energy of the products (e.g. H_2CO_3) is the same in both cases.

The graph contains four hotspots represented by plus signs. Hotspot 1 is present over the substrate. Hotspot 2 is present next to the label activation energy without enzyme. Hotspot 3 is present next to the label activation energy with enzymes. Hotspot 4 is present next to the label overall energy released during the reaction. By clicking on the hotspots it provides further details about each component.

The following items are revealed at respective hotspots:

Hotspot 1: The initial energy of the substrate(s) is the same.

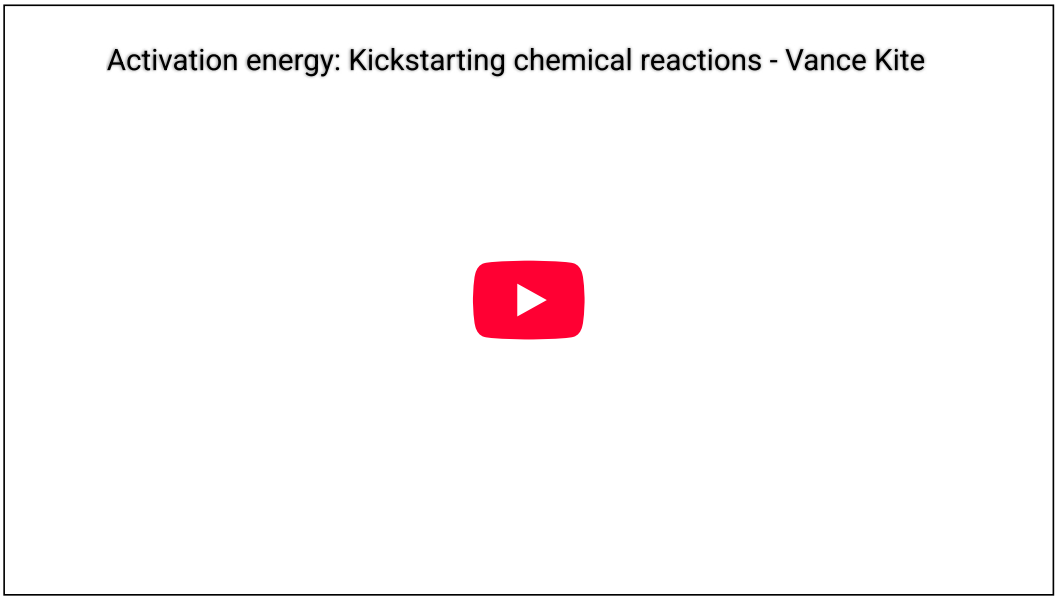
Hotspot 2: The activation energy needed to reach the transition state is much higher without an enzyme.

Hotspot 3: The activation energy needed to reach the transition state is much lower with an enzyme.

Hotspot 4: The overall energy released during the reaction is the same in both reactions.

The interactive explains how metabolic processes occur efficiently in living organisms. Enzymes act as biological catalysts by lowering the activation energy required for a reaction, enabling faster conversion of substrates to products without altering the overall energy change.

Watch **Video 1** to learn more about the effect of enzymes on activation energy.



Video 1. Activation energy.

Student view

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

Factors affecting enzyme activity

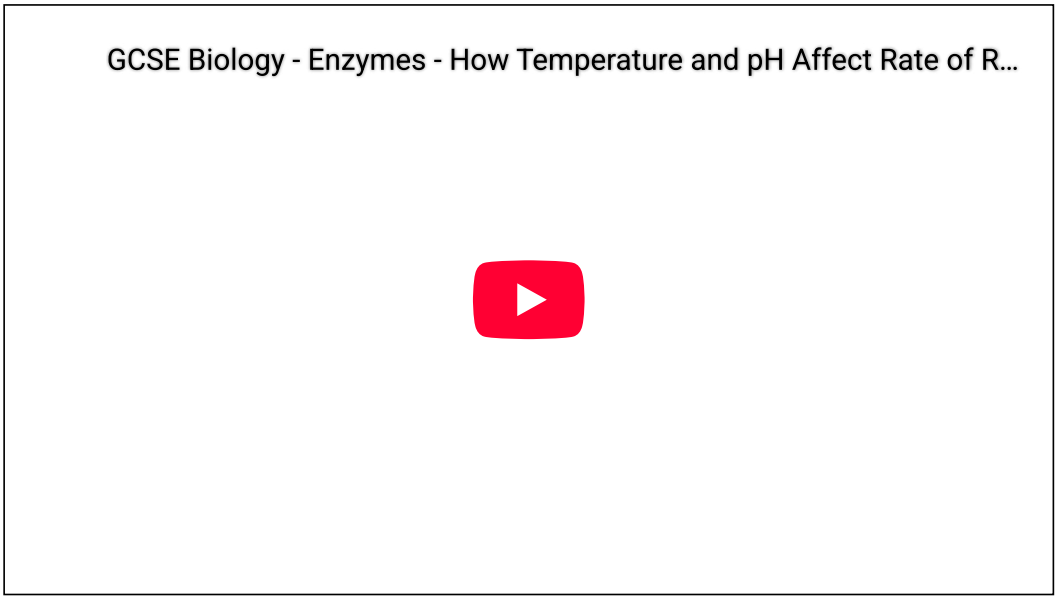
Almost all enzymes are proteins. Therefore, they can be denatured and lose their catalytic properties. The bonds between different amino acids break, causing structural changes to the active site of an enzyme. This can be caused by the following factors:

- temperature
- pH.

The following factors generally affect the rate of enzyme-catalysed reactions:

- substrate concentration
- enzyme concentration.

Watch **Video 2** for an introduction to the factors that affect enzyme activity.



Video 2. Factors affecting enzyme activity.

Effect of temperature

Enzymes are sensitive to temperature changes. When the temperature is low, molecules tend to move slowly. The chance of collision between substrate and enzyme molecules is also low. When the temperature rises, molecules move more rapidly and it is more likely that they will collide with each other. Each enzyme has an optimum temperature in which the rate of enzymatic reaction is the highest. The optimal temperature for human enzymes is around 37 °C. Interestingly, for enzymes in the bacterium *Thermus thermophilus*, which lives in hot springs, the optimal temperature is 65 °C. If the temperature is higher than optimal, an enzyme can be denatured. As a result, the rate of enzymatic reaction rapidly decreases (**Figure 1**).

Student view

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

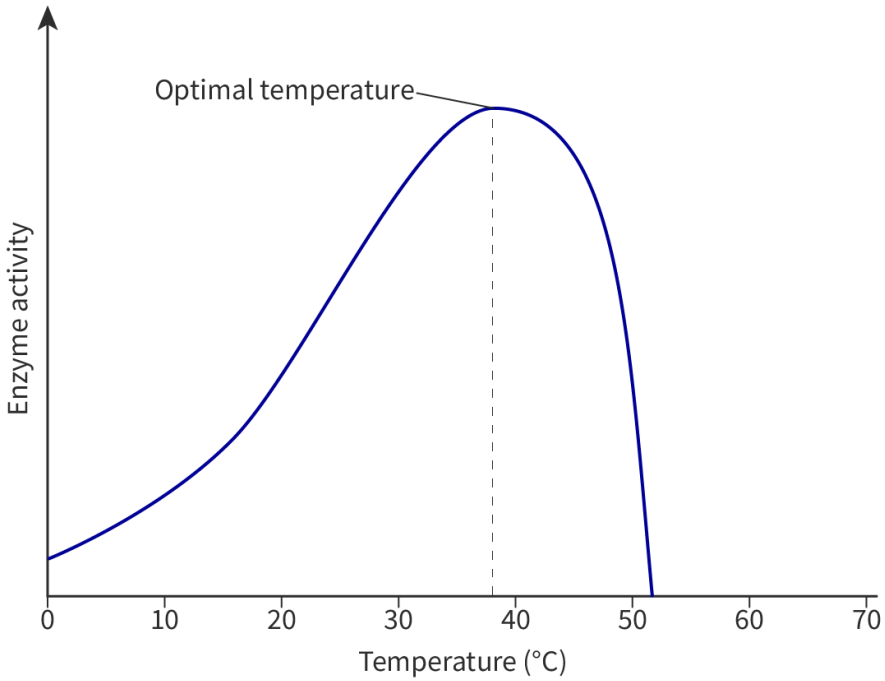


Figure 1. Most enzymes have their optimal temperature around 40 °C.

More information for figure 1

The graph illustrates the relationship between enzyme activity and temperature. The X-axis represents temperature in degrees Celsius, ranging from 0°C to 70°C. The Y-axis indicates enzyme activity. The curve starts near the origin, gradually increases, peaks at around 40°C indicating the optimal temperature, and then declines sharply. The trend shows that enzyme activity rises with temperature up to a point, after which it decreases rapidly, highlighting the denaturation of enzymes at higher temperatures.

[Generated by AI]

Effect of pH

Enzymes work in different environments. Examples include the stomach, where the pH is very low (pH = 2), and the small intestine, which is more alkaline (pH = 7.5). **Figure 2** shows two enzymes: pepsin and trypsin. Pepsin is an enzyme produced in the stomach, whereas trypsin is formed in the small intestine. Each enzyme has its own optimum pH at which its activity is the highest.

A change to pH from the optimum affects enzymes and their activity. Extreme pH values can denature an enzyme by altering the three-dimensional structure of its active site. Changing the pH will affect the charges on the amino acid molecules. Amino acids that attracted each other may no longer. Again, the shape of the enzyme, along with its active site, will change. If pH is lower or higher than the optimal, the rate of reaction gradually decreases.

Student view

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

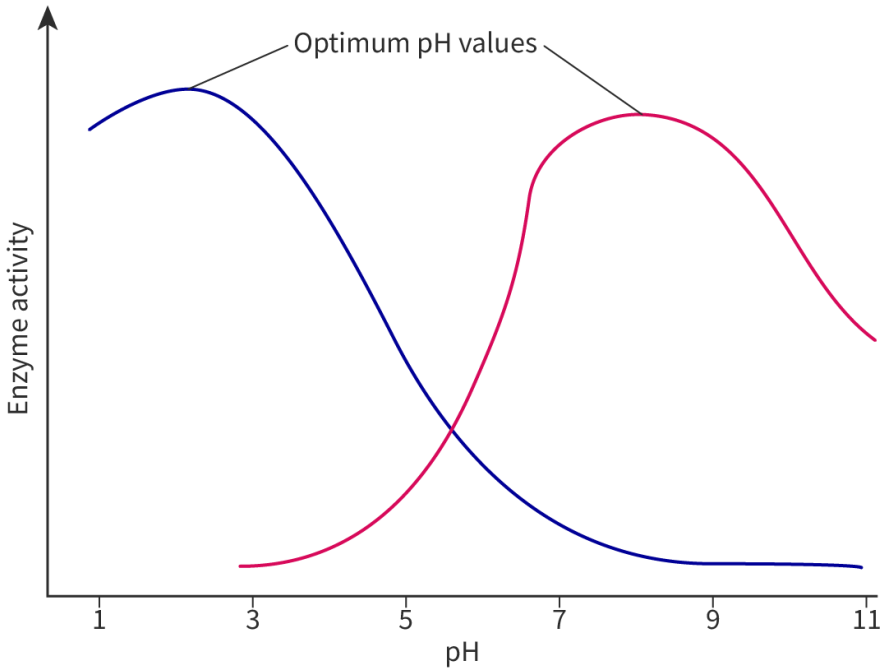


Figure 2. Effect of pH on pepsin (blue line) and trypsin (red line).

More information for figure 2

The graph illustrates the effect of pH on the activity of two enzymes: pepsin and trypsin. The X-axis represents pH level ranging from 1 to 11, while the Y-axis represents enzyme activity without specific units. A blue curve depicts pepsin activity, peaking at pH 2, indicating its optimal pH before declining sharply as pH increases. A red curve indicates trypsin activity, peaking at pH 8, marking its optimal pH before a gradual decrease. The graph highlights how enzyme activity is dependent on pH levels, showing optimal activity at their respective peaks and reduced activity as pH diverges from these optimal points.

[Generated by AI]

Effect of substrate concentration

When the substrate concentration is low, there are more enzyme molecules available than substrate. The rate of reaction is relatively low. Increasing the substrate concentration causes more chances of collision between substrate and enzyme molecules. Hence, the rate of enzymatic reaction rises gradually. However, this increase is halted when all active sites are occupied by substrate molecules. After this point, adding more substrate does not affect the rate of reaction. This can be seen in **Figure 3** (V_{max} is the maximum rate possible). Once V_{max} is reached (the maximal rate of reaction), substrates have to wait for enzyme active sites to become available before they can bind.

Student view

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

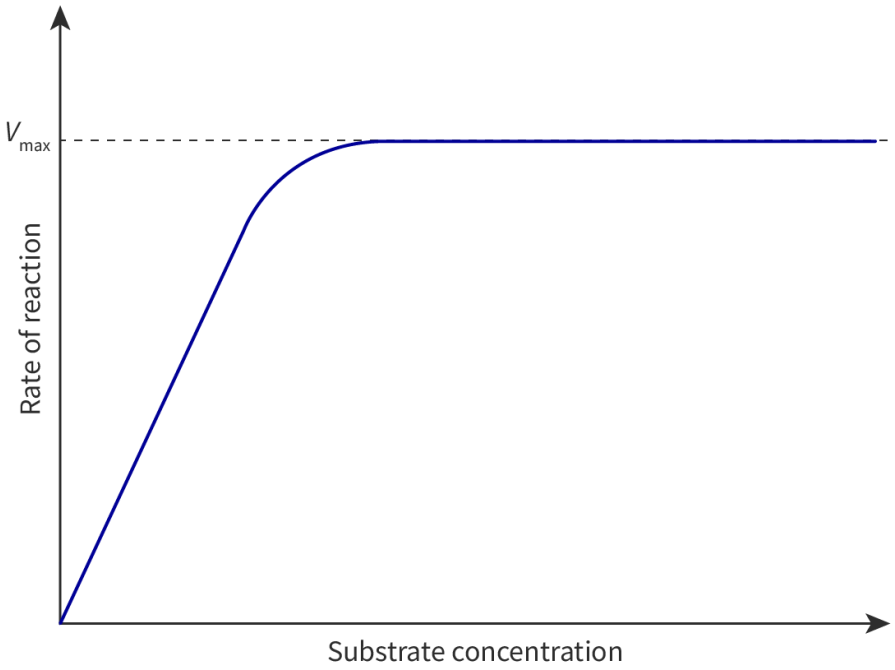


Figure 3. Effect of substrate concentration on the activity of an enzyme.

More information for figure 3

The graph illustrates the relationship between substrate concentration and the rate of reaction for an enzyme-catalyzed reaction. The X-axis represents substrate concentration, increasing from left to right. The Y-axis represents the rate of reaction, increasing from bottom to top and labeled with Vmax, indicating the maximum reaction rate.

Initially, the curve rises steeply, indicating an increase in the reaction rate as substrate concentration increases. This linear region suggests more substrate molecules colliding with enzyme molecules. However, the curve levels off, forming a plateau as it approaches Vmax. This signifies that all enzyme active sites are occupied, resulting in no further increase in the reaction rate despite additional substrate. The graph depicts an asymptote at Vmax, illustrating that the maximum reaction rate has been reached.

[Generated by AI]

Aspects:

- Patterns and Trends
- Experiments
- Models

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In scientific investigations, a research question is accompanied by a hypothesis that predicts the relationship between variables. After designing, collecting and processing relevant data, graphs are used to present the relationship between the variables in a visual form and hence deduce the relationship between the variables to either validate or invalidate the hypothesis. Generalised sketches of relationships are examples of models in biology.

When sketching your graph and to keep you thinking about your variables, you should always place your independent variable on the *x*-axis of a graph and the dependent variable on the *y*-axis of your graph (**Figure 4**).

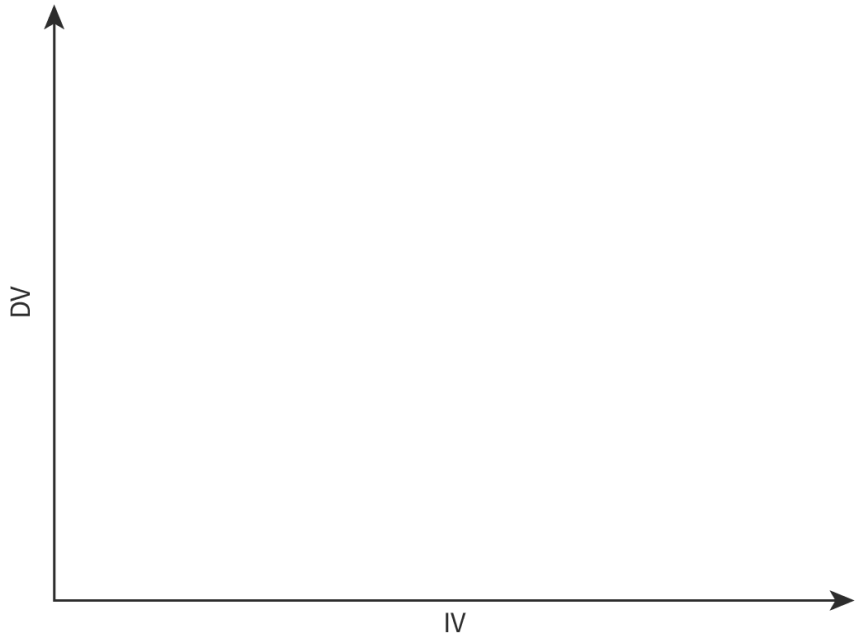

Figure 4. The placement of independent (IV) and dependent (DV) variables.

More information for figure 4

The image is a graph illustrating the placement of independent and dependent variables. The x-axis represents the independent variable (IV), and it is labeled at the bottom. The y-axis represents the dependent variable (DV), labeled on the left side. The graph's axes are empty, implying that no specific data points or line of best fit are shown. This setup demonstrates the common practice of displaying independent variables on the x-axis and dependent variables on the y-axis to analyze relationships between them.

[Generated by AI]

After plotting the data points on the graph a line of best fit could be used to determine the relationship between the variables and to make sense of your results that will lead you to a conclusion.

The following questions could help you reach a conclusion:

- Is there a trend?
- Can you find any correlation between independent and dependent variables?

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- Is the relationship linearly proportional, exponentially proportional or inversely proportional?
- Is there a plateau?
- Can you explain the results using correct scientific reasoning?
- Does the graph answer your research question?
- Is your hypothesis valid or invalid?

Figure 5 illustrates some examples of possible relationships. Generally speaking, if the graph shape goes up as *x* increases (left to right), then the relationship is a positive correlation, If the graph shape goes down as *x* increases, then the relationship is a negative correlation. The relationship can be also described as a strong/weak correlation depending on the closeness of the dots to the best fit line. If the graph shape shows a straight horizontal line then there is no relationship.

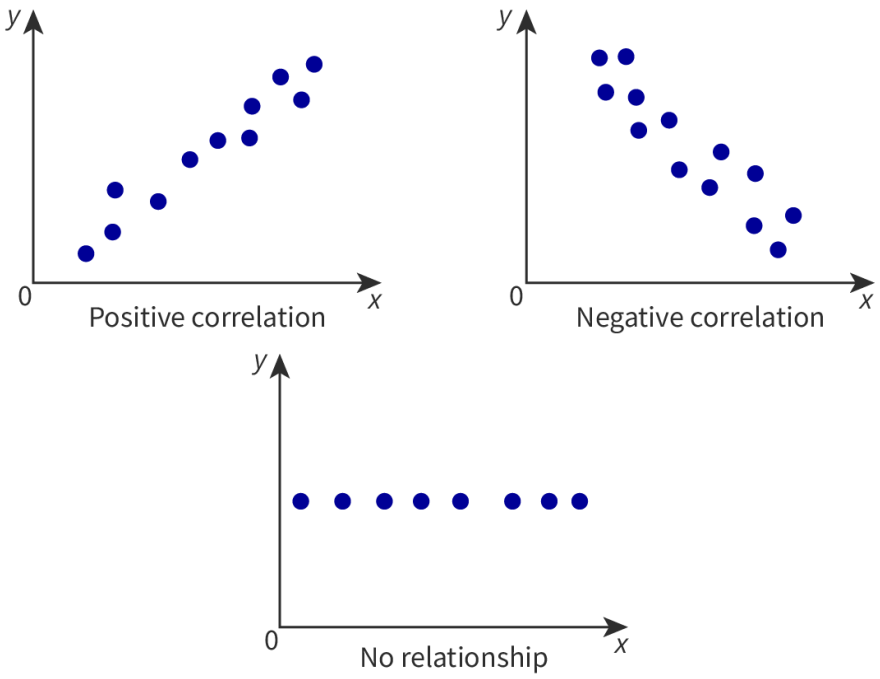

Figure 5. Different models of correlation between independent and dependent variables.

More information for figure 5

The image features three separate scatter plots representing different types of correlations between variables. The first plot, labeled "Positive correlation," shows data points arranged in an upward slope, indicating that as one variable increases, the other variable tends to increase as well. The second plot, labeled "Negative correlation," depicts data points in a downward slope, meaning that as one variable increases, the other tends to decrease. The third plot, labeled "No relationship," shows data points distributed in a horizontal line, demonstrating no apparent relationship between the two variables. All graphs have the x and y axes labeled, and each correlation type is given a clear visual example through the arrangement of blue data points.

[Generated by AI]

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Measurements in enzyme-catalysed reactions

When designing an experiment you should first choose your independent variable. This is the external factor that you will deliberately change to test its effect on enzyme activity. There are a few factors that can be your independent variable such as temperature, pH or substrate concentration.

When planning your experiment, you must take into consideration a significant range of the independent variable. For instance, if you want to test the effect of temperature on starch hydrolysis by amylase, you should consider testing the effect of several different temperatures (e.g. 10, 20, 30 and 40 °C).

The next thing to consider is your dependent variable – the variable that you will measure to assess the impact of the independent variable on enzyme activity. The dependent variable should be a measurable factor such as time, mass or volume. This will be your quantitative data. If possible, it is strongly recommended to collect qualitative data as well. You may record colour, texture or physical changes to a substance.

Your data collected through any experiment will only be valid if all other variables are controlled within narrow limits. These are known as control variables. When designing your experiment you should consider a list of variables that must be kept relatively constant. Usually, these are factors that may alter the dependent variable. For instance, if your independent variable is temperature and the dependent variable is mass of a product, factors such as pH, substrate and enzyme concentration should be controlled.

The apparatus in **Figure 6** can be used to investigate the effects of temperature or pH on catalase activity.

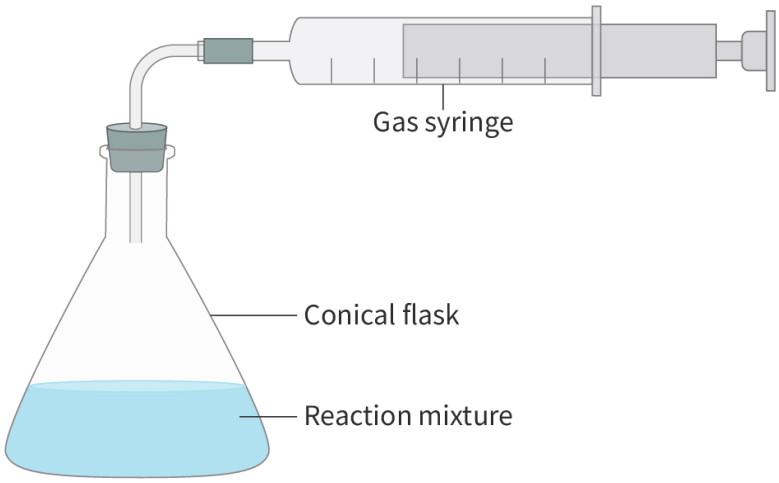

Figure 6. Experimental set-up to test the activity of catalase.

Student view

Overview (/study/app/bio/sid-422-cid-755105/o

More information for figure 6

The image is a diagram of an experimental set-up for testing catalase activity. It features a conical flask filled with a reaction mixture, labeled on the lower part of the flask. Attached to the flask is a gas syringe connected via a tube. The syringe is positioned horizontally and labeled as "Gas syringe." The diagram illustrates the apparatus components and their arrangement, which is likely used to measure gas evolved during the reaction with catalase. This setup allows for investigations into how factors like temperature or pH affect enzyme activity.

[Generated by AI]

Testing the effect of substrate concentration on the activity of catalase

You are expected to be able to design experiments that test the effect of temperature, pH and substrate concentration on the activity of enzymes. There are usually many enzymes available in your school laboratory. Investigating this is a popular focus for Internal Assessments.

One of the most common experiments in IB biology laboratories is the effect of substrate concentration on the activity of catalase. Catalase is a widely available enzyme that converts hydrogen peroxide into water and oxygen:

$$2H_2O_2 \dashrightarrow 2H_2O + O_2$$

You will study factors affecting this reaction in Practical 3: Investigating the activity of enzymes (/study/app/bio/sid-422-cid-755105/book/investigating-the-activity-of-enzymes-id-46694/). In this practical, you are going to be looking at the rate of activity of catalase in yeast. You may be able to modify this investigation to observe the catalase concentration in liver cells, or similar, if you wish.

Study skills

You should be able to sketch graphs to show the expected effects of temperature, pH and substrate concentration on the activity of enzymes. When sketching graphs you should remember the shape of each curve. For temperature, the rate of enzymatic reaction drastically drops after reaching the optimal temperature. When you sketch a rate of reaction for different substrate concentrations do not forget to draw a plateau phase in which the rate remains constant.

Student view

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Table 1 lists enzymes, their substrates and possible dependent variables and independent variables that can be investigated.

Table 1. Enzyme and substrate combinations with associated dependent and independent variables that can be used in designing experiments.

Name of enzyme	Substrate	Product	Independent variable	Dependent variable
Catalase (Source: potato, ginger, garlic, animal liver)	Hydrogen peroxide	Oxygen	• Source of catalase • Temperature • Concentration of substrate • Concentration of enzyme • pH	• Number of oxygen bubbles produced • Distance moved by meniscus in a connected glass tube • Oxygen produced measured with a gas sensor • Time taken for filter paper disc (soaked in enzyme) to rise to the surface of hydrogen peroxide solution
Lipase	Lipids	Fatty acids	• Temperature • Concentration of substrate • Concentration of enzyme • Type of milk (used as substrate)	Drop in pH observed after a specific time interval (this can be measured by pH meter or change in universal indicator paper)
Pepsin	Protein (boiled egg white)	Amino acids and short peptides	• Temperature • Concentration of substrate • Concentration of enzyme • pH	Decrease in the mass of boiled egg white soaked in an enzyme

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Name of enzyme	Substrate	Product	Independent variable	Dependent variable
Amylase	Starch	Maltose	• Temperature • Concentration of substrate • Concentration of enzyme • pH	• Time taken for the blue colour of starch—iodine complex to disappear • Measuring the decrease in blue colour after a specific time interval using a colorimeter

Calculating the rate of reaction

Reaction rates can be determined using experimentation or secondary data. Reaction rate is a quantitative measurement of the speed at which the product is produced or the substrate is consumed. The quantity of the produced product or consumed reactants is divided over the change in time.

Try the following activity to determine the rate of reaction of lactase under different conditions.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Providing a reasoned argument to support conclusions
- **Tool 1:** Experimental techniques — Measuring variables
- **Tool 2:** Technology — Applying technology to collect data
- **Tool 3:** Mathematics — Applying general mathematics
- **Inquiry 1:** Exploring and designing — Designing
- **Inquiry 2:** Collecting and processing data — Collecting data, Processing data, Interpreting results
- **Inquiry 3:** Concluding and evaluating — Concluding
- **Time required to complete activity:** 1 hour
- **Activity type:** Pair activity

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Investigating the effect of pH, temperature, substrate concentration on the reaction rate of lactase

Lactase breaks down lactose into glucose and galactose. The rate of the reaction can be determined by measuring the change in the concentration of glucose (mg/dL over time) (**Figure 7**). Your task is to determine the effect of the pH, temperature and lactose concentration on the rate of the reaction using the set-up in this Lactase enzyme simulation (https://sites.google.com/site/biologydarkow/enzymes/lactase-enzyme-simulation). Plan to conduct three trials for every independent variable, but statistically speaking, it is more advantageous to perform five trials.

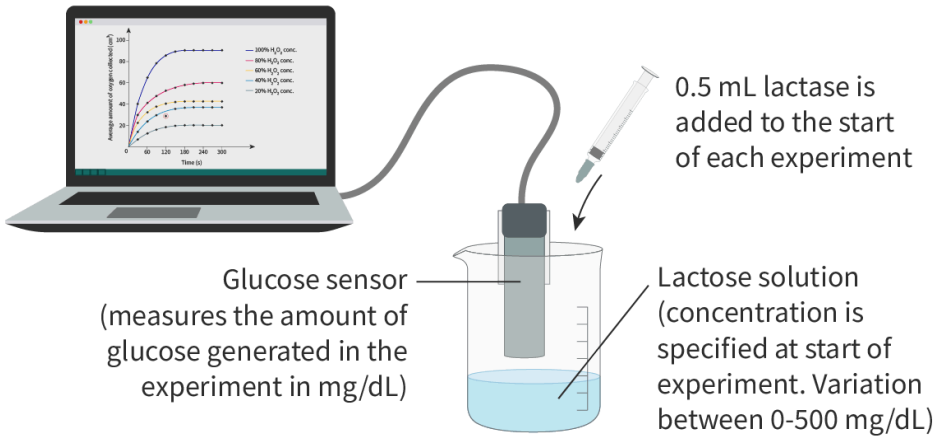

Figure 7. Experimental set-up.

More information for figure 7

The image depicts an experimental setup for measuring the effect of lactose concentration on glucose production by lactase. A laptop displays a graph with curves labeled as different percentages of H2O concentration over time, indicating the reaction's progress. A glucose sensor is submerged in a beaker containing a lactose solution, and a connected laptop records the glucose amount generated. There is a label indicating the glucose sensor's purpose: measuring the glucose output in mg/dL. Another label notes that 0.5 mL of lactase is added at the start of each trial. The lactose concentration is specified, ranging from 0 to 500 mg/dL. Arrows illustrate the process flow from a syringe adding lactase to the solution where the reaction occurs.

[Generated by AI]

Measuring the effect of temperature

Part 1:

Consider the following variables:

Independent variable:
Temperature (ranging from 0 to 100 °C)

Dependent variable:
The rate of the reaction in mg/dL/minute can be determined using the following

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equation:

$$\frac{\text{final glucose concentration} - \text{initial glucose concentration}}{\text{time}}$$

Control variables:
Consider the following control variables when you run the experiment.

- pH should be controlled at 7 as this is the optimum pH for lactase.
- Lactose concentration should be controlled and it should be abundant. The maximum concentration should be selected, which is 1000 mg/dL.
- Run three trials in the exercise (use the reset each time you run the experiment).
- Lactase volume has been controlled as 0.5 mL.
- The initial concentration of glucose is considered as 0 mg/dL in all trials.
- Time is controlled to be 20 minutes per run.

Part 2:

Run the simulation and complete a table similar to the one in **Table 2**.

Table 2. Sample results table.

Temperature (°C)	Final concentration of glucose after 20 minutes (mg/dL)			Rate of glucose production (mg/dL/minute)			Mean glu prod (mg/dL
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	
0							
25							
50							
75							
100							

Part 3:

Sketch the mean rate of glucose production against the range of temperatures from 0—100 °C using any digital tool.

Part 4:

Interpret the graph and explain the effect of temperature on the rate of lactase activity.

Measuring the effect of pH

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Part 1:

Consider the following variables:

Independent variable:
pH (ranging from 2 to 10)

Dependent variable:
The rate of the reaction in mg/dL/minute can be determined using the following equation:

$$\frac{\text{final glucose concentration} - \text{initial glucose concentration}}{\text{time}}$$

Control variables:
Consider the following control variables when you run the experiment.

- Temperature should be controlled at 40 °C as this is the optimum pH for lactase.
- Lactose concentration should be controlled and it should be abundant. The maximum concentration should be selected, which is 1000 mg/dL.
- Run three trials in the exercise (use the reset each time you run the experiment).
- Lactase volume has been controlled as 0.5 mL.
- The initial concentration of glucose is considered as 0 mg/dL in all trials.
- Time is controlled to be 20 minutes per run.

Part 2:

Run the simulation and complete complete a table similar to the one in **Table 3**.

Table 3. Sample results table.

pH	Final concentration of glucose after 20 minutes (mg/dL)			Rate of glucose production (mg/dL/minute)			Mean rate of glu production (mg/dL/minut
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	
2							
4							
6							
8							
10							

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Part 3:

Sketch the mean rate of glucose production against the range of pH from 2—10 using any digital tool.

Part 4:

Interpret the graph and explain the effect of pH on the rate of lactase activity.

5 section questions

C1. Interaction and interdependence: Molecules / C1.1 Enzymes and metabolism

Metabolic pathways (HL)

C1.1.11: Intracellular and extracellular enzyme-catalysed reactions (HL) C1.1.12: Generation of heat energy by metabolic reactions (HL)

C1.1.13: Cyclical and linear pathways in metabolism (HL)

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/metabolic-pathways-hl-id-46234/print/) Assign

Higher level (HL)

Learning outcomes

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

- Distinguish intracellular and extracellular enzyme-catalysed reactions.
- Distinguish cyclical and linear pathways in metabolism.
- Explain the generation of heat by metabolic reactions.

Did you know that around 75 000 enzymes are found in the human body? Many metabolic pathways do not take place in a single step, rather they occur in several steps. ReconX (https://www.vmh.life/#human/all) is an international collaboration to map the complete human metabolism. Advances in computer technology, both at the software and hardware level, have enabled large-scale in-depth analysis of these metabolic pathways.

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Intracellular and extracellular enzyme-catalysed reactions

Intracellular and extracellular metabolic pathways are two types of biochemical reactions that occur within and outside the cell, respectively, to carry out various metabolic reactions. See **Interactive 1** for an overview of intracellular and extracellular pathways.

> **Intracellular enzyme-catalysed reactions are metabolic reactions that take place inside the cell, and are catalysed by enzymes that are produced by free ribosomes.**

> **Extracellular enzyme-catalysed reactions are metabolic reactions that take place outside the cell, and are catalysed by enzymes that are produced by bound ribosomes and secreted outside the cell by exocytosis.**

Interactive 1. Intracellular and Extracellular Metabolic Pathways.

Making connections

Ribosomes are structures inside the cell that synthesise proteins; there are two types of ribosomes: ribosomes bound to the endoplasmic reticulum synthesise proteins to be secreted by exocytosis outside the cell; on the other hand, free ribosomes synthesise proteins to be used inside the cell (see subtopic A2.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43253/)).

Cyclical and linear pathways in metabolism

A metabolic pathway is any chain or cycle of linked reactions catalysed by enzymes. Sometimes there is a substrate, which is converted into an end-product in a few steps. However, more often, a pathway can be quite complex, with many intermediate products before an end-product is produced. Glycolysis, the conversion of glucose into pyruvate, is a great example (**Figure 1**).

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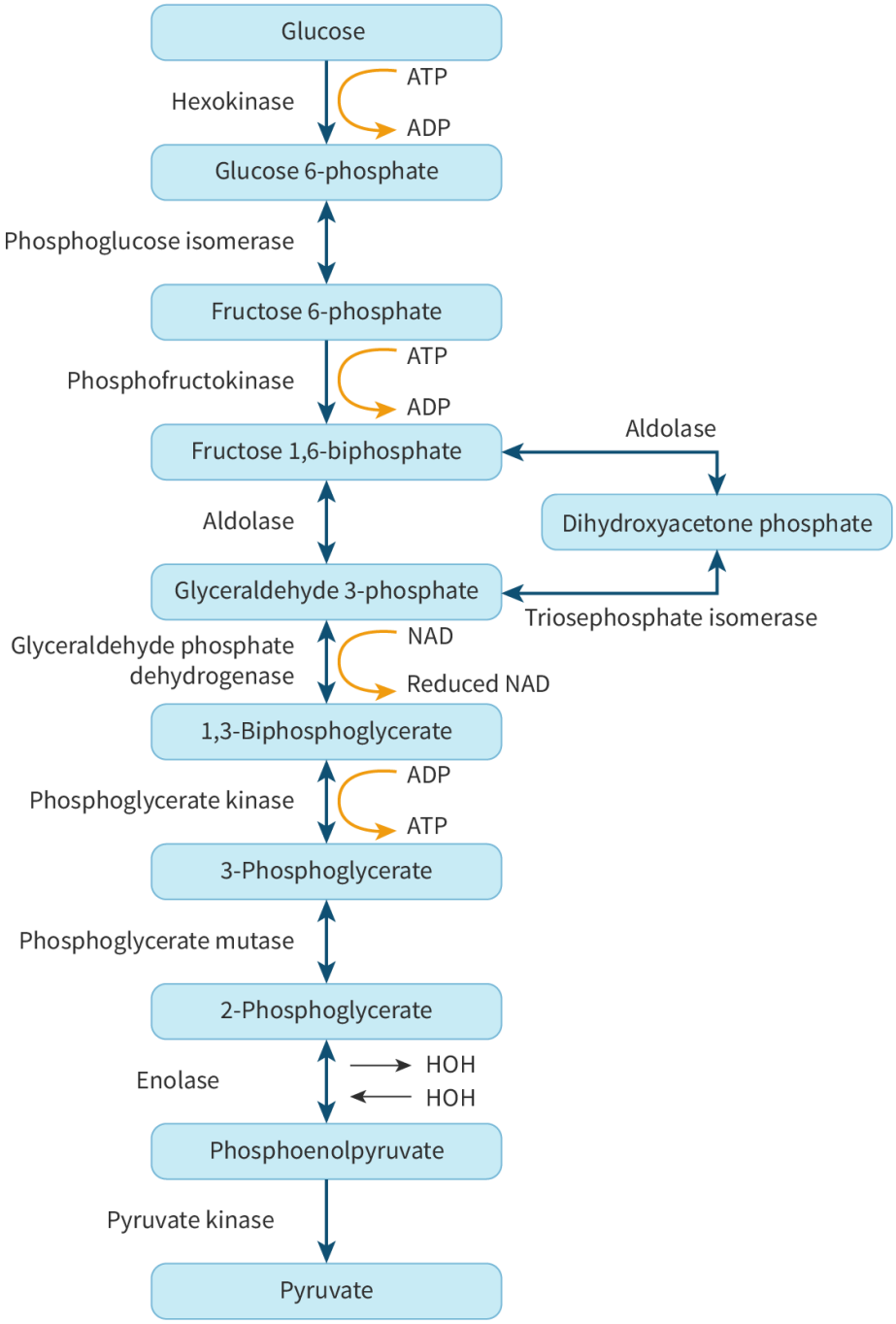

Figure 1. Glycolysis, an example of a linear metabolic pathway showing all the enzymes involved.

More information for figure 1

The image is a detailed diagram of the glycolysis pathway, illustrating a series of biochemical reactions. It begins with glucose, which is converted into glucose 6-phosphate through the action of the enzyme hexokinase, requiring ATP and producing ADP. Following this, phosphoglucose isomerase converts glucose 6-phosphate into fructose 6-phosphate.

Next, phosphofructokinase further transforms fructose 6-phosphate into fructose 1,6-bisphosphate, again using ATP and producing ADP. The enzyme aldolase then splits fructose 1,6-bisphosphate into two three-carbon molecules: dihydroxyacetone phosphate and glyceraldehyde 3-phosphate. These can interconvert via triosephosphate isomerase.

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Glyceraldehyde 3-phosphate is both phosphorylated and oxidized to form 1,3-bisphosphoglycerate, catalyzed by glyceraldehyde phosphate dehydrogenase, with NAD being reduced to NADH. Then, phosphoglycerate kinase converts 1,3-bisphosphoglycerate to 3-phosphoglycerate, producing ATP from ADP.

Following this, 3-phosphoglycerate is rearranged by phosphoglycerate mutase to 2-phosphoglycerate. The enzyme enolase converts this into phosphoenolpyruvate, releasing a water molecule. Finally, pyruvate kinase converts phosphoenolpyruvate to pyruvate, again producing ATP from ADP. This series of reactions shows a linear metabolic pathway and the involvement of various enzymes and metabolites.

[Generated by AI]

Some metabolic pathways are linked to other pathways. For example, glycolysis is directly linked to the Krebs cycle (or citric acid cycle, see **Figure 2**). This reaction is known as the link reaction.

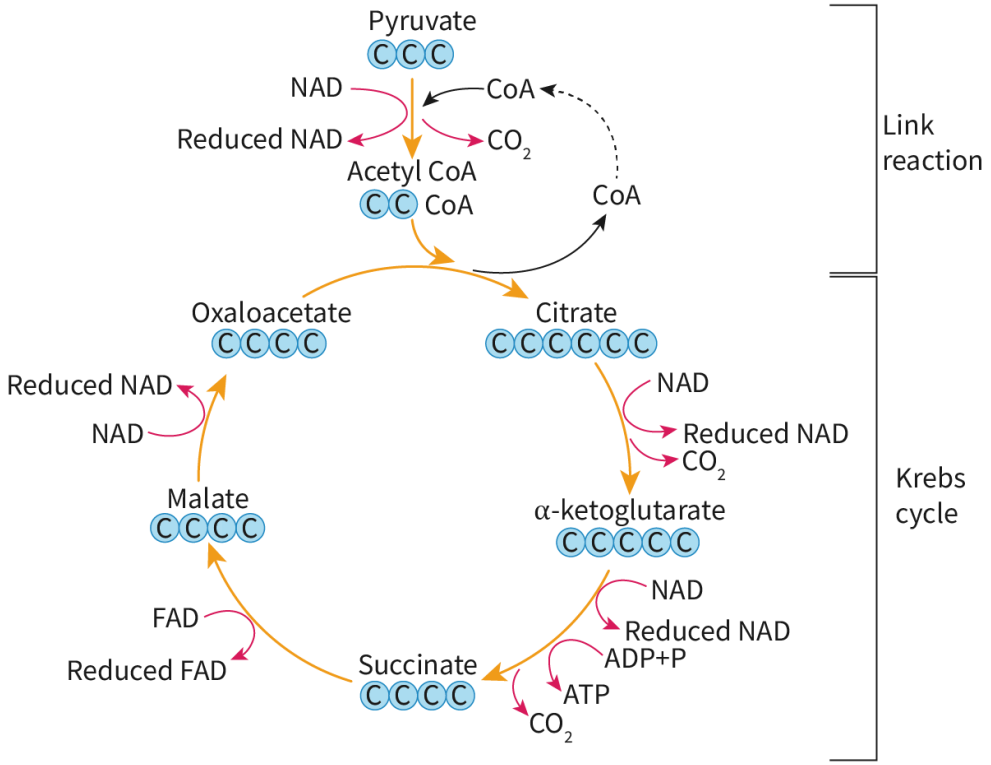

Figure 2. The Krebs cycle.

More information for figure 2

This is a diagram of the Krebs cycle, also known as the citric acid cycle. The cycle is depicted in a circular flow, illustrating the sequence of chemical reactions involved in cellular respiration. Key components in the diagram include:

- **Pyruvate:** At the top, it reacts with NAD, forming Acetyl CoA, and releases CO2.
- **Acetyl CoA** enters the cycle and combines with Oxaloacetate to form Citrate.
- **Citrate** is then converted to α-ketoglutarate, releasing NADH and CO2.
- **α-ketoglutarate** is converted to Succinyl-CoA, yielding NADH and CO2, and then to Succinate.

Student view

- **Succinate** is converted to Fumarate, generating FADH2.
- **Fumarate** then becomes Malate, and further conversion results in Oxaloacetate, completing the cycle.
- Throughout the cycle, various reductions and oxidations involve NAD to NADH and FAD to FADH2, essential for the electron transport chain.

Each step is represented by arrows, with labels indicating the chemical transformations. The diagram effectively shows how energy carriers like NADH, FADH2, and ATP are generated.

[Generated by AI]

In summary, metabolic pathways are linked, enzymatically catalysed reactions. Some are linear, for example glycolysis, and some are cyclic, for example the Krebs cycle and Calvin cycle.

Watch **Video 1** for an example of a metabolic pathway – glycolysis. Note how the reaction is divided into steps and what other chemical substances are involved.

Video 1. Glycolysis.

Generation of heat by metabolic reactions

According to the second law of thermodynamics, no transformation of energy is ever 100% efficient, that is, some energy is always 'lost' as heat. This also applies to metabolic reactions where there is always loss of energy as heat. Warm-blooded animals such as mammals and birds use the heat generated from metabolic reactions to maintain a constant body temperature that is higher than the ambient temperature. Other organisms such as the three-toed sloth use behavioural adaptations to maintain body temperature such as changing body posture.

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Theory of Knowledge

Is scientific observation of the components of a system a valid means of investigating a complex phenomenon?

Complex systems are more easily investigated by looking at their components. Living processes have emergent properties that can only be understood by consideration of all the components in their entirety. In the 19th century, Pasteur and Liebig hotly disputed the role of yeast in fermentation. Pasteur's stance was that fermentation could only occur in the presence of living cells, a vitalist approach. Liebig maintained that it was a chemical process not requiring live yeast cells. And 35 years later, the Buchner brothers crushed yeast cells to a paste and demonstrated fermentation of sugars by a medium containing no cells — one of the earliest investigations into metabolic pathways.

Hans Krebs first postulated the mechanism of the cycle named after him in 1937. A series of elegant experiments by a number of teams of researchers observed single reactions over the course of almost 15 years. This eventually allowed them to work out the whole cycle. Entire complex systems cannot easily be investigated. A systems approach allows the whole process to be understood once the components are assembled in order. The step-by-step progress of knowledge of fermentation eventually led to an understanding of the entire process after many years of investigations upon its components.

Engage in the following activity to gain a deeper understanding of how the body generates heat to regulate its temperature.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type**: Individual activity

An organism's metabolic rate is the amount of energy needed by that organism in a given time period. Different living organisms have different metabolic rates. One of the factors that affect the metabolic rate is the body mass. Study the graph in **Figure 3** showing the effect of mass of different organisms on metabolic rate and answer the following questions.

Student view

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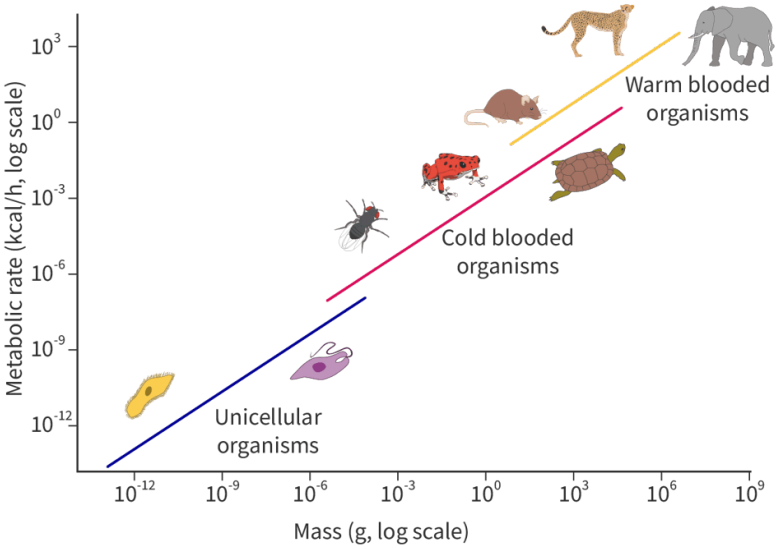

Figure 3. The correlation between mass and metabolic rate.

More information for figure 3

The graph illustrates the correlation between the mass of various organisms and their metabolic rates. The X-axis represents mass in grams (g) on a logarithmic scale ranging from 10^-12 to 10^9 grams. The Y-axis represents metabolic rate in kilocalories per hour (kcal/h) also on a logarithmic scale, ranging from 10^-12 to 10^3 kcal/h.

Three categories of organisms are represented: unicellular, cold blooded, and warm blooded organisms. The graph includes a blue line for unicellular organisms showing a low mass and low metabolic rate, a pink line for cold blooded organisms with moderate mass and metabolic rates, and a yellow line depicting warm blooded organisms with higher mass and metabolic rates. Illustrations of different organisms, such as a paramecium, fly, frog, mouse, cheetah, and elephant are placed along the lines, indicating their approximate mass and metabolic rates.

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1. Define metabolism.
2. State what is meant by rate.
3. Explain the cause of heat production in metabolic reactions.
4. Outline the significance of metabolic heat in the regulation of body temperature in living organisms.
5. Describe the correlation between body mass and metabolic rate.
6. Propose a method for assessing metabolic rate.
7. Discuss the correlation between body mass, metabolic rate and the ability of organisms to regulate body's temperature.

Student view

5 section questions

Enzyme inhibition (HL)

Higher level (HL)

Learning outcomes

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

- Distinguish competitive and non-competitive inhibition and give examples.
- Explain the end-product inhibition and give examples.
- Explain mechanism-based inhibition.

Enzyme inhibition is a fundamental principle in drug discovery and development. By identifying and designing molecules that can selectively inhibit specific enzymes involved in disease processes, researchers can develop drugs to treat various conditions. Examples include enzyme inhibitors used in the treatment of hypertension, diabetes, cancer and Alzheimer's disease.

Competitive and non-competitive inhibition

There are two types of enzyme inhibition (**Figure 1**):

- competitive inhibition
- non-competitive inhibition.

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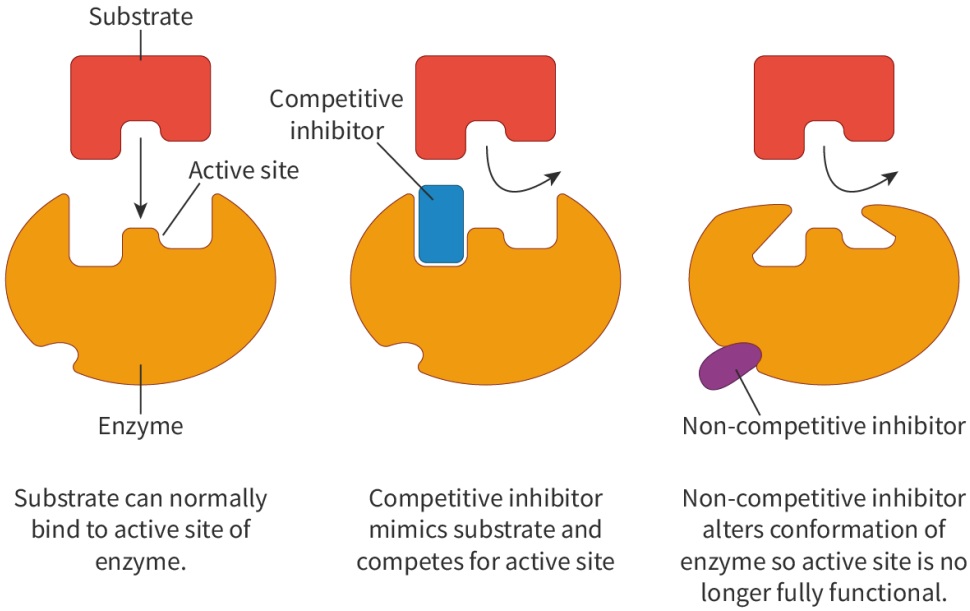

Figure 1. Competitive and non-competitive inhibition of enzymes.

More information for figure 1

The diagram illustrates three scenarios of enzyme and inhibitor interactions.

1. **Normal Binding**: On the left, a substrate (red shape) is shown above an enzyme (orange shape) with an arrow pointing towards the active site, indicating the substrate binding to it. The text below reads: "Substrate can normally bind to active site of enzyme."
2. **Competitive Inhibition**: The middle image shows a similar setup with the addition of a competitive inhibitor (blue shape) occupying the active site. This indicates that the competitive inhibitor mimics the substrate and competes for the active site, preventing the substrate from binding. The text reads: "Competitive inhibitor mimics substrate and competes for active site."
3. **Non-Competitive Inhibition**: On the right, a non-competitive inhibitor (purple shape) binds to a different part of the enzyme, altering its conformation. This prevents the active site from functioning properly, even if the substrate tries to bind. The text reads: "Non-competitive inhibitor alters conformation of enzyme so active site is no longer fully functional."

[Generated by AI]

The competitive inhibitor competes with the substrate for the same active site. In competitive inhibition, the maximum rate of reaction (V_{max}) is eventually the same as the reaction without inhibitors. When the substrate concentration increases, the rate will increase because there is more available substrate than inhibitor. Therefore, there is a greater chance of the substrate binding to the enzyme's active site and forming product(s) (**Interactive 1**).

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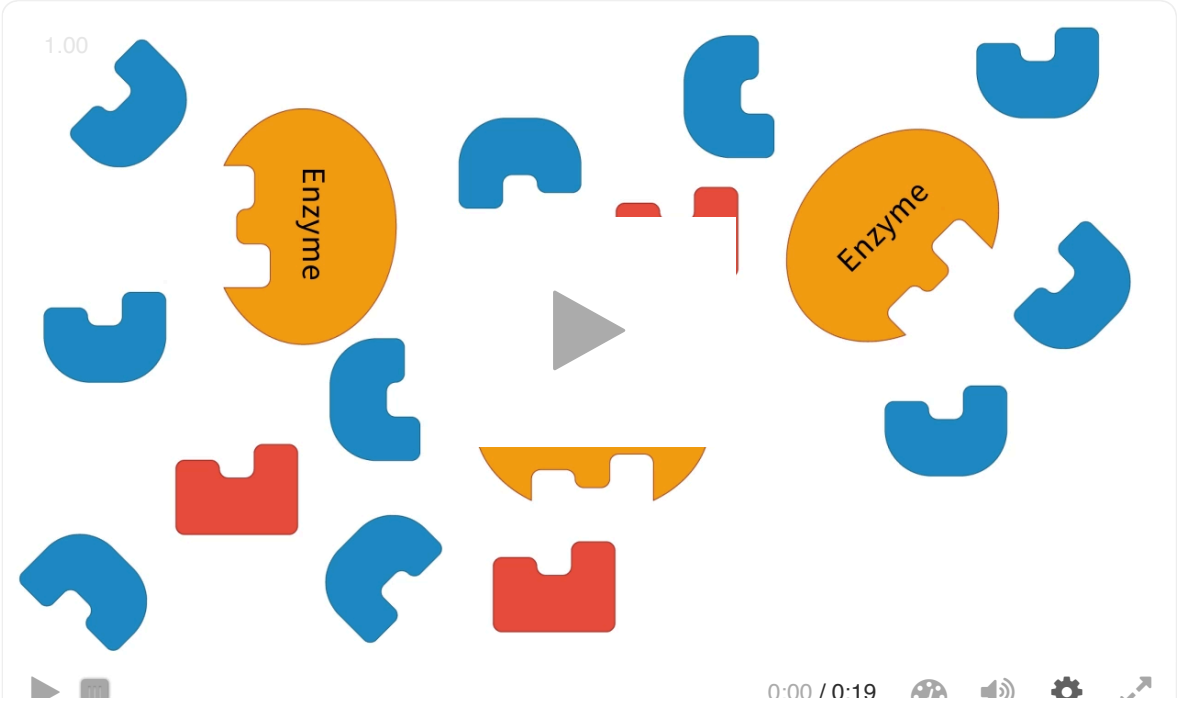

Interactive 1. Competitive Inhibition of Enzymes.

More information for interactive 1

The interactive time-lapse video illustrates the process of competitive inhibition, where an inhibitor molecule competes with the substrate for binding to an enzyme's active site. The visualization emphasizes key biochemical principles. The interactive uses color-coded molecules and real-time binding dynamics to enhance understanding.

The interactive depicts the dynamic interaction between enzymes, substrates, and drug molecules (or inhibitors). The enzyme (yellow) is a biological catalyst that binds to specific substrates to facilitate reactions, substrate (red) is the molecule upon which the enzyme acts, fitting into the enzyme's active site like a lock and key. "Enzyme-substrate complex" is a temporary structure formed when the substrate binds to the enzyme. After catalysis, the substrate is converted into products which are released. These are labeled "end products". The enzyme remains unchanged and is now ready to bind new substrates.

The "drug" is a molecule structurally similar to the substrate, allowing it to bind reversibly to the enzyme's active site, creating an "enzyme-drug complex". The inhibitor blocks the active site, preventing substrate binding and slowing reaction rate.

At low substrate concentrations, inhibition dominates, few substrates compete for active sites. At high substrate concentrations, substrates outcompete the inhibitor, restoring the reaction rate. The maximum rate of reaction (V_{max}) remains unchanged because sufficient substrate can overcome inhibition.

The interactive demonstrates how competitive inhibition regulates enzyme activity through molecular competition. Users understand that inhibitors must resemble substrates to bind active sites and substrate levels determine inhibition efficacy.

Non-competitive inhibitors bind reversibly at a site away from the active site usually referred to as the allosteric site, altering the shape of the enzyme. In non-competitive inhibition, the rate levels off and never reaches the same level that it would without inhibitor. This difference is caused by the fact that all enzyme molecules to which the

Student view

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inhibitor is attached are effectively blocked from reacting with the substrate due to modification of their active site. Therefore, fewer enzyme molecules (free of inhibitor) are available to catalyse the reaction **(Figure 2)**.

For example, hexokinase is an enzyme that plays an important role in the first step of glucose metabolism. It converts glucose to glucose-6-phosphate, which is essential for energy production. In the brain, hexokinase has a strong affinity for glucose and helps maintain appropriate glucose levels. Glucose 6-phosphate, the product of hexokinase's activity, can bind to a separate site on the enzyme, causing a change in its shape and reducing its ability to function; therefore, it helps regulate glucose metabolism in the brain.

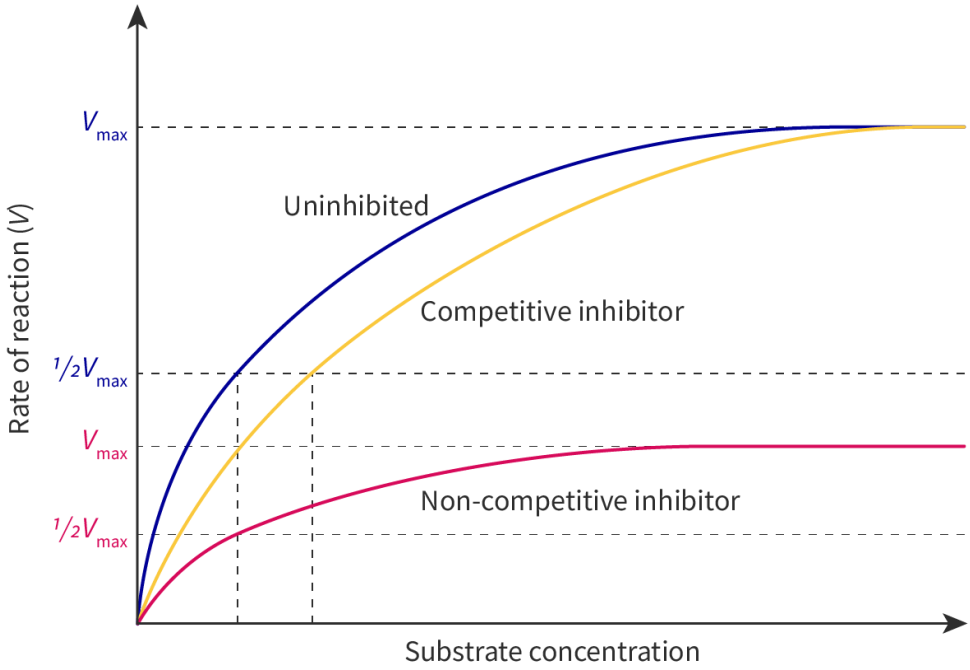

Figure 2. Competitive versus non-competitive inhibition of enzymes.

More information for figure 2

The image is a graph depicting the rate of reaction (V) against substrate concentration. It illustrates three curves: one for uninhibited reaction, one for competitive inhibition, and one for non-competitive inhibition. The X-axis represents substrate concentration, while the Y-axis represents the rate of reaction V. The uninhibited curve reaches the maximum rate of reaction (Vmax) more steeply compared to the inhibited curves. The competitive inhibitor curve approaches Vmax as substrate concentration increases but does so slower than the uninhibited curve, while the non-competitive inhibitor curve reaches a lower maximum rate of reaction. The points Vmax and 1/2 Vmax are marked for clarity, showing how the presence of inhibitors affects the rates. The uninhibited curve is the highest, followed by the competitive and then the non-competitive inhibitor curves.

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Table 1 highlights the differences between competitive and non-competitive inhibition.

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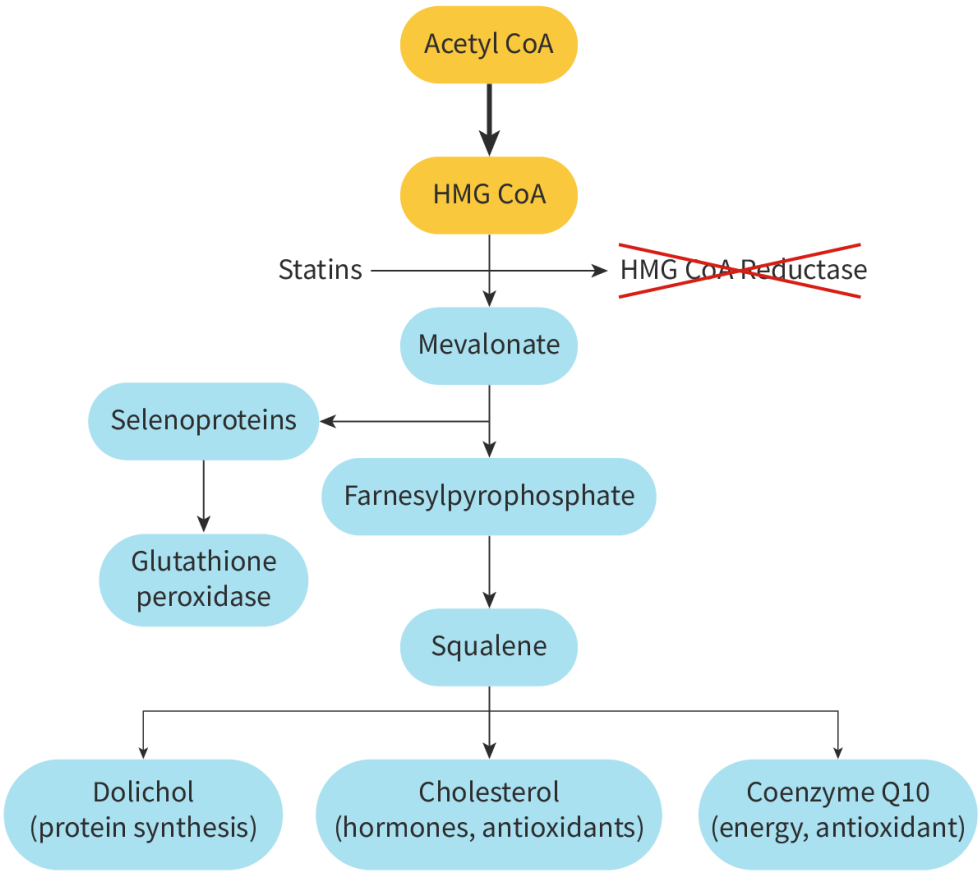
Table 1. Competitive inhibition compared with non-competitive inhibition.

Competitive inhibitor	Non-competitive inhibitor
It is chemically quite similar to the substrate.	It has no similarity to the substrate.
It binds to the active site of the enzyme.	It binds to the enzyme at a site other than the active site.
Binding of the inhibitor to the enzyme does not modify its active site.	Binding of the inhibitor to the enzyme modifies its active site, hence preventing binding of substrate (if it does bind, the enzyme will not be able to catalyse the reaction).
As the concentration of substrate is increased, the effect of the inhibitor on the reaction is reduced.	Increasing the concentration of the substrate does not decrease the impact of the inhibitor. Therefore, the rate of reaction is lower than normal at all substrate concentrations.

Statin drugs are commonly used to lower cholesterol levels. They competitively inhibit the enzyme HMG-CoA reductase, which plays a crucial role in cholesterol synthesis. By binding to the active site of the enzyme, statins prevent the substrate from binding, therefore reducing cholesterol production (**Figure 3**).



Student view

Figure 3. The role of statins in inhibiting the synthesis of cholesterol.

More information for figure 3

The flowchart depicts the biochemical pathway of cholesterol synthesis and how statins interfere with it.

1. The process begins with Acetyl CoA, which converts to HMG CoA. Both are illustrated in yellow ovals.
2. HMG CoA is normally converted into Mevalonate by the enzyme HMG-CoA reductase. However, this step is blocked by statins, as indicated by a red cross over an arrow between HMG CoA and HMG-CoA reductase. The statin inhibitor is represented by a horizontal black line marked as "Statins."
3. Mevalonate (in blue) continues the pathway, converting into Farnesylpyrophosphate.
4. From Farnesylpyrophosphate, the pathway splits:
    - Upward towards Selenoproteins and Glutathione peroxidase.
    - Downward direction leads to Squalene.
5. Squalene divides into three pathways leading to:
    - Dolichol (for protein synthesis).
    - Cholesterol (for hormones and antioxidants).
    - Coenzyme Q10 (for energy and antioxidant roles).

Each step in the pathway is represented with directional arrows showing the flow of information, intended to demonstrate the sequence and interactions that statin disrupts.

[Generated by AI]

Complete the Venn diagram in **Interactive 2** to distinguish competitive and non-competitive inhibition.

Interactive 2. Comparison Between Competitive and Non-Competitive Inhibition.

End-product inhibition

Cells need to be economical with their resources. How can this be achieved? One of the ways is feedback inhibition, also called end-product inhibition. When the end-product of a pathway is no longer needed, it makes sense to stop the reactions at the first step of the pathway. In most cases, the enzymes that catalyse the first reaction of the pathway are allosterically inhibited (a form of non-competitive inhibition) by the end-product of the pathway.

The pathway shown in **Figure 4** is the synthesis of isoleucine from threonine. It is a good example of end-product inhibition, and a useful one to know. Isoleucine is an essential amino acid. It cannot be made by the human body so it must be consumed

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from food. Some organisms such as bacteria can synthesise isoleucine from threonine.

The normal pathway starts at (a) with Threonine represented by the half circle with two cut-outs, then to (b), and continues through each step to (e). Isoleucine (represented by red triangle) can bind to the enzyme that catalyses the first step of the pathway in a non-competitive way. It binds allosterically to the enzyme and changes the conformation of the active site (g). As a result, the substrate can no longer bind to the enzyme, as shown in (f), (h) and (i).

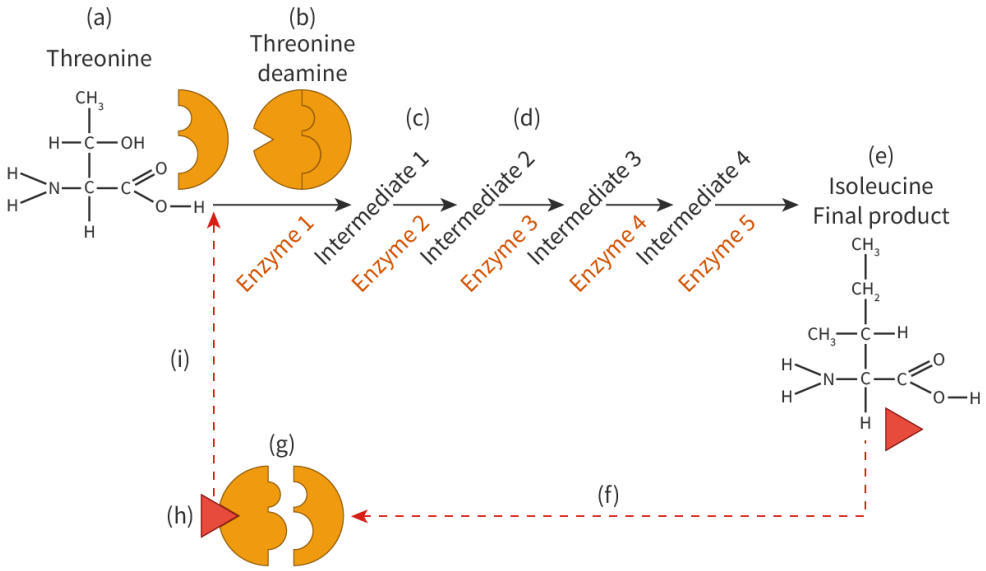

Figure 4. End-product inhibition by isoleucine.

More information for figure 4

The diagram illustrates the biochemical pathway for isoleucine synthesis with a focus on end-product inhibition. It begins with threonine at step (a) depicted by a half-circle with two cut-outs, transitioning to threonine deamine at step (b). The pathway involves several intermediates: Intermediate 1 with Enzyme 2 at step (c), Intermediate 2 with Enzyme 3 at step (d), Intermediate 3 with Enzyme 4, and Intermediate 4 with Enzyme 5 leading to the final product, isoleucine, at step (e). Isoleucine is represented by a red triangle.

Isoleucine binds to the enzyme that catalyzes the first step of the pathway in a non-competitive manner. This binding is shown as isoleucine attaching allosterically to the enzyme in step (g), altering the active site's shape. As a result, the substrate can no longer bind to the enzyme, depicted in steps (f), (h), and (i). The inhibiting mechanism is illustrated by red dashed lines returning from the final product, isoleucine, to the initial enzyme binding sites.

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Mechanism-based inhibition

Mechanism-based inhibition is caused by the irreversible binding of the inhibitor to the active site of a specific enzyme through a covalent bond. This produces a stable inhibitor–enzyme complex causing the enzyme to lose its catalytic activity permanently. Mechanism-based inhibition is harmful to organisms and often also used in the development of treatments such as AZT – a treatment for HIV.

Another example of mechanism-based inhibition is penicillin. The bacterial cell wall protects the bacterial cells and prevents it from bursting. Transpeptidase is an enzyme produced in bacteria and maintains the rigidity of the cell wall by forming cross-links between polysaccharide chains. Penicillin binds to transpeptidase irreversibly, thereby inhibiting its function. As a result the cell wall is weakened and the bacterial cells burst and are killed. One interesting note is that bacterial cells can become resistant to penicillin by changing the structure of transpeptidase so penicillin cannot bind to it (**Figure 5**).

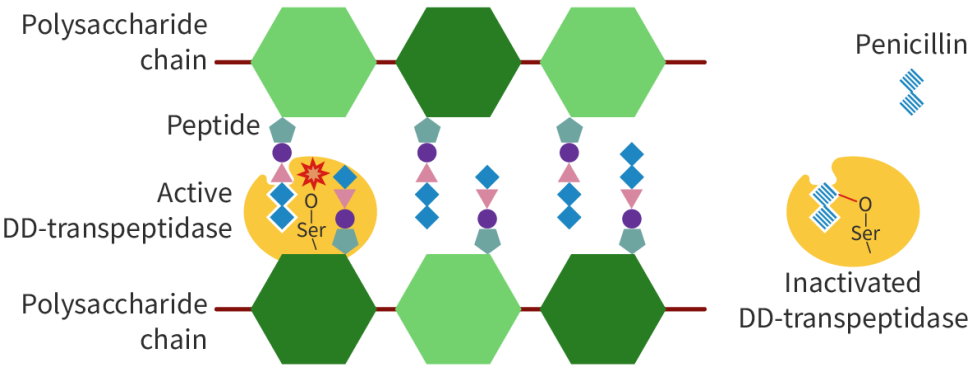

Figure 5. Penicillin: mechanism-based inhibition.

More information for figure 5

The diagram displays the mechanism of penicillin as a mechanism-based inhibitor. Two polysaccharide chains are shown on the left side, connected by peptides. The enzyme, DD-transpeptidase, is labeled as active and shown as binding these structures together. The binding site consists of Serine (Ser) indicated in the diagram.

An explosion symbol on the diagram shows the point where penicillin acts, as it irreversibly binds to the active site of DD-transpeptidase. This inactivation is highlighted in a separate section to the right, portraying the inactivated form of the enzyme.

Above the inactivated enzyme, penicillin is depicted separately, suggesting how it connects to the enzyme. The interaction between penicillin and the serine on the enzyme is crucial to inhibiting the enzyme's function, preventing it from maintaining the bacterial cell wall structure. As a result, the bacterial cells cannot maintain their rigidity and burst.

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Try the activity to help with your understanding of inhibitors.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Read the following and answer the questions.

A 10 year-old-boy accidentally drank up to 50 ml of a radiator coolant containing 95% ethylene glycol. The boy was taken to the doctor with severe headache, fatigue, lack of coordination and slurred speech.

Antifreeze is used in vehicle radiators to prevent the liquid coolant from freezing, it typically contains ethylene glycol, methanol and propylene glycol. If it is accidentally ingested the body can metabolise it into toxic alcohol products. Symptoms of antifreeze intoxication may take time to develop and can be similar to alcohol intoxication and can cause kidney failure.

The first step in metabolism involves an enzyme called alcohol dehydrogenase (**Figure 6**). Two inhibitors of this enzyme used in treating antifreeze poisoning are ethanol and fomepizole. The chemical structures of antifreeze and the two inhibitors are shown in **Figure 7**.

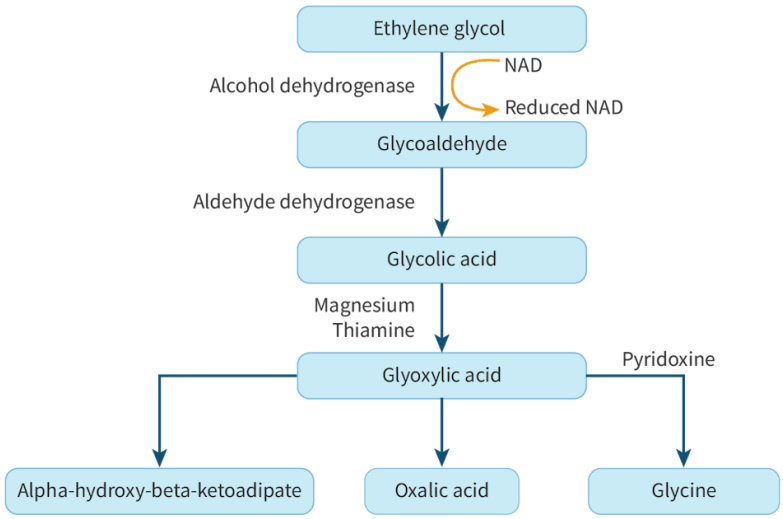

Figure 6. Ethylene glycol metabolic pathway.

More information for figure 6

The flowchart depicts the metabolic pathway of ethylene glycol. It begins with ethylene glycol, which undergoes a transformation facilitated by the enzyme alcohol dehydrogenase. This step involves the conversion of NAD to Reduced NAD. The next product formed is

Student view

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glycolaldehyde. This compound is further metabolized by aldehyde dehydrogenase to produce glycolic acid. Following this, magnesium and thiamine contribute to the next transformation, leading to glyoxylic acid. Glyoxylic acid diverges into three different pathways: it can transform into alpha-hydroxy-beta-ketoadipate, oxalic acid, or glycine. The conversion of glyoxylic acid to glycine is influenced by pyridoxine.

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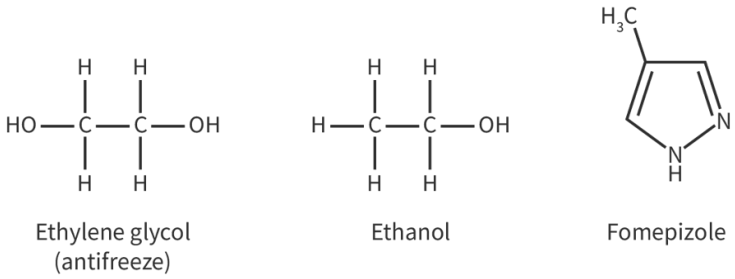

Figure 7. Chemical structures of antifreeze and the two inhibitors.

More information for figure 7

The image shows three distinct chemical structures:

1. **Ethylene Glycol (Antifreeze)**: Displayed on the left, it consists of a two-carbon (C) chain, each bonded with adjacent hydrogen (H) atoms. Hydroxyl groups (OH) are connected to each carbon atom, making the molecular formula HO-CH2-CH2-OH.
2. **Ethanol**: Located in the middle, it is a two-carbon molecule. The first carbon is bonded to two hydrogen atoms and another carbon. The second carbon is bonded to two hydrogens and a hydroxyl group, forming a chain: H-CH2-CH3-OH.
3. **Fomepizole**: Found on the right, it has a five-membered ring containing three carbon atoms, two nitrogen atoms, and a methyl group (CH3) attached to one of the carbon atoms. The structure forms a heterocyclic ring, which is typical for more complex organic compounds.

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1. State if the metabolic pathway is linear or cyclic and justify your answer.
2. State the name of the substrate, the enzyme and the product of the first reaction in the metabolic pathway.
3. Determine which inhibitor is competitive and which one is non-competitive; justify your answer.
4. Studies have shown that fomepizole may be preferred to ethanol as a treatment. Suggest a reason for this.

Student view

5 section questions

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C1. Interaction and interdependence: Molecules / C1.1 Enzymes and metabolism

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/summary-and-key-terms-id-46236/print/) Assign

- Metabolism is the complex network of interdependent and interacting chemical reactions that occur in living organisms. Metabolic pathways can be either cyclical or linear.
- Metabolic reactions can be either anabolic or catabolic reactions. Anabolic reactions build up big molecules from smaller ones and need energy in the process. Catabolic reactions break down big molecules into smaller ones and release energy in the process.
- Enzymes are globular proteins that act as catalysts with an active site.
- Enzymes can be denatured by extreme temperatures and pH.
- Enzymes increase the rate of metabolic reaction by lowering the activation energy of the reaction.
- Enzymes are specific and can only bind to one substrate or a range of similar substrates.
- Reactants in metabolic reactions are called substrates and they bind specifically to the active site. Collisions between the substrate and the active site are important for the catalysis to take place.
- Enzyme activity can be affected by pH, temperature and substrate concentration, and the reaction rate can be determined and compared through experimentation.

Higher level (HL)

- The activity of the enzymes can be inhibited through competitive, non-competitive, end-product inhibition and mechanism-based inhibition.
- Enzymes can either act intracellularly (inside cells) or extracellularly (outside the cells).

Student view

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Key terms

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Checklist

What you should know

After studying this subtopic you should be able to:

- Define metabolism.
- Distinguish between anabolism and catabolism and give examples.
- Describe the structure and role of enzymes.
- Describe the mechanism of enzyme catalysis.
- Describe the role of molecular motion and substrate—active site collisions in enzyme catalysis.
- Explain the relationship between the structure of the active site, enzyme—substrate specificity and denaturation.
- Explain the effect of enzymes on the activation energy.
- Explain the effect of temperature, pH, substrate concentration on the enzyme activity.
- Determine reaction rate through experimentation and secondary data.

Higher level (HL)

- Distinguish intracellular and extracellular enzyme-catalysed reactions.
- Distinguish cyclical and linear pathways in metabolism.
- Explain the generation of heat by metabolic reactions.
- Distinguish competitive and non-competitive inhibition and give examples.
- Explain the end-product inhibition and give examples.
- Explain mechanism-based inhibition.

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Practical skills

Once you have completed this subtopic, go to Practical 3: Investigating the activity of enzymes (/study/app/bio/sid-422-cid-755105/book/investigating-the-activity-of-enzymes-id-46694/) to investigate how temperature, pH and substrate concentration affect the activity of enzymes.

C1. Interaction and interdependence: Molecules / C1.1 Enzymes and metabolism

Investigation

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/investigation-id-46238/print/) Assign

- **IB learner profile attribute:**
  - Thinker
  - Communicator
- **Approaches to learning:**
  - Thinking skills – Applying key ideas and facts in new contexts, Providing a reasoned argument to support conclusions,
  - Communication skills – Presenting data appropriately.
- **Inquiry:**
  - **1 –** Exploring and designing – State and explain predictions using scientific understanding
  - **2 –** Collecting and processing data – Processing data, Interpret qualitative and quantitative data
  - **3 –** Concluding and evaluating – Interpret processed data and analysis to draw and justify conclusions
- **Tools**
  - **1 –** Experimental techniques – Make careful observations
  - **2 –** Technology – Represent data in a graphical form
  - **3 –** Mathematics – Applying general mathematics including calculating the rate, Graphing
- **Time required to complete activity:** 1 hour
- **Activity type:** Individual/pair activity

Student view

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Your task

The plastic-eating enzyme, PETase, is produced naturally by a type of bacteria called *Ideonella sakaiensis*. This naturally occurring enzyme is referred to as "wild-type." Scientists (https://www.sciencenews.org/article/chemistry-recycling-plastic-landfills-trash-materials) have modified the enzyme by altering the sequence of amino acids in the active site, with the goal of addressing the issue of plastic pollution. The efficacy of the modified enzyme was tested against the original enzyme using coloured plastic flakes from PET bottles, and the percentage breakdown of PET was measured over a period of 21 minutes. **Table 1** compiles the secondary data. Answer the questions below which are based on these data.

Table 1. Percentage breakdown of PET with natural enzyme versus modified enzyme.

Time (minutes)	Breakdown in the presence of wild type enzyme (%)	Breakdown in the presence of modified enzyme (%)
3	28	35
6	40	60
9	45	70
12	50	78
15	50	80
18	50	80
21	50	80

1. State the independent and the dependent variables in the investigation.
2. Describe four significant variables that should be kept controlled in this investigation.
3. Sketch a graph using any digital tool.
4. Describe the trend shown in the graph for both enzymes.
5. Calculate the rate of breakdown (%) of both forms over the first 12 minutes.
6. Compare the rate of breakdown of both forms of enzymes.
7. Suggest why the modified enzyme resulted in a higher rate of breakdown compared to the natural enzyme.
8. Explain the reason why the percentage breakdown did not change from 15 to 21 minutes of the investigation.

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Creativity, activity, service

Strand: Creativity
Learning outcome: Demonstrate engagement with issues of global significance

Collaboratively create a large-scale art installation using recycled plastic. You can collect plastic waste from your surroundings and creatively arrange it into a visually striking display that represents the environmental consequences of plastic pollution.

Reflection

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/reflection-id-46881/print/) Assign

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/the-big-picture-id-43208/).

- In what ways do enzymes interact with other molecules?
- What are the interdependent components of metabolism?

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:

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- 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

Submit

Rate subtopic C1.1 Enzymes and metabolism

Help us improve the content and user experience.

☆ ☆ ☆ ☆ ☆

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