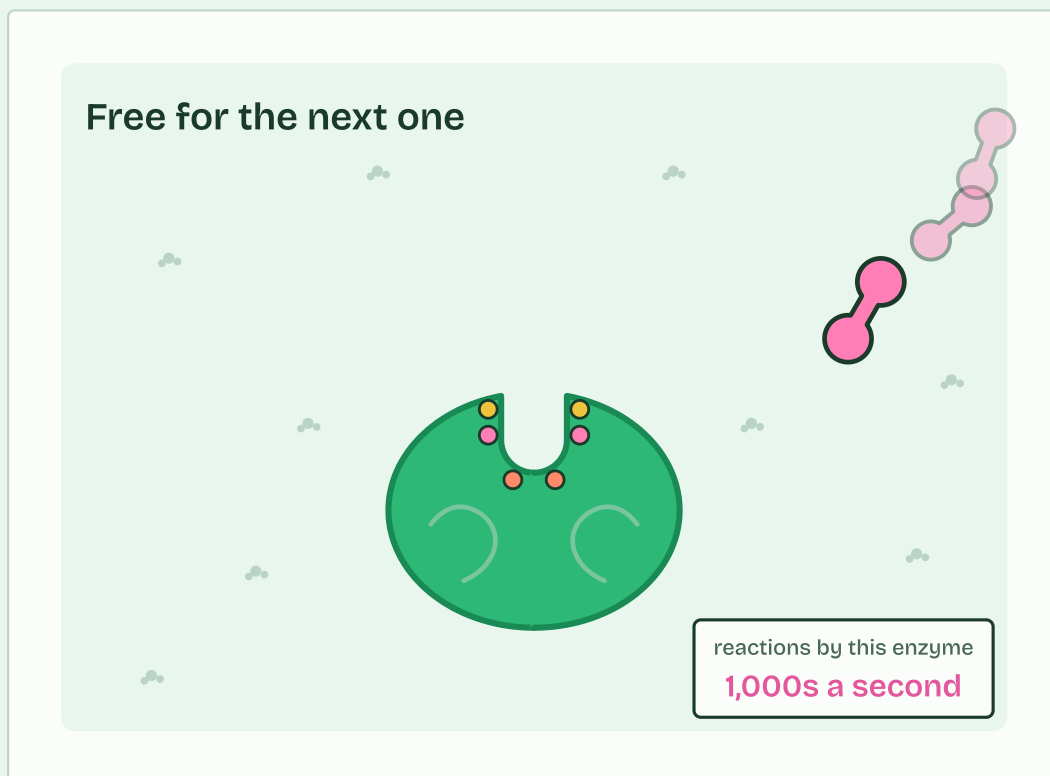


REVISION GUIDE

Every reaction, its own *enzyme*

Enzymes and metabolism

Most of the reactions in your cells would take years, or millions of years, on their own. Enzymes finish them in a blink, at body temperature, each one only the reaction it was shaped for. Here is how they do it, what stops them, and how a cell keeps the whole web of reactions under control.



Contents

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By the end you can

- ☐ Explain why cells need catalysts, and what an enzyme's speed does for digestion, growth and keeping cool enough to live C1.1.1
- ☐ Describe metabolism as a web of linked reactions, and sort reactions into anabolic and catabolic with an example of each C1.1.2, C1.1.3
- ☐ Read an energy diagram and explain how an enzyme lowers the activation energy without changing the energy released C1.1.10
- ☐ Explain how a few amino acids, held in place by the whole folded protein, make an active site, and how induced fit works C1.1.4, C1.1.5
- ☐ Explain why substrate and active site must collide, and how enzymes fixed in membranes still meet their substrates C1.1.6
- ☐ Explain how the shape of the active site makes an enzyme specific, and why denaturation stops it working C1.1.7
- ☐ Sketch and explain the effects of temperature, pH and substrate concentration on the rate, using collision theory and denaturation C1.1.8
- ☐ Work out a rate from your own results or from secondary data, including the initial rate from a tangent C1.1.9
- ☐ Compare enzymes at work inside cells and outside them, and linear pathways with cycles C1.1.11, C1.1.13
- ☐ Explain why metabolism always releases heat, and how mammals and birds use it C1.1.12
- ☐ Explain how a molecule binding an allosteric site stops an enzyme, and why the binding can be undone C1.1.14
- ☐ Explain how statins inhibit an enzyme competitively, and contrast competitive and non-competitive inhibition on a graph C1.1.15
- ☐ Explain how isoleucine controls its own pathway by feedback inhibition C1.1.16
- ☐ Explain how penicillin inhibits transpeptidase for good, and how a changed transpeptidase makes bacteria resistant C1.1.17

Tick each one when you can do it without the book.

01

C1.1.1 ENZYMES AS CATALYSTS

Seconds, not *millions of years*

A **catalyst** is a substance that speeds up a chemical reaction without being used up by it. The same molecule works again and again. **Enzymes** are the catalysts of living things, and nearly all of them are proteins (chapter 4 shows how their shape does the job).

Cells need them because many of the reactions in a cell are possible but hopelessly slow on their own at body temperature. The **rate of reaction** has to be fast enough for life, and an enzyme raises it enormously.

Speed matters in three places:

KEY POINTS

- **Digestion.** Food spends only a few hours in your gut. Its starch, protein and fat must be broken down in that time, or the food leaves unabsorbed.
- **Growth.** A cell has to copy all of its DNA before it divides.
- **Response.** A nerve or a muscle has to respond in a fraction of a second.

There is another way to speed up a reaction: heat it. A cell cannot do that, because a temperature high enough to make these reactions fast would unfold the cell's own proteins (chapter 6). Enzymes give the speed at 37 °C instead.

An enzyme is not used up, so a cell needs only a little of each one. A single catalase molecule can deal with millions of hydrogen peroxide molecules every second. Enzymes do not make impossible reactions happen. They make possible ones fast (chapter 3 shows how).

KEY TERMS

catalyst

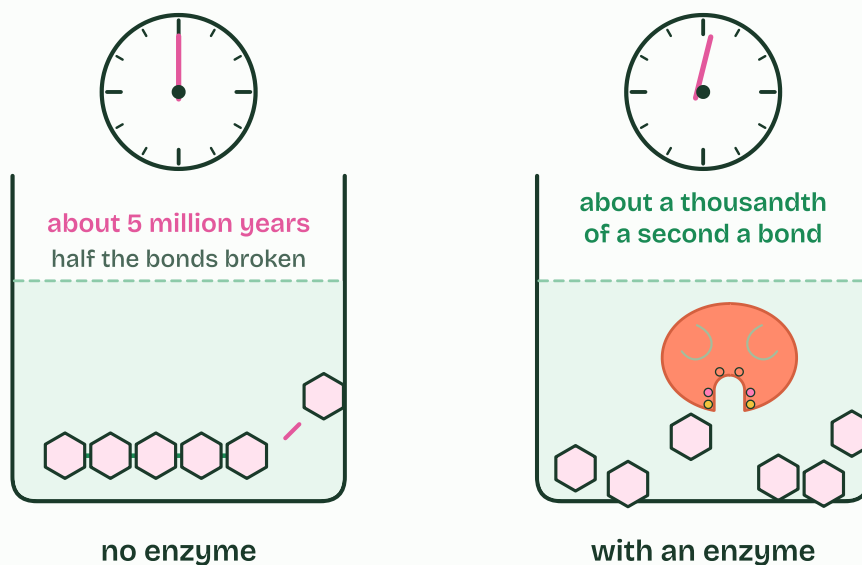
A substance that speeds up a chemical reaction without being used up or changed by it, so the same molecule can work again and again.

enzymes

The catalysts of living things. Nearly all of them are proteins.

rate of reaction

How much substrate is used up, or how much product is made, in a given time.



STEP BY STEP

3 STEPS

1

The same bond in starch, broken two ways.

2

With water alone at room temperature, half the bonds take **millions of years** to break.

3

Amylase breaks each one in about **a thousandth of a second**, at body temperature.

WATCH OUT

An enzyme is not used up by the reaction it catalyses. The substrate changes; the enzyme comes out as it went in.

PREDICT

With no enzyme at all, how long would water at room temperature take to break half the bonds between the glucose units in starch?

- (A) About a week
- (B) About a hundred thousand years
- (C) About five million years
- (D) About two hundred years

Decide before you look. Answer on page 47.

02

C1.1.2

C1.1.3

ROLE OF ENZYMES IN METABOLISM; ANABOLIC AND CATABOLIC REACTIONS

A web of reactions, an *enzyme* for each

Metabolism is every chemical reaction going on in an organism. There are thousands of them, and they are linked: the product of one reaction is the substrate of the next, and many molecules feed several reactions at once. It is a web, not a list. A **metabolic pathway** is one thread of it, a series of steps with an enzyme for each.

Each enzyme catalyses one reaction, or one kind of reaction. This **enzyme specificity** (chapter 6 shows why) is why a cell needs thousands of different enzymes, one for each step. It is also how a cell stays in control: a reaction runs only if its enzyme is there and working. Make more of an enzyme, or less, or switch it off, and that step speeds up, slows or stops.

At higher level, chapters 11 to 13 show how a cell switches enzymes off.

Metabolic reactions fall into two groups. **Anabolic** reactions build larger molecules from smaller ones and take in energy. Monomers are joined into macromolecules by **condensation**, as when amino acids become a polypeptide in protein synthesis, or glucose becomes glycogen. Photosynthesis is anabolic too: it builds glucose from carbon dioxide and water.

Catabolic reactions break larger molecules into smaller ones and release energy. In digestion, macromolecules are broken into monomers by **hydrolysis**. In respiration, substrates such as glucose are broken down by **oxidation**. Drawing on a glycogen store, by breaking it back into glucose, is catabolic too. So not all catabolism is hydrolysis.

KEY TERMS

metabolism

All the chemical reactions in an organism: a complex network of interdependent, interacting reactions.

metabolic pathway

A series of enzyme-catalysed reactions in which the product of one is the substrate of the next.

enzyme specificity

An enzyme catalyses only one reaction, or a few very similar ones, because only certain substrates fit its active site.

anabolic

Reactions that build larger molecules from smaller ones. They take in energy.

condensation

A reaction that joins two molecules and releases a water molecule for every bond made.

catabolic

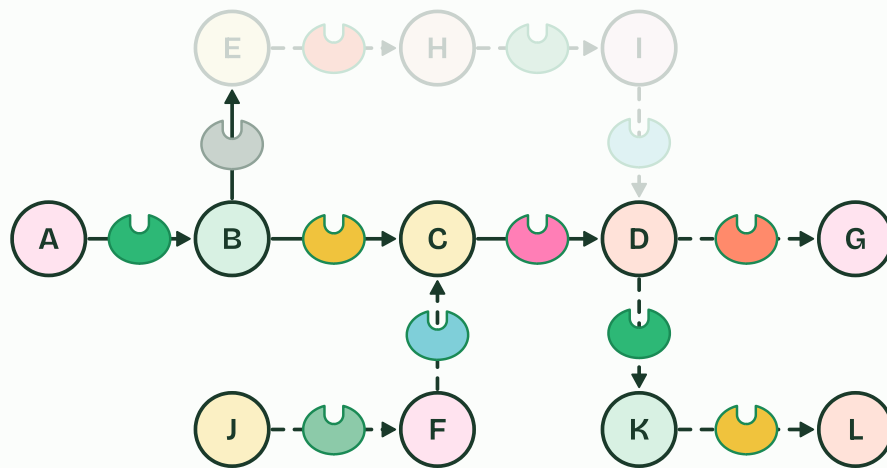
Reactions that break larger molecules into smaller ones. They release energy.

hydrolysis

A reaction that breaks a bond by adding a water molecule, one for every bond broken.

oxidation

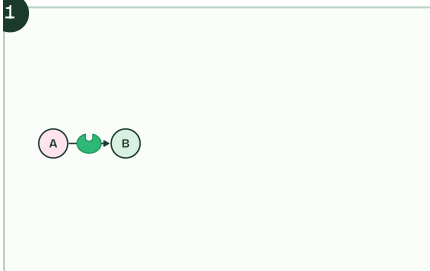
A reaction in which a substance loses electrons or hydrogen, or gains oxygen. In respiration, glucose is oxidised.



A, B, C ... are molecules; each arrow has its own enzyme.

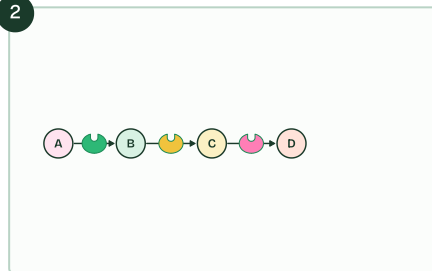
STEP BY STEP

1



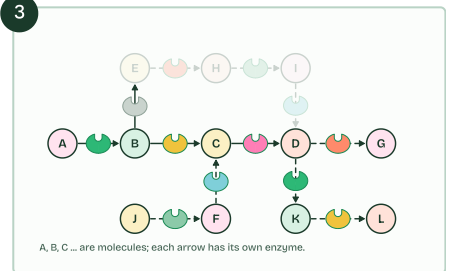
One reaction, one enzyme.

2



The product of one reaction is the substrate of the **next**.

3



Thousands of linked reactions make **metabolism**. Switch off one enzyme and one step stops.

Anabolic: builds up

Catabolic: breaks down

Six reactions to sort

Amino acids joined into a polypeptide at a ribosome

Glucose oxidised to carbon dioxide and water in respiration

Glucose joined into glycogen in a liver cell

Starch digested to maltose in the mouth

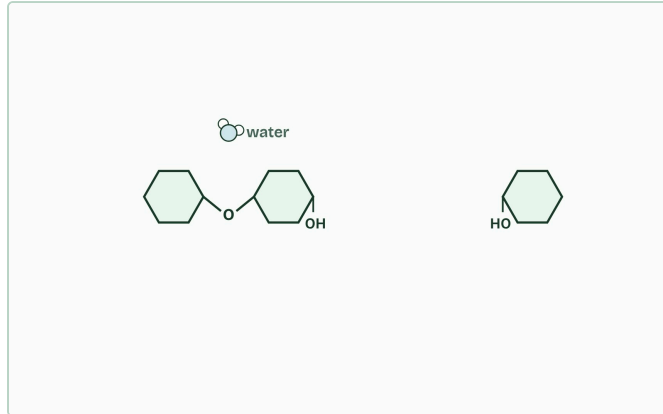
Carbon dioxide and water made into glucose in a leaf

Proteins digested to amino acids in the stomach and intestine

Six reactions in a cell or an organism. Is a bigger molecule being made, or a big one being taken apart?

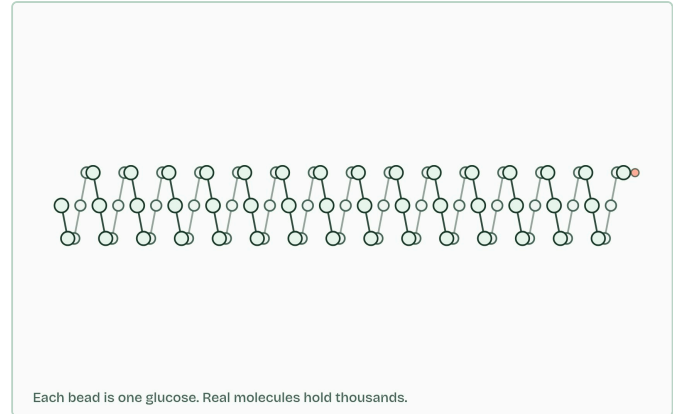
1

WATER RELEASED: 1

Glucose units join one at a time; a **water** molecule leaves at each link.

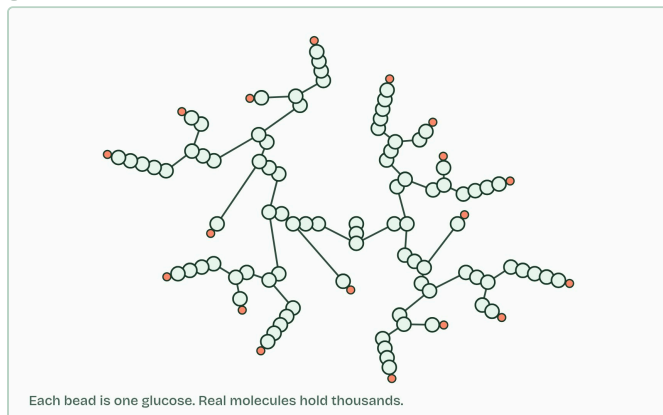
2

ENDS: 1

Amylose **coils** into a helix: a lot of glucose in a small space.

3

ENDS: 18

Amylopectin and glycogen **branch**, so they have many ends.

4

ENDS: 8, GLUCOSE RELEASED: 43

Enzymes take glucose off the **ends**, using a water molecule each time.Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-1-enzymes-and-metabolism#metabolism

REMEMBER IT

The two halves of metabolism

A
Add

Anabolic

builds bigger molecules from smaller ones, takes in energy

C
Cut

Catabolic

breaks bigger molecules into smaller ones, releases energy

WATCH OUT

In science, metabolism is not how fast you burn food. It is every reaction in the body, building as well as breaking.

PREDICT

A liver cell makes thousands of different enzymes. Why so many?

- (A) Each enzyme catalyses one kind of reaction
- (B) Enzymes are used up, so the cell keeps spares
- (C) More kinds of enzyme make every reaction faster
- (D) Each organelle needs its own copy of every enzyme

Decide before you look. Answer on page 47.

03

C1.1.10 EFFECT OF ENZYMES ON ACTIVATION ENERGY

A lower hill to *climb*

For a substrate to react, some of its bonds must be strained and broken, and breaking bonds takes energy. The energy needed before the reaction can run is the **activation energy**. On an **energy diagram** it is a hill that the reaction has to climb: energy up the side, progress of the reaction along the bottom. At the top of the hill the substrate is in an unstable in-between state, part way between substrate and products.

Bond breaking takes in energy. **Bond making** releases it. When the new bonds of the products form, energy comes out. If more comes out than went in, the reaction releases energy overall and the products sit lower than the substrate. Most catabolic reactions are like this. If less comes out, the reaction takes in energy overall and needs a supply of energy to run, as most anabolic reactions do.

An enzyme lowers the hill. As the substrate binds, the active site strains its bonds and holds it in the right position to react (chapter 4), so less energy is needed to reach the top. At 37 °C many more molecules have that much energy, and the reaction runs faster.

Reading the graph: measure the activation energy from the substrate's level up to the peak, and the energy released or taken in overall from the substrate's level to the products'.

KEY POINTS

- Activation energy is the energy needed to strain and break bonds so the reaction can start.
- Breaking bonds takes in energy; making bonds releases it.
- On an energy diagram, activation energy is the climb from the substrate up to the peak.

KEY TERMS

activation energy

The energy needed to strain and break the substrate's bonds so that a reaction can start.

energy diagram

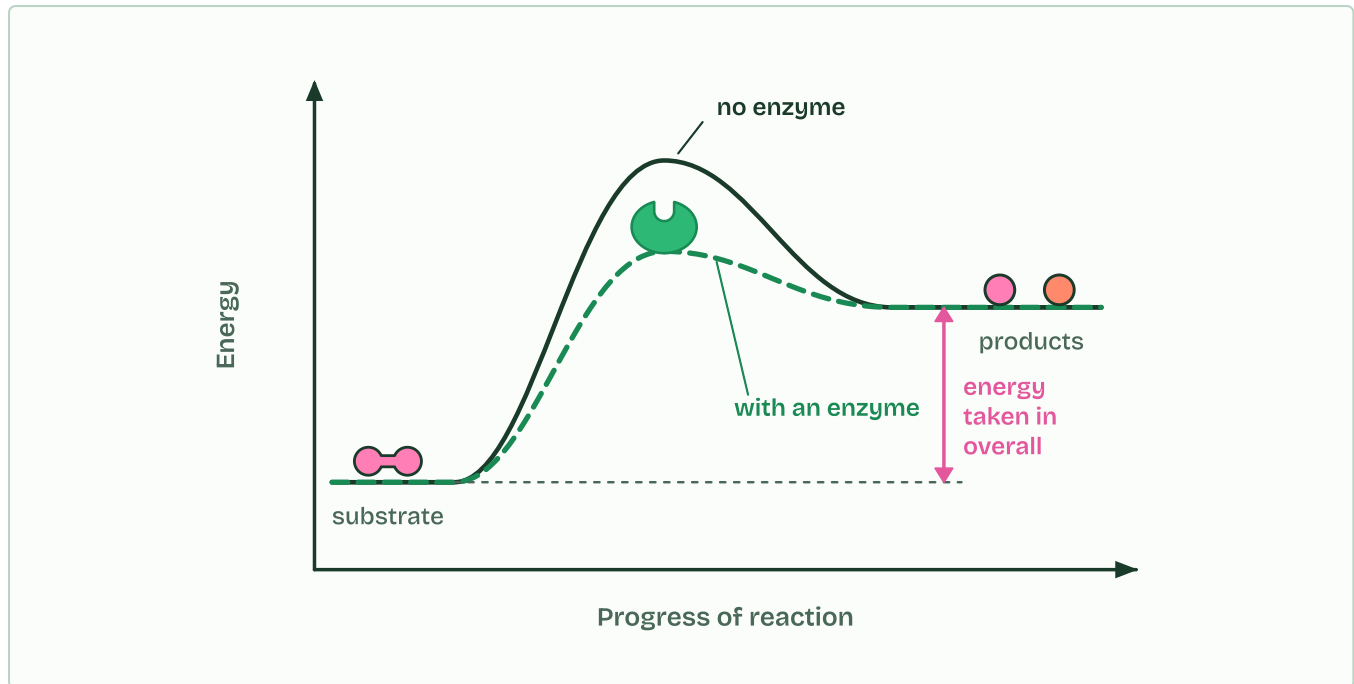
A graph with energy on the vertical axis and the progress of a reaction across, showing the hill of activation energy and the levels of substrate and products.

bond breaking

Splitting a bond takes in energy.

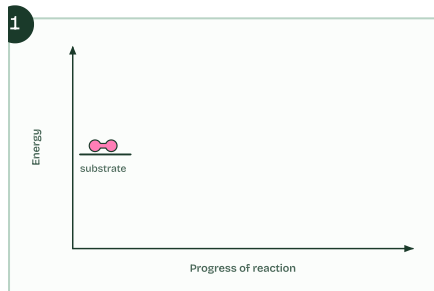
bond making

Forming a new bond releases energy.

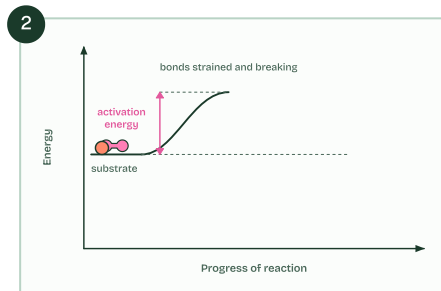


STEP BY STEP

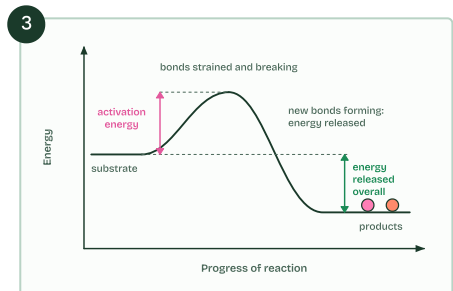
5 STEPS



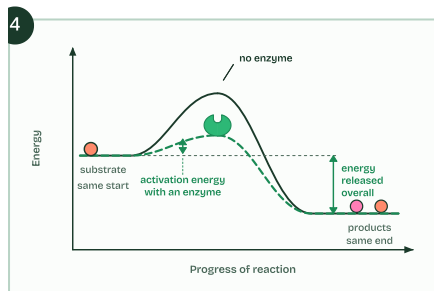
A substrate, before it reacts.



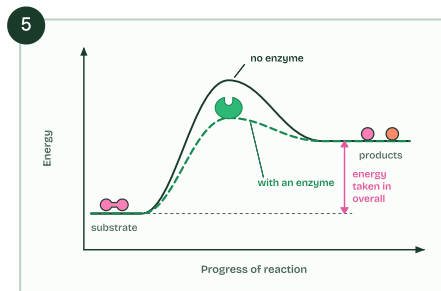
Breaking its bonds needs energy first: the **activation energy**.



Making new bonds releases energy. Here more comes out than went in.



With an **enzyme**, the hill is lower. Start and end do not move.



A building reaction ends higher than it starts. An enzyme lowers its hill too.

WATCH OUT

An enzyme does not give the substrate energy, and it does not change how much energy a reaction releases. It lowers the energy needed to get the reaction started.

PREDICT

An enzyme lowers the activation energy of a reaction that releases energy. What happens to the energy released overall?

- (A) It rises, because less goes into the climb
- (B) It falls, because the enzyme keeps some of it
- (C) It doubles, because two reactions now happen
- (D) Nothing: the start and end levels stay put

Decide before you look. Answer on page 47.

C1.1.4

C1.1.5

GLOBULAR PROTEINS WITH AN ACTIVE SITE; INDUCED-FIT BINDING

04 A pocket held in *shape*

Enzymes are **globular proteins**: one or more polypeptide chains folded into a compact, roughly round shape that dissolves in water (B1.2). Their water-loving R groups mostly face outwards and the water-hating ones are tucked inside, which is why they dissolve. Most enzymes are named for their substrate or their job, with the ending *-ase*: lipase acts on lipids, a protease on proteins and lactase on lactose.

The **active site** is the small region where the **substrate** binds and the reaction happens. It is made of only a few amino acids, often from far-apart places in the chain, brought together by the fold. In lysozyme from egg white, a protein of 129 amino acids, a handful line a groove in its surface and two of them do the chemistry.

The rest of the protein matters as much. Interactions between amino acids all through the folded chain hold the active site in shape and give it the right charges and chemical groups for catalysis.

When the substrate binds, the two form an **enzyme-substrate complex**. Both change shape as it forms: the active site closes in around the substrate, and the substrate is pulled and bent, straining the bonds that are about to break. This is **induced fit**. The substrate is converted into **products**, which no longer fit and leave, and the enzyme returns to its starting shape, ready for another substrate.

KEY TERMS

globular proteins

Proteins whose polypeptide chains are folded into a compact, roughly round shape. Most dissolve in water.

active site

The small region of an enzyme where the substrate binds and the reaction happens. It is made of a few amino acids.

substrate

The molecule an enzyme acts on.

enzyme-substrate complex

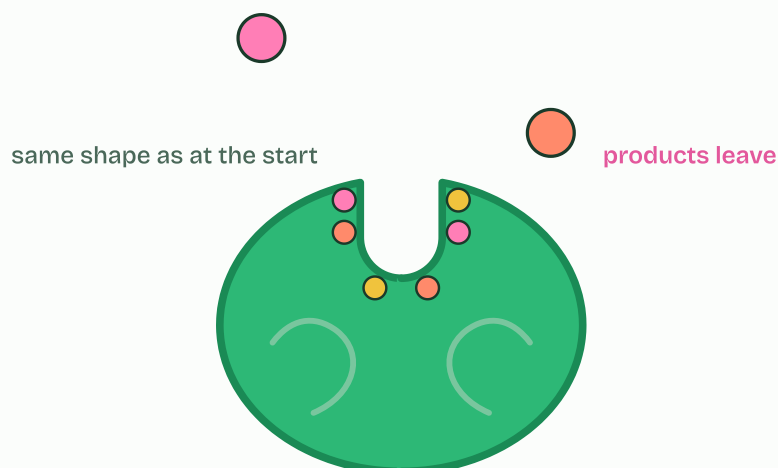
The enzyme with its substrate bound in the active site.

induced fit

The change in shape of both the active site and the substrate as they bind, which strains the substrate's bonds.

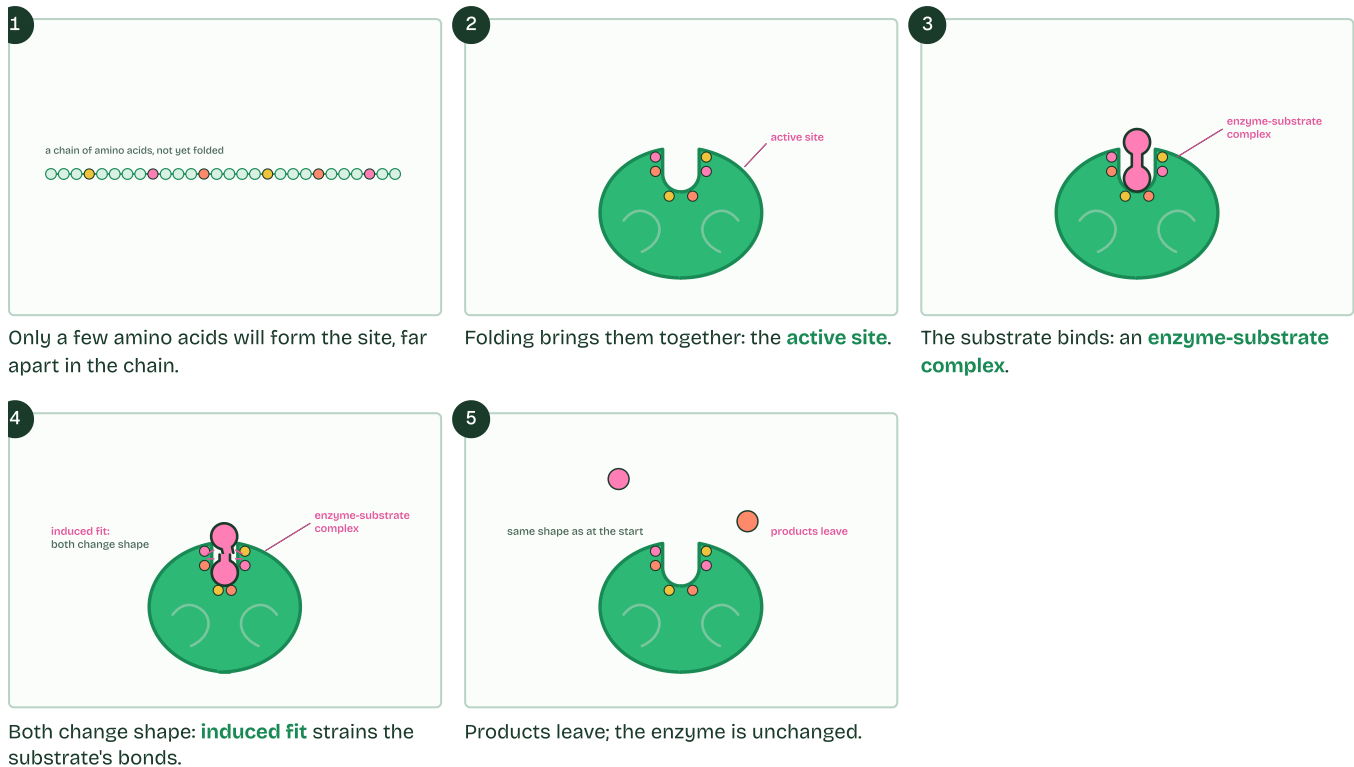
products

The molecules made from the substrate in an enzyme-catalysed reaction.



STEP BY STEP

5 STEPS



REMEMBER IT

What happens at the active site

B Bind	B Bend	B Break	B Bye
Binding the substrate binds the active site	Induced fit both change shape; the substrate's bonds are strained	Reaction bonds break and new ones form: products	Release the products leave; the enzyme is free again

BUILT AS A MODEL

Two models, a century apart. Emil Fischer's lock and key (1894) pictured a rigid site that the substrate fits like a key. Daniel Koshland's induced fit (1958) pictured a site that changes shape as the substrate binds. Both are models. Lock and key cannot explain how binding can improve the fit, or how bonds get strained; induced fit explains both, and matches what is seen in hexokinase, whose two lobes close like jaws round glucose.

WATCH OUT

The active site is not the whole enzyme, and not a fixed, rigid hole. It is a few amino acids that move as the substrate binds.

PREDICT

An enzyme has 300 amino acids, and only about six touch the substrate. A mutation changes one amino acid far from the active site, and the enzyme stops working. How?

- (A) Every amino acid touches the substrate at some moment
- (B) It changed how the chain folds, so the site lost its shape
- (C) The substrate now binds to the changed amino acid instead
- (D) The enzyme can no longer move through the cytoplasm to meet substrates

Decide before you look. Answer on page 47.

05

C1.1.6

MOLECULAR MOTION AND SUBSTRATE-ACTIVE SITE COLLISIONS

Meeting by *chance*

Enzymes and substrates are dissolved in water: in the cytoplasm, in the contents of the gut, in blood plasma. Their molecules move all the time and at random, jostled by the water molecules around them. This **molecular motion** is what brings them together.

A reaction can happen only when a substrate and an active site meet in a **collision**, and only if the substrate arrives the right way round (its **orientation**) and close enough to bind. Most collisions miss the site, or arrive the wrong way round, and the molecules bounce apart.

More collisions a second means a faster rate. Warmer molecules move faster and collide more often; more substrate or more enzyme in the same volume means more meetings. Chapter 7 puts numbers on both, and the film that follows it lets you watch these meetings and change them.

Movement is needed, but not both partners have to move. Sometimes an **immobilised enzyme** is held still, embedded in a membrane. Sometimes it is a large substrate that is held still, such as a cellulose fibre in a plant cell wall, and the enzyme moves to it: cellulase released by a fungus reaches the fibre and digests it where it lies. Tap the three states to compare them.

Fixing an enzyme in place also keeps it where its products are wanted. Lactase sits in the membrane of the cells that line the small intestine, so the glucose and galactose it makes appear right at the surface of the cells that absorb them.

KEY TERMS

molecular motion

The constant random movement of molecules in a liquid or gas, caused by their energy and by collisions with other molecules.

collision

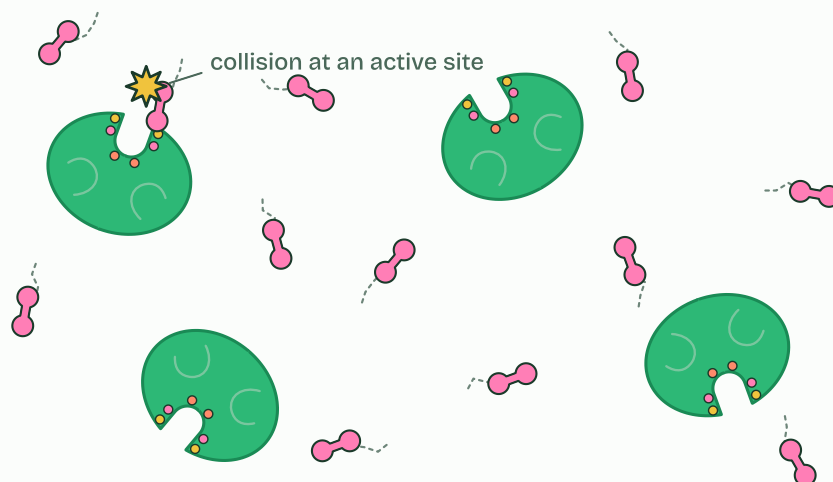
Two molecules striking each other. An enzyme reaction needs a collision between a substrate and an active site.

orientation

The way a molecule faces when it collides. A substrate must meet the active site the right way round to bind.

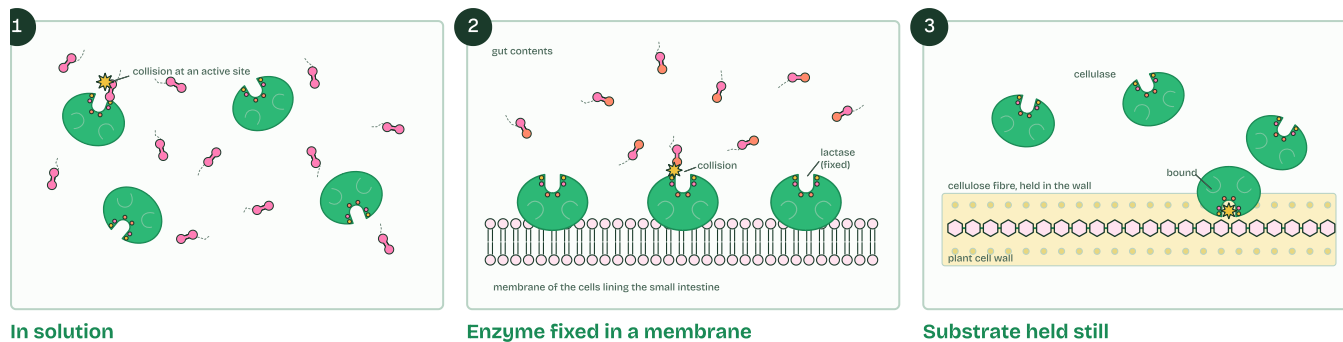
immobilised enzyme

Here, an enzyme held in place, for example embedded in a membrane, so that the substrate moves to it.



SWITCH IT

3 SETTINGS



ON PURPOSE

Industry fixes enzymes on purpose too: lactase held on beads makes lactose-free milk as the milk flows past.

PREDICT

Lactase sits fixed in the membrane of cells lining your small intestine. It cannot move. How does lactose reach its active site?

- (A) The membrane pumps lactose to it
- (B) The active site attracts lactose from across the whole gut
- (C) Lactase reaches out and grabs passing lactose
- (D) Lactose molecules move at random and collide with it

Decide before you look. Answer on page 47.

06

C1.1.7 ACTIVE SITE STRUCTURE, SPECIFICITY AND DENATURATION

Lose the shape, lose the *fit*

The active site's shape and charges match its substrate's, so few other molecules bind. This is **enzyme-substrate specificity**. Some enzymes act on one substrate, or very nearly: urease on urea. Others act on a family of similar substrates: lipase on many lipids, a protease on many peptide bonds. The rule is the same: what binds is what fits.

The shape is held by weak interactions between amino acids: hydrogen bonds, ionic bonds and interactions between non-polar R groups (B1.2), with a few strong ones. That is why the shape can be lost. You watched a protein unfold in B1.2.

Heat makes the chain vibrate harder. Above a certain temperature the weak bonds break, the chain unfolds and the active site loses its shape. A pH far from the enzyme's normal one changes the charges on R groups in and around the site, because they gain or lose hydrogen ions, so ionic bonds break and the site's charges no longer match the substrate. Either way the substrate no longer binds, or binds and does not react. This is **denaturation**.

A denatured enzyme is not killed: it was never alive. Heat denaturation is usually permanent, and cooling does not refold the chain. A small, brief change in pH can sometimes be undone when the pH returns, but an extreme one usually cannot. Cold does not denature an enzyme at all. It slows the enzyme, because there are fewer collisions (chapter 7), and the enzyme works again when it is warmed.

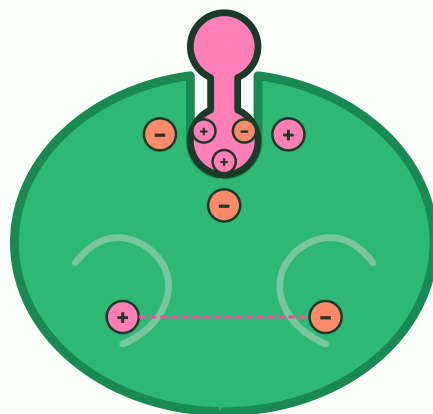
KEY TERMS

enzyme-substrate specificity

Only a substrate whose shape and charges match the active site can bind, so each enzyme acts on one substrate, or a few similar ones.

denaturation

A change in the three-dimensional shape of a protein, caused by heat or a pH far from its normal one, so that it can no longer do its job. It is usually permanent.



The shapes fit and the charges match: opposite signs sit side by side.

SWITCH IT

4 SETTINGS

1

The shapes fit and the charges match: opposite signs sit side by side.

Its substrate

2

A different molecule: wrong shape and charges, so it does not bind.

A different molecule

3

Heated: the chain loosens, the groove is gone, and the substrate drifts by.

Too hot

4

Wrong pH: the site's charges change, a bond in the fold breaks, and the substrate no longer matches.

Wrong pH

WATCH OUT

Enzymes are not killed by heat, and cold does not denature them. Heat denatures; cold only slows.

PREDICT

Pepsin digests protein in the stomach at about pH 2. Carried on into the small intestine at about pH 8, what happens to it?

- (A) It denatures: its active site changes shape and charge
- (B) It works faster, because collisions are more frequent at pH 8
- (C) It is unaffected, because pH only changes the substrate
- (D) It reshapes its active site to fit the new substrates there

Decide before you look. Answer on page 47.

07

C1.1.8

EFFECTS OF TEMPERATURE, PH AND SUBSTRATE CONCENTRATION

Three graphs to *know*

Sketch it first. On paper or a whiteboard, sketch rate of reaction against temperature, against pH and against substrate concentration before you play the figure. Then check yourself against it.

Temperature. Below the **optimum**, warming the solution makes enzyme and substrate move faster, so they collide more often and more collisions have enough energy to react. The rate rises, roughly doubling for every 10 °C. Above the optimum the enzyme denatures faster than the extra collisions can help, and the rate falls steeply. So the curve is not symmetrical: a gentle rise, a steep fall. Optima differ. Many human enzymes work best at about 37 to 40 °C; the DNA polymerase of a bacterium from hot springs works best at about 75 °C.

pH. Each enzyme works fastest at its own optimum pH, and the rate falls either side as the charges in the active site change and, further out, the enzyme denatures. Pepsin in the stomach prefers about pH 2, salivary amylase about pH 7 and trypsin in the small intestine about pH 8.

Substrate concentration. At low concentration, more substrate means more collisions with free active sites, so the rate rises almost in step. Then the curve bends over and levels off at a maximum. More enzyme would raise that maximum. All three effects follow from **collision theory** and denaturation.

Describe a graph in parts, with numbers from its axes: "rises steadily to an optimum near 40 °C, then falls steeply". These smooth curves are **sketch graphs**: models of the general pattern, not the data of one enzyme. Real results scatter and have their own optimum, and a model is tested against results from experiments such as the dry lab's.

Inhibitors change these graphs too: chapters 11 and 12.

KEY TERMS

optimum

The value of temperature or pH at which an enzyme's rate is highest.

collision theory

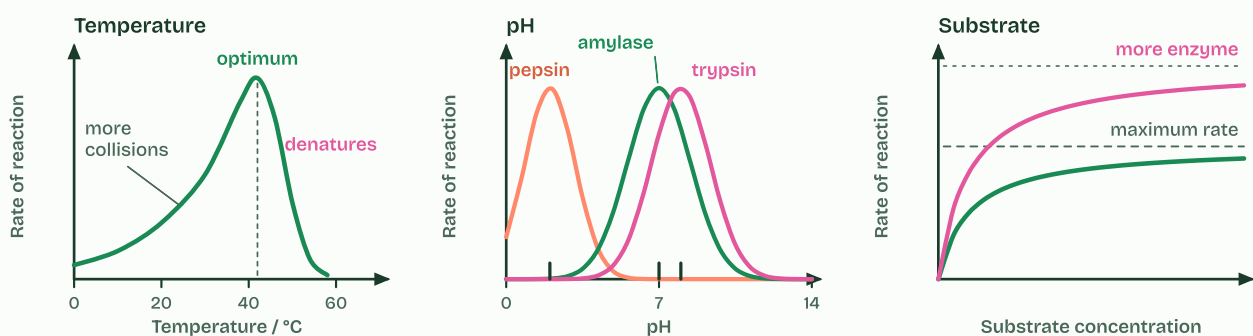
The idea that a reaction needs a collision, with enough energy and the right orientation, between the reacting particles.

sketch graphs

Generalised graphs of a relationship. They are models in biology: they show the general pattern, not the data of any one enzyme.

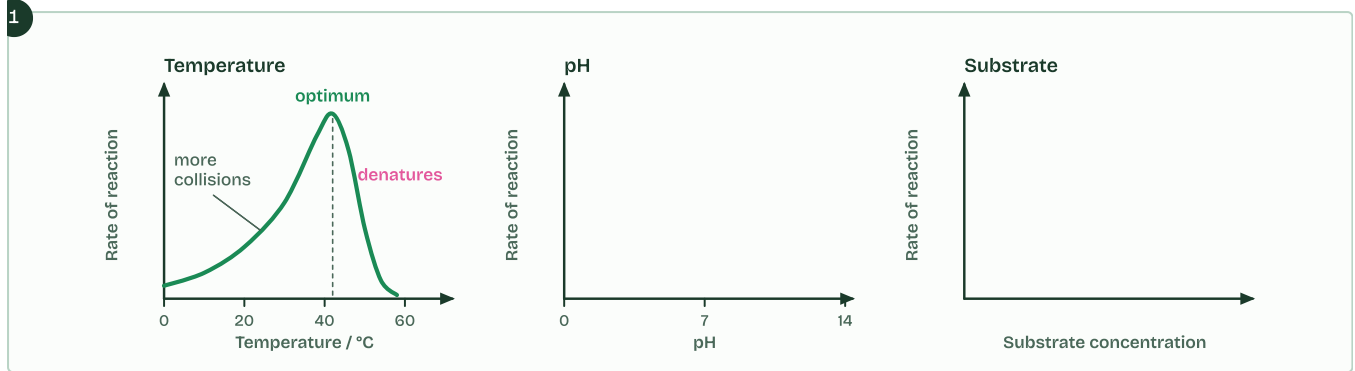
saturation

With nearly every active site occupied at any moment, so that more substrate barely raises the rate.

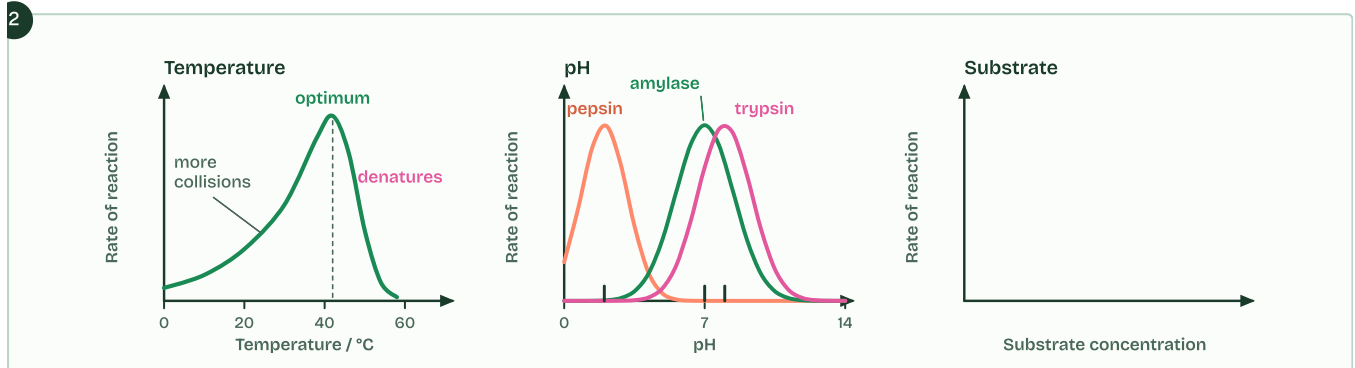


STEP BY STEP

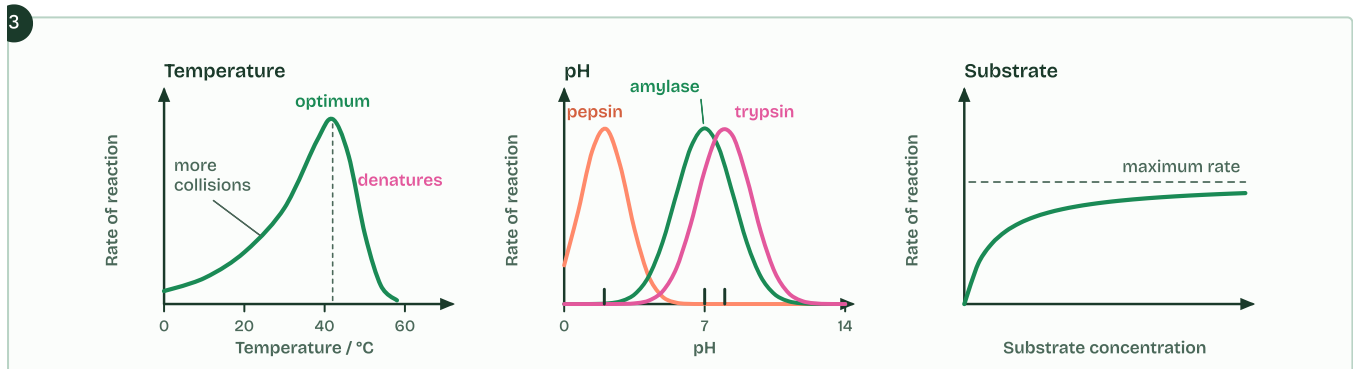
4 STEPS



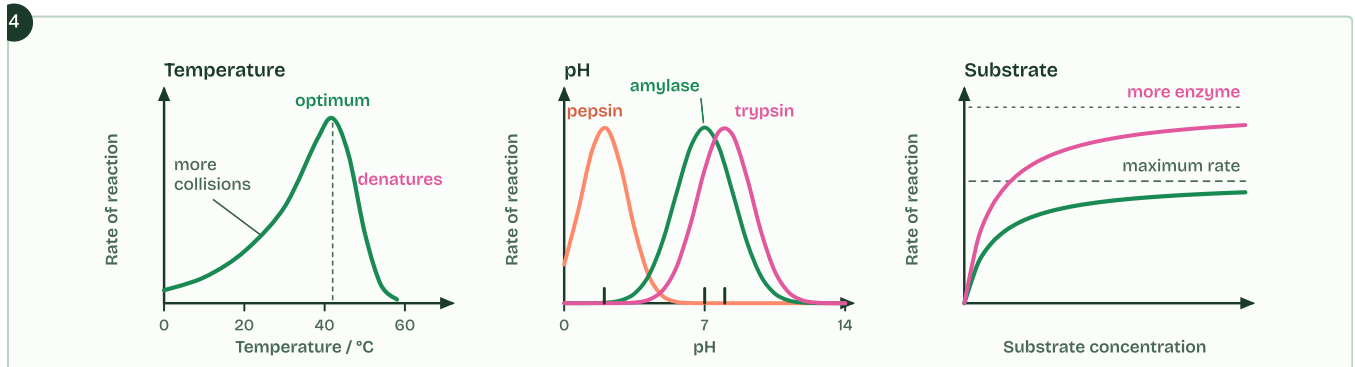
Temperature: faster collisions, then **denaturation**.



pH: each enzyme has its own **optimum**.



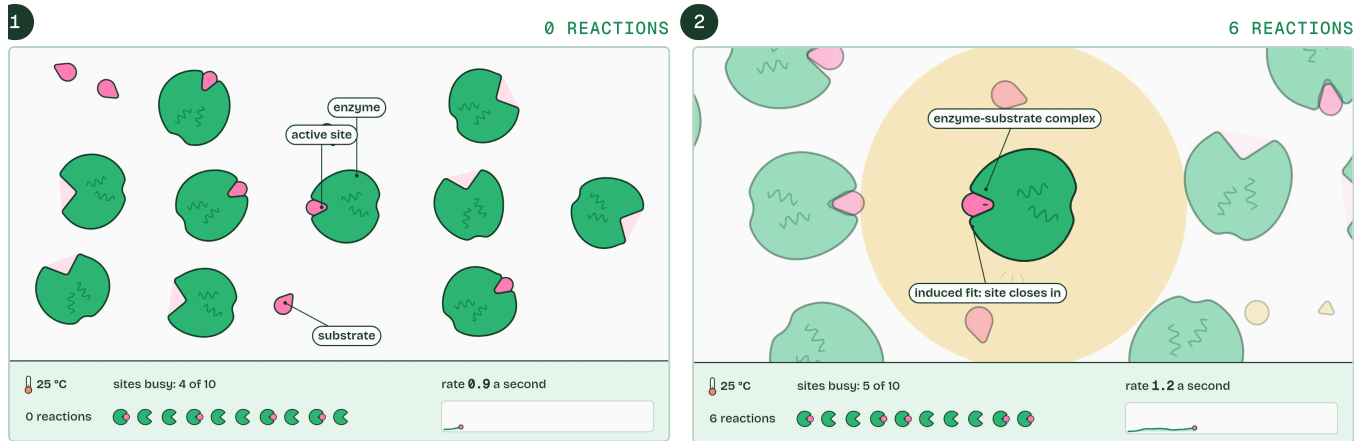
Substrate: the rate rises, then **levels off**.



More enzyme raises the maximum.

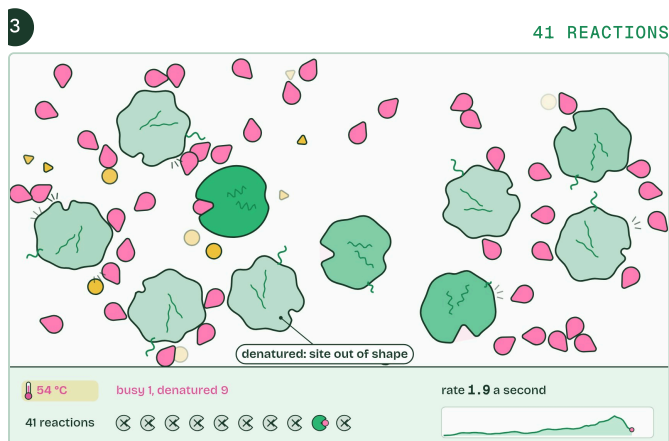
ANIMATION · WATCH IT HAPPEN: COLLISIONS, SUBSTRATE AND HEAT

3 MOMENTS



Molecules move at **random**, and most collisions miss the active site.

A **successful collision**: it binds and reacts, and the enzyme is unchanged.



Too hot: enzymes **denature**. Active sites lose their shape, and the rate falls.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-1-enzymes-and-metabolism#factors

REMEMBER IT

The three factors you must explain

T Tigers Temperature collisions, then denaturation	P Prefer pH charges in the active site	S Steak Substrate concentration collisions, then saturation
--	--	---

WATCH OUT

The optimum is not always 37 °C. That is roughly where many human enzymes peak; enzymes from other organisms peak far higher or lower.

PREDICT

On a graph of rate against substrate concentration, the curve levels off. Why?

- (A) The substrate has all been used up
- (B) The enzyme is denatured by so much substrate
- (C) Nearly every active site is already busy
- (D) Molecules collide less often when crowded

Decide before you look. Answer on page 47.

08

C1.1.9 MEASUREMENTS IN ENZYME-CATALYSED REACTIONS

Measuring a *rate*

A **rate of reaction** is a change per unit time. For an enzyme, you can measure either how fast a product appears or how fast the substrate disappears. Catalase makes oxygen, which can be collected in a gas syringe and read in $\text{cm}^3 \text{min}^{-1}$. Amylase uses up starch, which can be tested with iodine solution: you time how long it takes before a drop no longer turns blue-black.

Plot the product against time and the curve is steepest at the start, then flattens as the substrate is used up. The **initial rate** is the gradient at the very start, before the substrate runs low, and it measures the enzyme under the conditions you set. Draw a **tangent** to the curve at time zero and work out its gradient: rise over run, with units.

Where you only time an end point (the starch has gone, a paper disc has floated up), the rate is $1 \div \text{time}$, in s^{-1} . Twice as fast means half the time.

One enzyme can be followed three ways. For catalase: the oxygen collected in a gas syringe; the oxygen collected over water in an upturned measuring cylinder; or a small filter paper disc soaked in extract, dropped into the peroxide and timed as it rises on the oxygen it makes.

A fair test changes one variable (the independent variable), measures the rate (the dependent variable) and keeps everything else the same: temperature in a water bath, pH with a buffer, the same volumes and concentrations. Repeat each value at least three times, and include controls, such as no enzyme and boiled enzyme.

You can also work out rates from **secondary data**: someone else's results in a table or graph. Reading the gradients is the same. The dry lab below is the place to do it all.

KEY TERMS

rate of reaction

How much substrate is used up, or how much product is made, in a given time.

initial rate

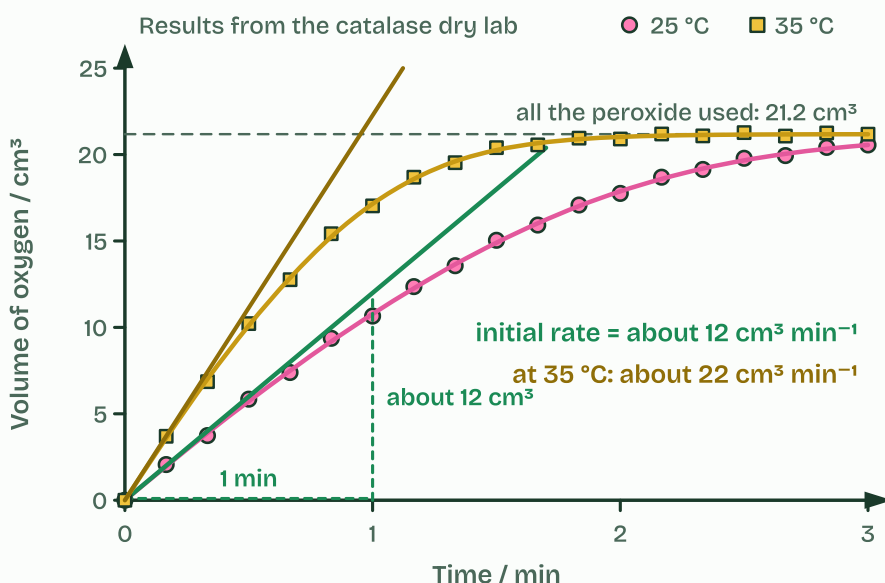
The rate at the very start of a reaction, found as the gradient of a tangent to the curve at time zero, before the substrate runs low.

tangent

A straight line that touches a curve at one point and has the same gradient as the curve there.

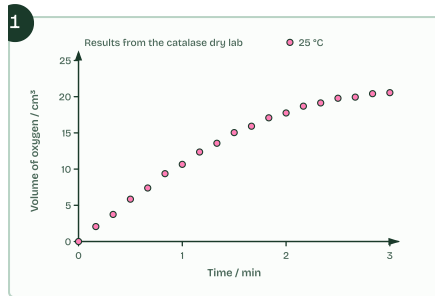
secondary data

Data collected by someone else, such as results in a table or a graph in a paper, that you analyse yourself.

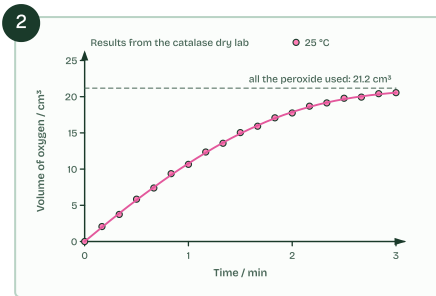


STEP BY STEP

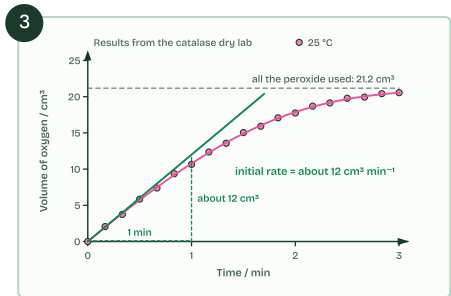
4 STEPS



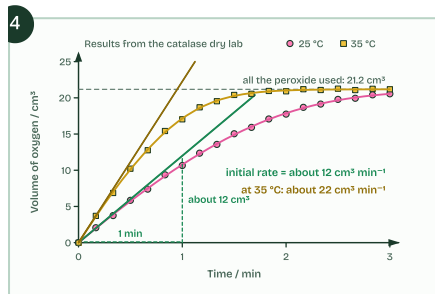
Oxygen collected every 10 seconds.



Fast at first, then slower as the **substrate** runs out.



The **initial rate** is the gradient of a tangent at the start.



Warmer: a steeper start, the same total.

WATCH OUT

The total amount of product at the end measures how much substrate you put in, not how fast the enzyme works. Use the initial rate.

PREDICT

A drop of a starch and amylase mixture stops turning iodine blue-black after 40 s at 30 °C and after 80 s at 20 °C. Compare the rates.

- (A) The rate is higher at 20 °C, because it took longer
- (B) The rate at 30 °C is double: rate is 1 ÷ time
- (C) The rates are the same: the same starch was broken down
- (D) The rate at 30 °C is 40 units higher than at 20 °C

Decide before you look. Answer on page 48.

C1.1.11 HL

C1.1.13 HL

INTRACELLULAR AND EXTRACELLULAR REACTIONS; LINEAR AND CYCLICAL PATHWAYS

09

Chains, cycles, inside and *out*

Intracellular reactions happen inside cells, catalysed by enzymes that stay there. "Inside" means anywhere inside: in the cytoplasm, as glycolysis, the first stage of respiration, does, or inside an organelle, as the Krebs cycle does in the matrix of a mitochondrion. **Extracellular** reactions happen outside the cells that made the enzymes. The example is chemical digestion in the gut: cells of the salivary glands, the stomach lining and the pancreas make digestive enzymes and secrete them into the gut, where they hydrolyse food molecules.

The two kinds are made in different places. Enzymes that stay in the cytoplasm, such as those of glycolysis, are made by free ribosomes. Enzymes for export are made by ribosomes on the rough endoplasmic reticulum, packaged by the Golgi apparatus and released by exocytosis (B2.2).

Most metabolism runs as pathways, a series of steps each with its own enzyme. In a **linear pathway** the first substrate is turned, step by step, into a different end product. **Glycolysis** is the example: glucose goes in at the start and pyruvate comes out about ten steps later. A **cyclical pathway** ends by remaking the molecule it started from. Something is added at each turn and something leaves, but the carrier molecule comes back round, so a small amount of it keeps the cycle turning. The **Krebs cycle** (C1.2) and the **Calvin cycle** (C1.3) are the examples.

Why pathways, and not one leap? Each step needs only a small activation energy, energy is released or used a little at a time, and each step's enzyme is a point of control (chapter 13).

KEY TERMS

intracellular

Inside a cell: in the cytoplasm or inside an organelle.

extracellular

Outside the cells that made the enzymes. Chemical digestion in the gut is the example.

linear pathway

A pathway in which the first substrate is converted step by step into a different end product.

glycolysis

The first stage of respiration: a linear pathway of about ten steps in the cytoplasm that converts glucose to pyruvate.

cyclical pathway

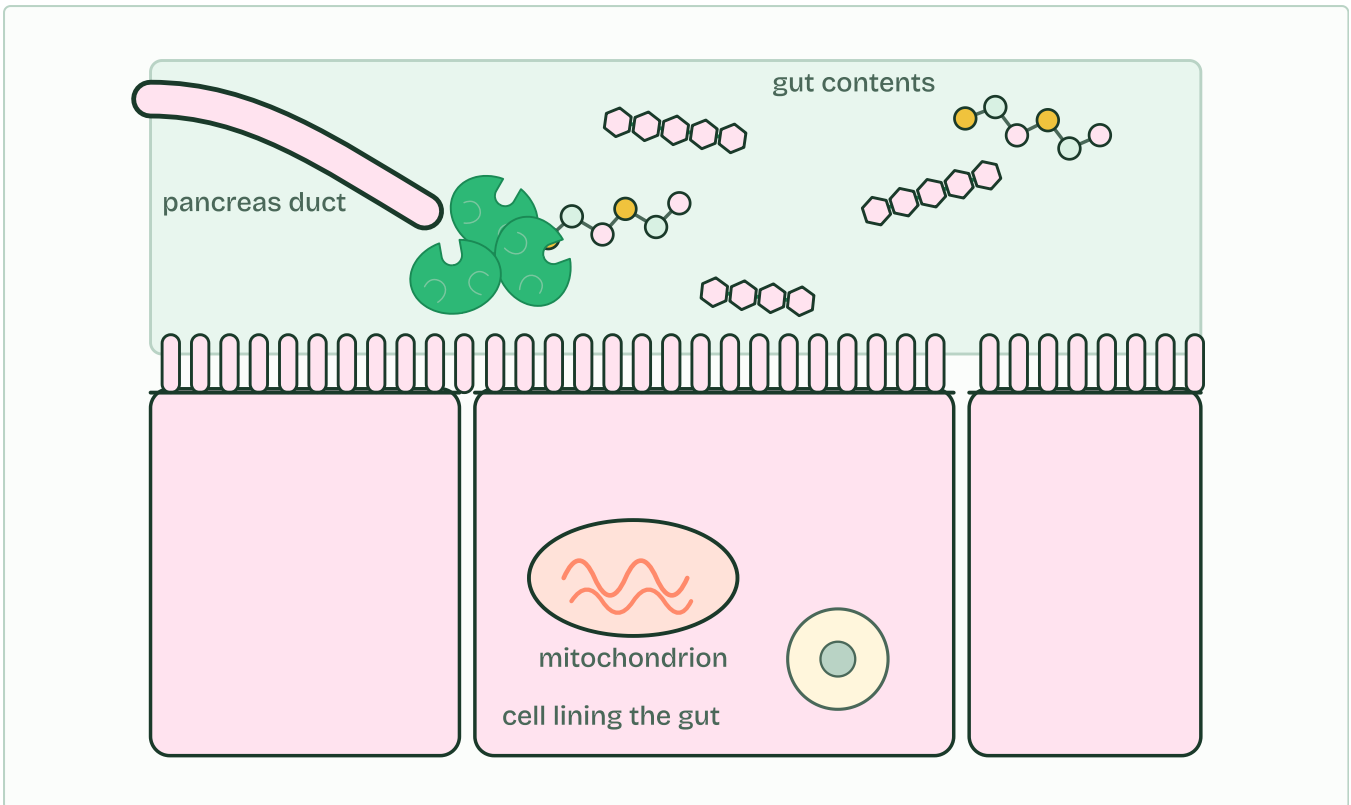
A pathway that ends by remaking the molecule it started from, so that a small amount of that carrier keeps the cycle turning.

Krebs cycle

A cyclical pathway in the matrix of the mitochondrion, part of aerobic respiration (C1.2).

Calvin cycle

A cyclical pathway in the stroma of the chloroplast that builds sugar from carbon dioxide (C1.3).



The gut contents This is outside every cell. Digestive enzymes that were secreted into the gut break the food down here: an extracellular reaction.

Inside a cell Glycolysis runs here, in the cytoplasm. Everything inside the cell's membrane is intracellular.

An organelle inside the cell The Krebs cycle runs in the matrix of the mitochondrion. This is inside a cell too, so it is intracellular.

Duct from the pancreas Cells in the pancreas make digestive enzymes and secrete them along this duct into the gut.

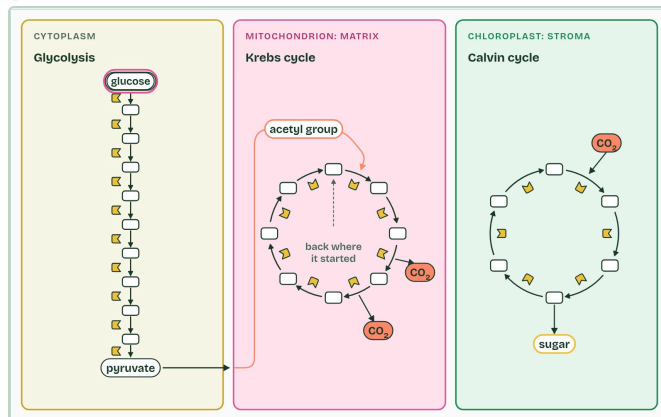
The cell's own membrane Microvilli, its fingers, carry enzymes fixed in the membrane that finish digestion at the cell surface (chapter 5).

1

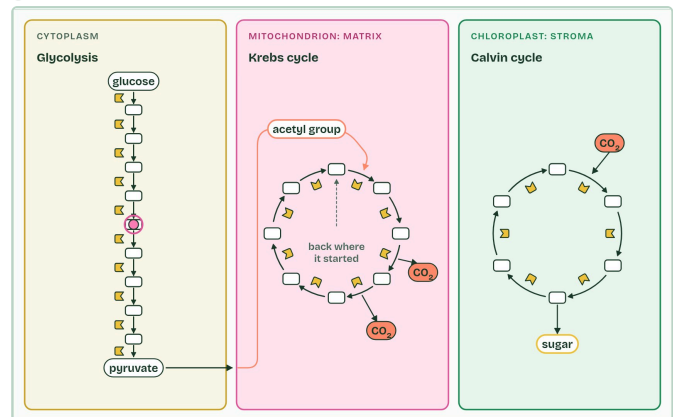
GLYCOLYSIS

2

GLYCOLYSIS



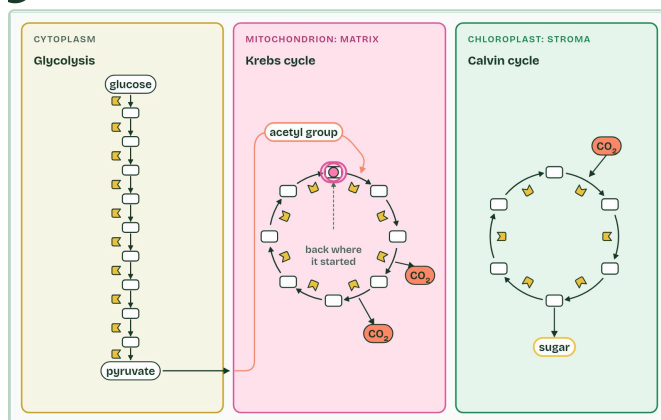
Glycolysis, in the cytoplasm: glucose is changed a step at a time, each step by its own enzyme.



A **linear** pathway: what goes in at one end leaves at the other as something else, pyruvate.

3

KREBS CYCLE



Back where it started: the last step remakes the molecule the first step needs. A **cycle**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-1-enzymes-and-metabolism#pathways

WATCH OUT

A cycle does not make something from nothing. Molecules join at each turn and products leave; what comes back round is the carrier molecule.

PREDICT

Glycolysis runs in the cytoplasm, the Krebs cycle inside mitochondria, and protein digestion in your stomach. Which are intracellular?

- (A) Protein digestion only: it happens inside an organ
- (B) Glycolysis only: mitochondria are outside the cytoplasm
- (C) All three: the stomach is inside your body
- (D) Glycolysis and the Krebs cycle: both inside cells

Decide before you look. Answer on page 48.

10

Warm from the *inside*

C1.1.12 HL GENERATION OF HEAT BY METABOLISM

No energy transfer in metabolism is 100% efficient. The **efficiency** of a transfer is the share of the energy that ends up where it is wanted. When respiration releases the energy in glucose, only about a third is captured in ATP, and the rest is released as **heat**. When the ATP is then used, to contract a muscle or to build a protein, most of that energy ends as heat too. Heat generation is inevitable.

The faster the metabolism, the more heat. You get hot when you run because your muscles respire faster, and a resting adult gives off about as much heat as a lamp of 80 to 100 watts.

Mammals and birds depend on this heat. They keep a high and constant body temperature, about 37 °C in most mammals and about 40 to 42 °C in most birds, mostly well above the air around them, by generating heat from their metabolism. They are **endotherms**. A few other animals warm themselves from their own metabolism at times: a bumblebee shivers its flight muscles to warm up before take-off.

This is how an endotherm keeps its temperature steady. When the air turns colder it loses heat faster, so its metabolic rate rises to replace what is lost, and its body temperature stays where it was (D3.3 shows how the change is controlled).

Why does it pay? Enzymes work fastest near their optimum, so a steady warm body keeps every reaction fast and predictable, whatever the weather (chapter 7).

KEY TERMS

efficiency

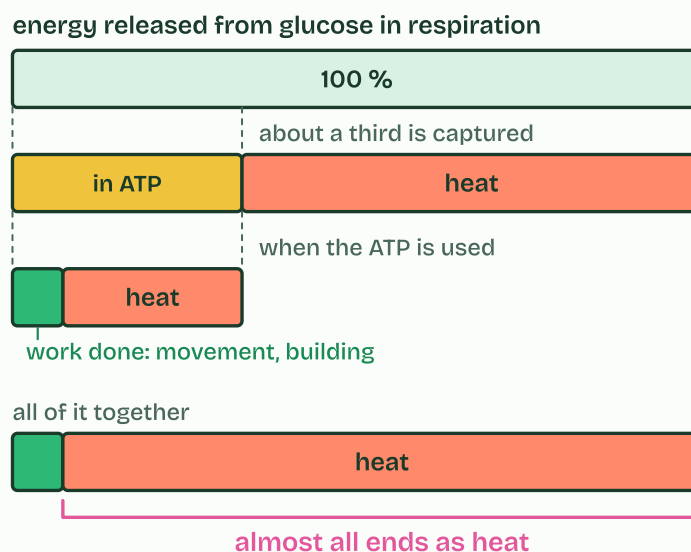
The share of the energy put into a process that ends up where it is wanted, rather than as heat.

heat

The form of energy that is given off by every metabolic reaction, because no energy transfer is completely efficient.

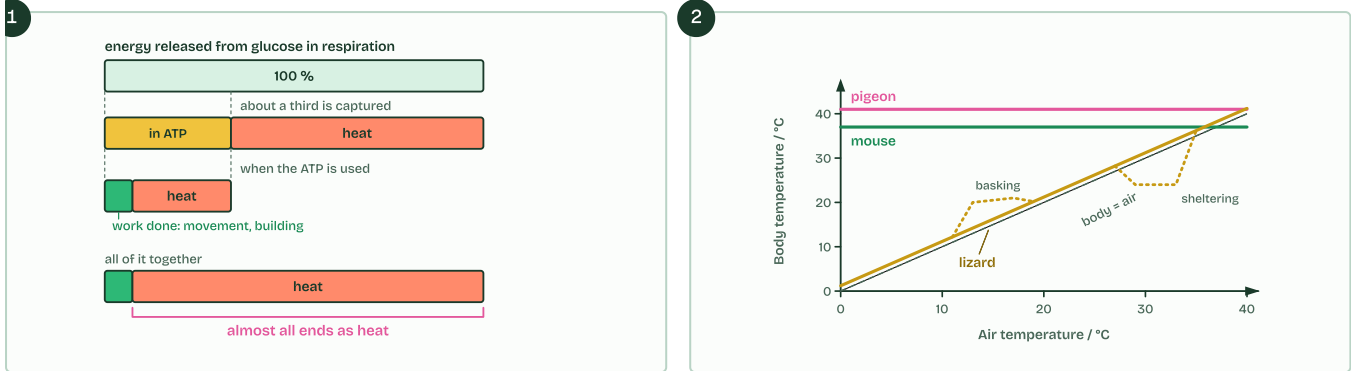
endotherms

Animals that keep a constant body temperature, above that of their surroundings, by generating heat from their own metabolism.



SWITCH IT

2 SETTINGS



Energy from glucose

Body against air temperature

WATCH OUT

Heat from metabolism is not a fault to be fixed. It is unavoidable, and for mammals and birds it is what keeps every enzyme near its optimum.

PREDICT

A mouse and a lizard of the same mass sit at 20 °C for a day. Which needs more food, and why?

- (A) The lizard: it must make up for its cold body
- (B) Neither: animals of the same mass need the same food
- (C) The mouse: heat from respiration keeps it at 37 °C
- (D) The mouse: its enzymes waste more of their energy

Decide before you look. Answer on page 48.

11

C1.1.14 HL ALLOSTERIC SITES AND NON-COMPETITIVE INHIBITION

A second *site*

An **inhibitor** is a molecule that binds to an enzyme and slows or stops its reaction. Many enzymes have, as well as the active site, a second site elsewhere on the molecule: an **allosteric site**. Like the active site, it is specific: only particular molecules fit and bind.

When one binds, it changes the interactions inside the enzyme, so the enzyme's shape changes, a **conformational change**, and that alters the active site enough to stop catalysis. The substrate no longer binds, or binds and does not react. This is **non-competitive inhibition**: the inhibitor does not compete with the substrate for the active site.

The binding is **reversible**. When the inhibitor leaves, the enzyme returns to its working shape. So the amount of inhibition depends on how much inhibitor there is: the more inhibitor, the bigger the share of enzyme molecules switched off at any moment.

Adding more substrate does not help, because substrate cannot push a molecule off a site it does not bind to (the graph is in chapter 12). And this is how a cell switches enzymes off and on (chapter 13).

KEY TERMS

inhibitor

A molecule that binds to an enzyme and slows or stops its reaction.

allosteric site

A site on an enzyme, away from the active site, where only a specific molecule can bind. Binding changes the enzyme's shape and so its active site.

conformational change

A change in the three-dimensional shape of a protein, here caused by something binding at the allosteric site.

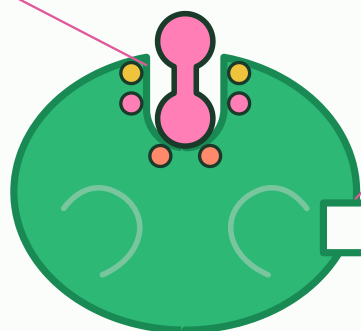
non-competitive inhibition

Inhibition by a molecule that binds an allosteric site, changing the active site, so it does not compete with the substrate for the active site.

reversible

Able to be undone: the molecule can leave again, and the enzyme returns to its working shape.

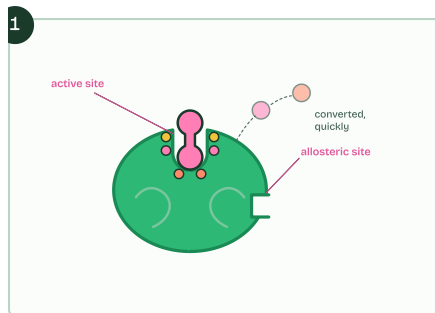
active site



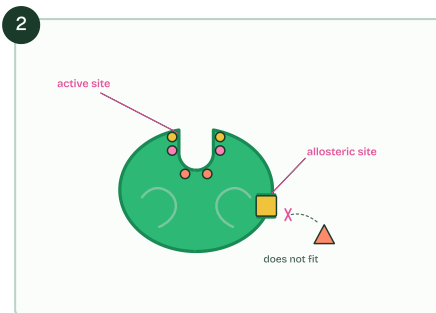
allosteric site

STEP BY STEP

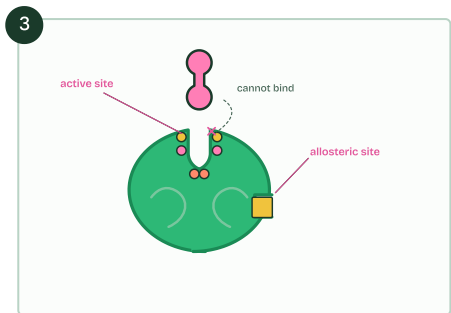
4 STEPS



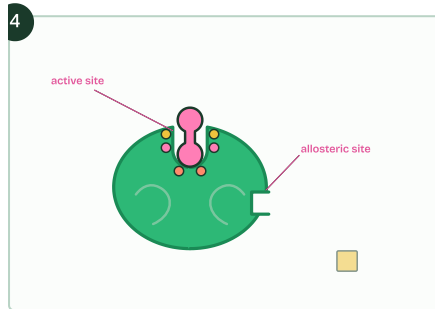
An active site, and a second site elsewhere: the **allosteric site**.



Only a specific molecule fits the allosteric site.



Binding changes the enzyme's shape, and with it the **active site**.



The binding is **reversible**: the inhibitor leaves, the enzyme works again.

WATCH OUT

Not every inhibitor blocks the active site. A non-competitive inhibitor never touches it.

PREDICT

An allosteric inhibitor binds nowhere near the active site. How can it stop the enzyme?

- (A) Binding changes the enzyme's shape, active site included
- (B) It blocks the path the substrate takes to the active site
- (C) It reacts with the substrate before the enzyme can
- (D) It breaks peptide bonds deep inside the enzyme's folded chain

Decide before you look. Answer on page 48.

12

C1.1.15 HL COMPETITIVE INHIBITION

A look-alike in the *active site*

A **competitive inhibitor** is similar enough in shape and chemistry to the substrate to bind the active site. While it is there, no substrate can bind. It is not converted, and it leaves again, so the binding is reversible.

Substrate and inhibitor take turns: each active site is taken by whichever happens to collide with it first. So the effect depends on how much of each there is.

A non-competitive inhibitor is different (chapter 11): it binds elsewhere and changes the site. How do the two behave when you add more substrate? Make your prediction, then open the graph.

Statins are the example. They are taken to lower blood cholesterol. In liver cells the enzyme **HMG-CoA reductase** converts HMG-CoA to mevalonate, an early step on the pathway that makes **cholesterol**. Part of a statin molecule resembles HMG-CoA, so it binds the active site and blocks it. Less cholesterol is made in the liver, and the level in the blood falls. A statin binds the site far more tightly than the substrate does, so a small dose is enough.

On a graph of rate against substrate concentration, a competitive inhibitor gives a curve that starts low but climbs towards the same plateau as the uninhibited enzyme. A non-competitive inhibitor gives a curve with a lower plateau.

KEY TERMS

competitive inhibitor

A molecule similar enough to the substrate to bind the active site, so substrate and inhibitor compete for it. The binding is reversible.

statins

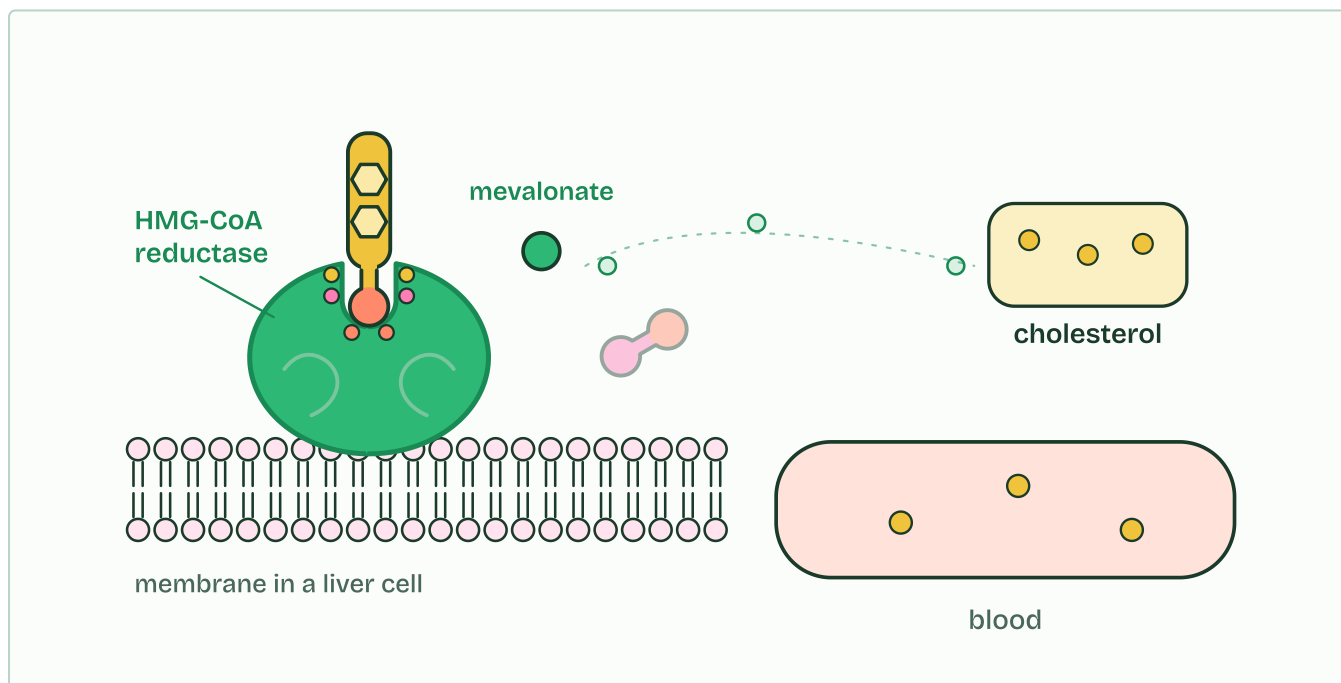
Drugs taken to lower blood cholesterol. They are competitive inhibitors of HMG-CoA reductase.

HMG-CoA reductase

The liver enzyme that converts HMG-CoA to mevalonate, an early step on the pathway that makes cholesterol.

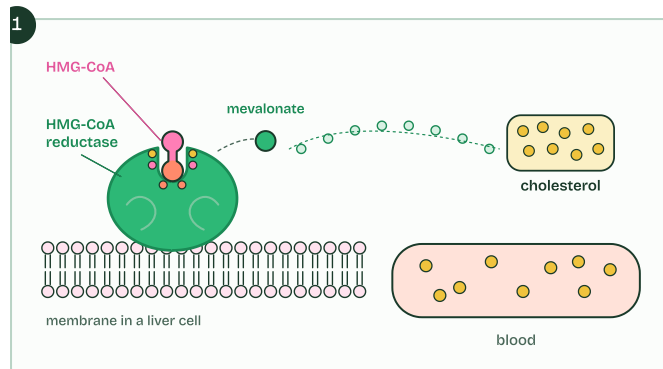
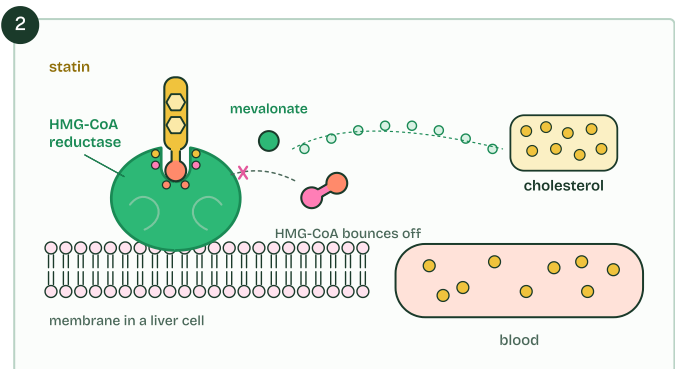
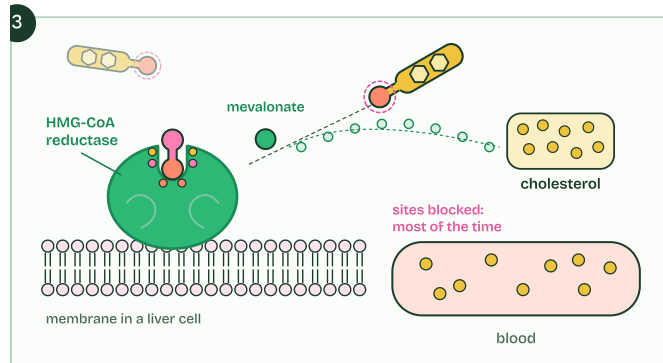
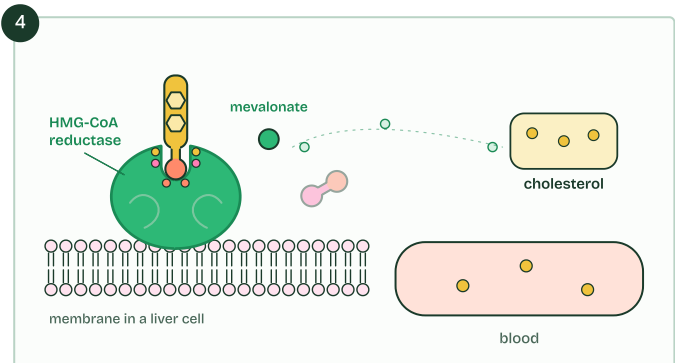
cholesterol

A steroid made in the liver and taken in from food. Too much in the blood is a risk to health.

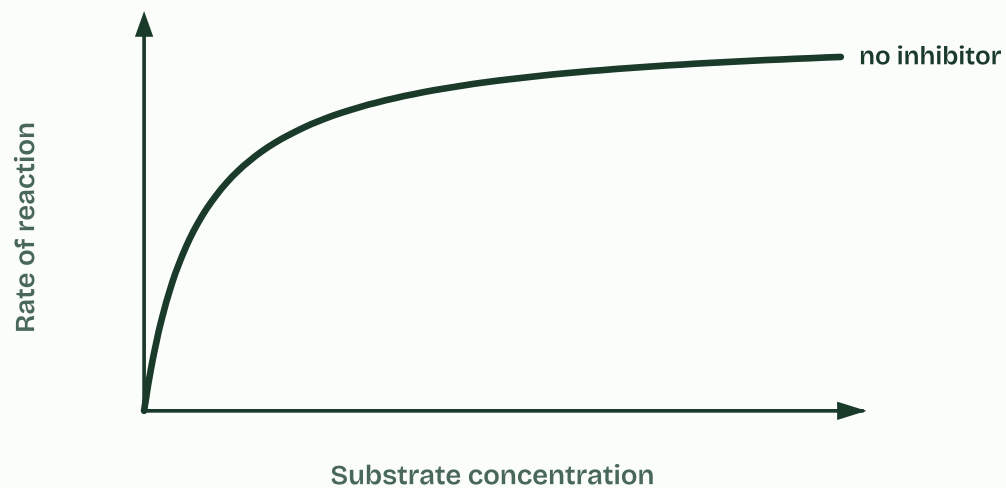


STEP BY STEP

4 STEPS

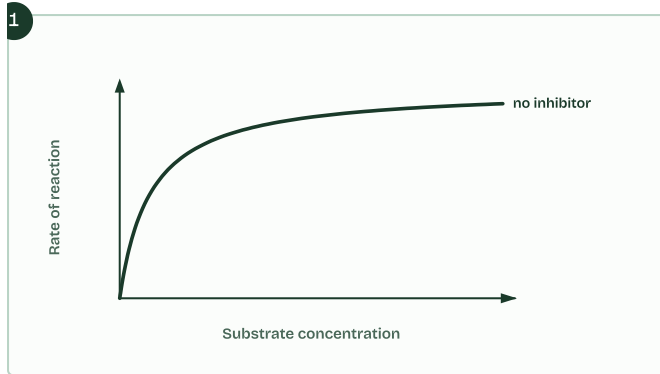
HMG-CoA reductase: an early step on the way to **cholesterol**.Part of a **statin** looks like the substrate and binds the active site.It binds and leaves: **competitive** and **reversible**.

Less cholesterol is made, and blood cholesterol falls.

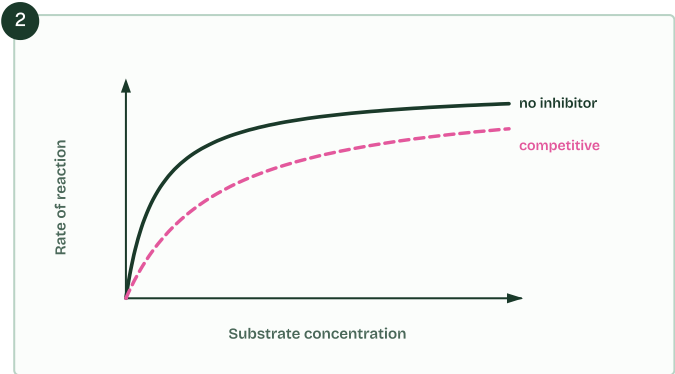


SWITCH IT

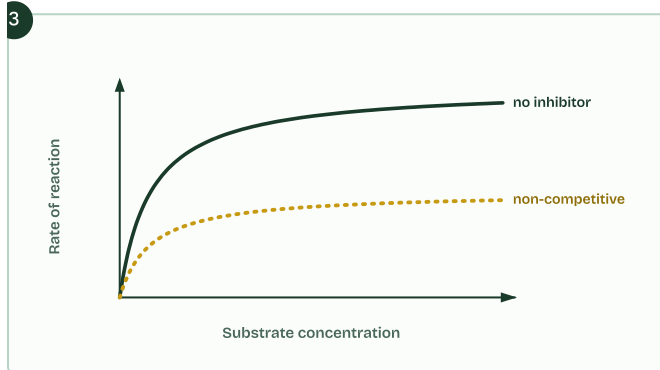
4 SETTINGS



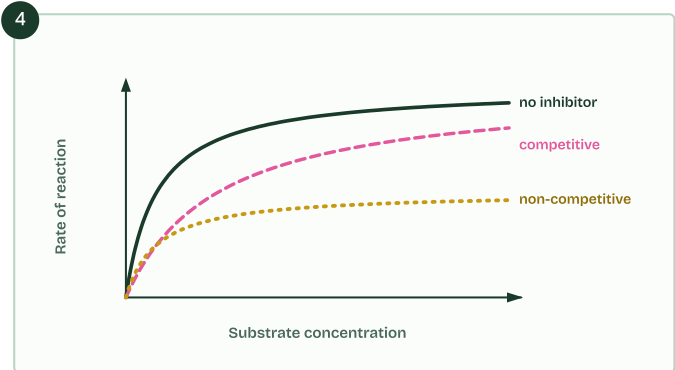
No inhibitor



Competitive

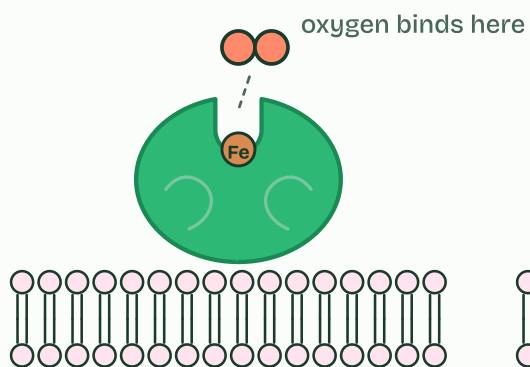


Non-competitive



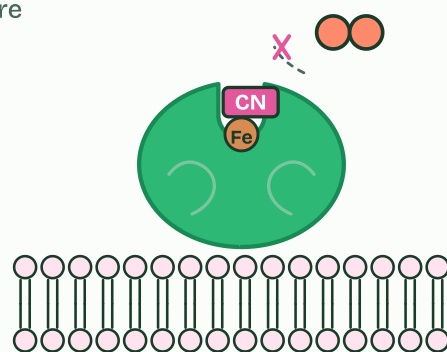
All three

normal



oxygen takes the iron atom's site
the last enzyme in a mitochondrion's respiration chain

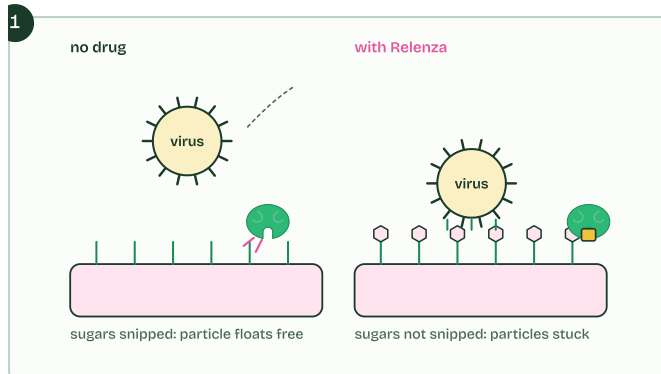
with cyanide



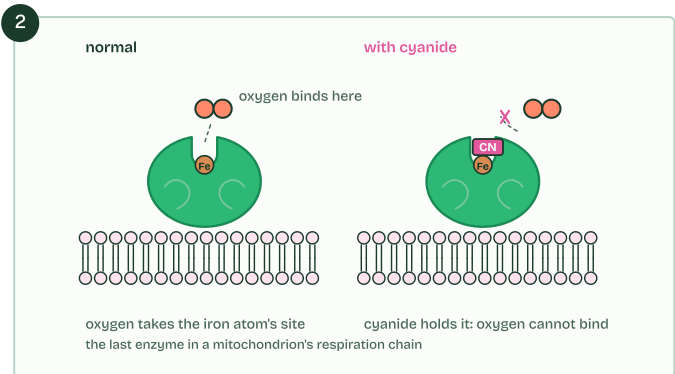
cyanide holds it: oxygen cannot bind

STEP BY STEP

2 STEPS



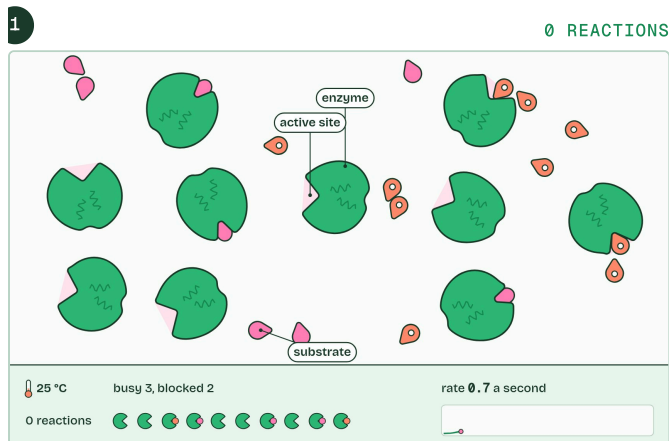
Relenza: a competitive inhibitor designed to fit a virus's enzyme.



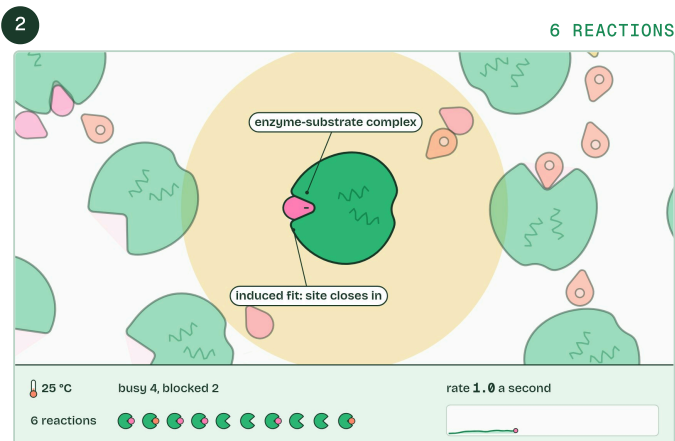
Cyanide: a poison that takes the place where oxygen binds.

ANIMATION · ADD AN INHIBITOR

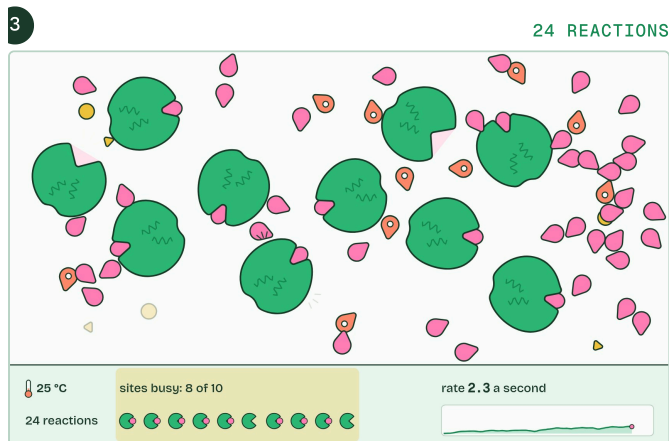
3 MOMENTS



Molecules move at **random**, and most collisions miss the active site.



A **successful collision**: it binds and reacts, and the enzyme is unchanged.



Plenty of substrate outcompetes it, so the rate climbs back near its **maximum**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c1-1-enzymes-and-metabolism#competitive

PREDICT

Two samples of an enzyme: one with a competitive inhibitor, one with a non-competitive inhibitor. You add far more substrate to both. In which does the inhibitor's effect fade?

- (A) The non-competitive one: substrate pushes it off
- (B) Both, equally: more substrate means more collisions
- (C) Neither: once bound, inhibitors stay for good
- (D) The competitive one: substrate wins the site back

Decide before you look. Answer on page 48.

TWO MORE, NOT TO LEARN

Relenza, a drug for influenza, was designed in Australia from the shape of the active site of the virus's enzyme neuraminidase. The enzyme snips sugar ends off the cell surface so that new virus particles can float free; Relenza fills the site, so they stay stuck. It is a competitive inhibitor.

Cyanide is a poison that stops the last enzyme of the respiration chain. It is often called a non-competitive inhibitor, but it binds the iron atom at the very spot where oxygen binds, so it is better described as blocking that site. Neither is in the syllabus: the examples to know are statins and penicillin.

13

C1.1.16 HL REGULATION OF METABOLIC PATHWAYS BY FEEDBACK INHIBITION

The end product shuts the *gate*

In **feedback inhibition** (end-product inhibition), the last product of a pathway inhibits an enzyme near its start, usually the first, by binding to its allosteric site (chapter 11). When the product builds up, more of the first enzyme's molecules have it bound, so the pathway slows. When the cell uses the product up, it leaves the allosteric sites, the enzyme works again and the pathway speeds up. The product's own level sets its rate of production. This is negative feedback.

The example is the pathway that makes the amino acid **isoleucine**. Plants and bacteria make it from another amino acid, **threonine**, in five steps, each with its own enzyme. Isoleucine binds the allosteric site of the first enzyme, **threonine deaminase**. Humans cannot make isoleucine (it is an essential amino acid, B1.2) and get it from food.

Nothing here is switched simply on or off. The share of enzyme that is inhibited follows the end product's concentration, so production matches use. In the valve, change how fast the cell uses isoleucine and watch the first enzymes (the six small ones with a notch) fill and empty.

KEY TERMS

feedback inhibition

The last product of a pathway acts as an inhibitor of an enzyme near the start of the pathway, usually the first, by binding to its allosteric site. Also called end-product inhibition.

isoleucine

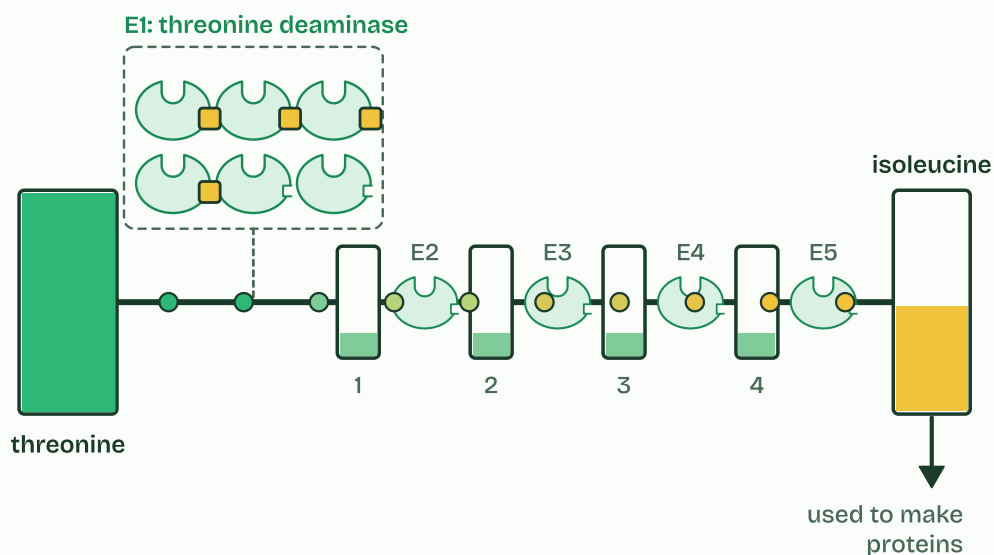
An amino acid that plants and bacteria make from threonine. Humans cannot make it, so they need it in their diet.

threonine

An amino acid. Plants and bacteria convert it to isoleucine in five steps.

threonine deaminase

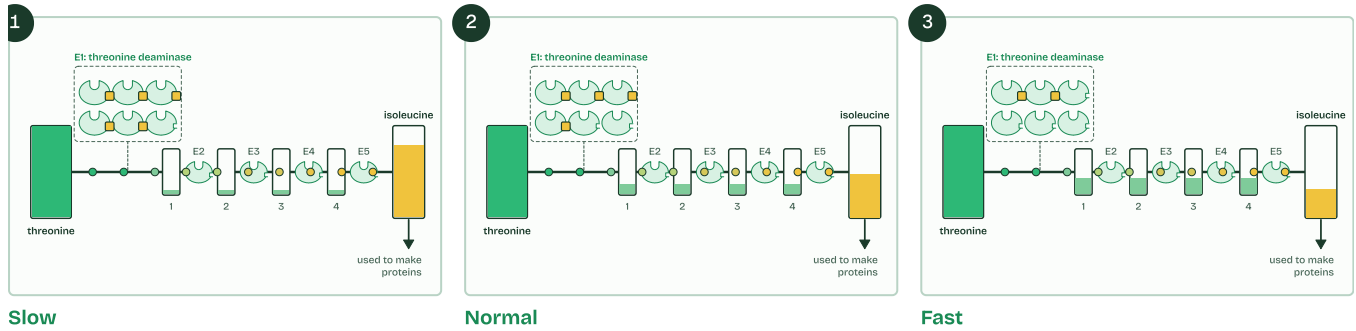
The first enzyme of the pathway from threonine to isoleucine. Isoleucine binds its allosteric site and inhibits it.



Five enzymes turn threonine into isoleucine, and the cell uses the isoleucine to make proteins. Change how fast it does that, then untick the box.

SWITCH IT

3 SETTINGS



WATCH OUT

Feedback inhibition is not permanent and not an on and off switch. It is reversible binding, and the share of the enzyme inhibited follows the end product's concentration.

PREDICT

Isoleucine inhibits the first enzyme of its five-step pathway, not the last. Why the first?

- (A) The first enzyme is the only one with an active site
- (B) So no threonine is spent on intermediates nobody needs
- (C) Isoleucine is too large to reach the later enzymes
- (D) The last enzyme makes isoleucine, so it cannot be stopped

Decide before you look. Answer on page 48.

14

A trap that springs *once*

C1.1.17 HL MECHANISM-BASED INHIBITION

In **mechanism-based inhibition** an inhibitor enters the active site as if it were a substrate, and the enzyme starts to act on it. But the reaction stops part way, with the inhibitor held by a **covalent bond**. The active site is chemically changed and stays blocked for good: the inhibition is **irreversible**. That enzyme molecule is out of action until the cell makes new ones.

Penicillin is the example, and it was the first widely used antibiotic (Fleming noticed it in 1928, and it came into use in the early 1940s). A bacterial cell wall (A2.2) is made of long sugar chains cross-linked by short peptides, and the enzyme **transpeptidase** makes those cross-links.

Penicillin looks like the end of the peptide that transpeptidase normally joins. It enters the active site and the enzyme attacks it: a ring in the penicillin molecule opens, and penicillin ends up bonded covalently to the active site. New wall is then built without cross-links, so it is weak. As the bacterium grows, water enters, the wall gives way and the cell bursts. Human cells have no cell wall, and so none of the wall-building enzyme that penicillin targets, so penicillin does not harm them (C3.2 returns to antibiotics).

Some bacteria are not harmed. They show **antibiotic resistance**: they carry a changed transpeptidase, whose active site has a different shape that penicillin binds poorly but that still makes cross-links, so their walls are built normally in penicillin. MRSA is the well-known case. Such variants arise by mutation and spread by natural selection when penicillin is used (C3.2). Other bacteria resist in another way, by making an enzyme that breaks penicillin down, but that is a different mechanism.

KEY TERMS

mechanism-based inhibition

Inhibition in which the inhibitor enters the active site as if it were a substrate and the enzyme starts to act on it, but the reaction stops part way, with the inhibitor held by a covalent bond.

covalent bond

A strong bond in which two atoms share electrons. It does not break easily.

irreversible

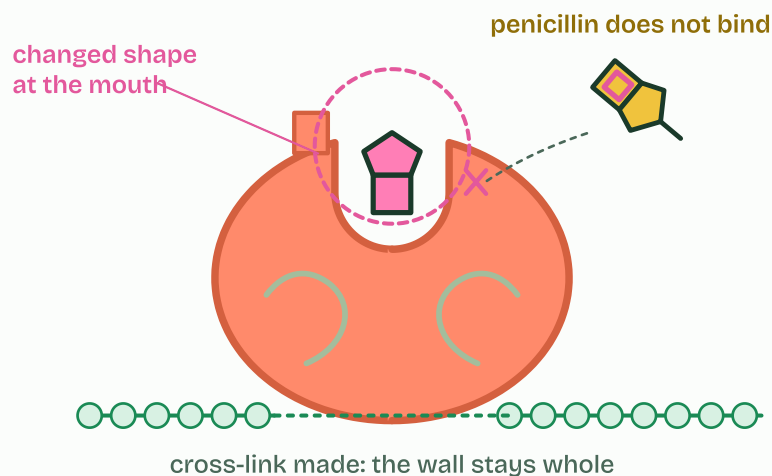
Not able to be undone: the inhibitor stays bound, and the enzyme molecule is out of action for good.

transpeptidase

The bacterial enzyme that makes the cross-links between the sugar chains of the cell wall.

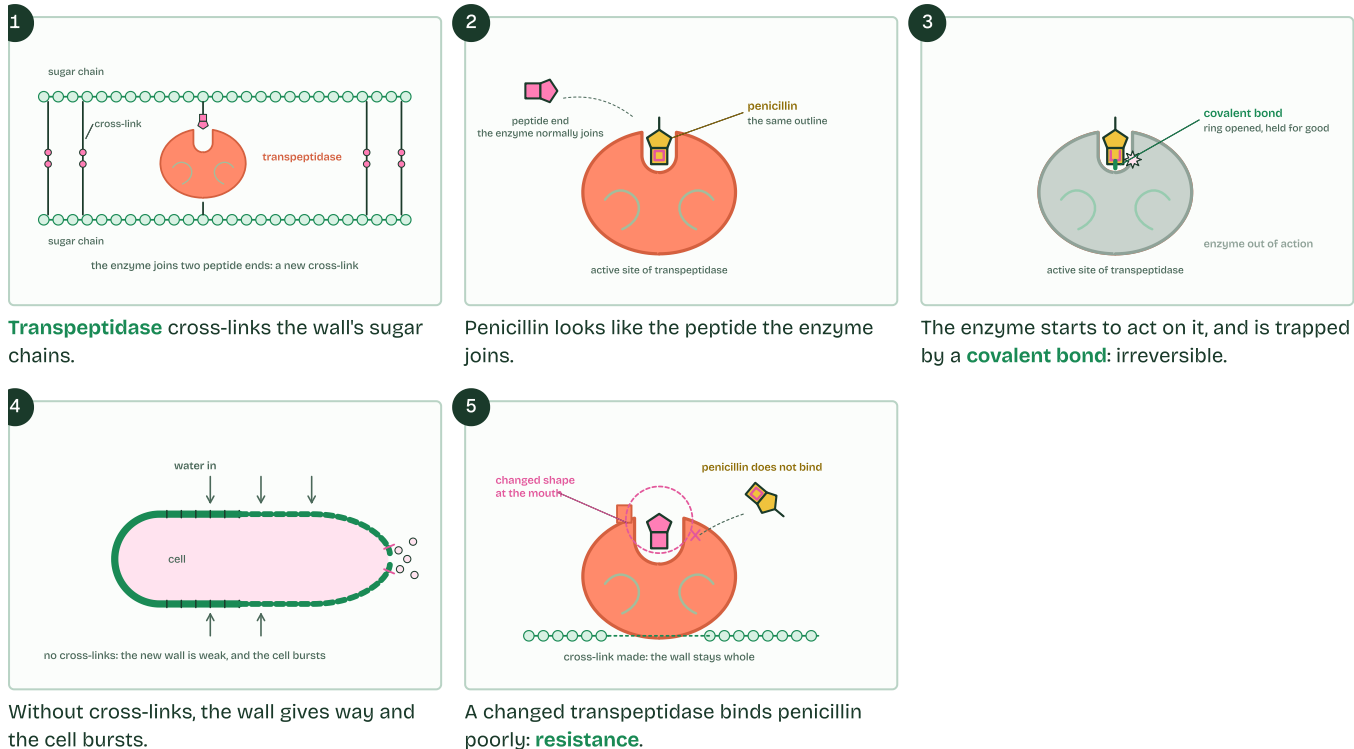
antibiotic resistance

The ability of bacteria to keep growing in the presence of an antibiotic.



STEP BY STEP

5 STEPS



REMEMBER IT

Three ways to stop an enzyme

C Copycat	N Nudge	M Mousetrap
Competitive a look-alike takes the active site, reversibly	Non-competitive binds the allosteric site and changes the active site, reversibly	Mechanism-based springs once in the active site and holds for good

WATCH OUT

Penicillin is not a competitive inhibitor that "stays a long time". It is bonded covalently and the enzyme never recovers.

PREDICT

A strain of bacteria keeps building strong walls in penicillin. Its transpeptidase still makes cross-links. What has most likely changed?

- (A) It has stopped making a cell wall at all
- (B) Penicillin now binds an allosteric site on the enzyme instead
- (C) Its transpeptidase's active site binds penicillin poorly
- (D) Its wall has grown so thick that penicillin cannot get in

Decide before you look. Answer on page 48.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

activation energy 03

The energy needed to strain and break the substrate's bonds so that a reaction can start.

active site 04

The small region of an enzyme where the substrate binds and the reaction happens. It is made of a few amino acids.

allosteric site 11

A site on an enzyme, away from the active site, where only a specific molecule can bind. Binding changes the enzyme's shape and so its active site.

anabolic 02

Reactions that build larger molecules from smaller ones. They take in energy.

antibiotic resistance 14

The ability of bacteria to keep growing in the presence of an antibiotic.

bond breaking 03

Splitting a bond takes in energy.

bond making 03

Forming a new bond releases energy.

Calvin cycle 09

A cyclical pathway in the stroma of the chloroplast that builds sugar from carbon dioxide (C1.3).

catabolic 02

Reactions that break larger molecules into smaller ones. They release energy.

catalyst 01

A substance that speeds up a chemical reaction without being used up or changed by it, so the same molecule can work again and again.

cholesterol 12

A steroid made in the liver and taken in from food. Too much in the blood is a risk to health.

collision 05

Two molecules striking each other. An enzyme reaction needs a collision between a substrate and an active site.

collision theory 07

The idea that a reaction needs a collision, with enough energy and the right orientation, between the reacting particles.

competitive inhibitor 12

A molecule similar enough to the substrate to bind the active site, so substrate and inhibitor compete for it. The binding is reversible.

condensation 02

A reaction that joins two molecules and releases a water molecule for every bond made.

conformational change 11

A change in the three-dimensional shape of a protein, here caused by something binding at the allosteric site.

covalent bond 14

A strong bond in which two atoms share electrons. It does not break easily.

cyclical pathway 09

A pathway that ends by remaking the molecule it started from, so that a small amount of that carrier keeps the cycle turning.

denaturation 06

A change in the three-dimensional shape of a protein, caused by heat or a pH far from its normal one, so that it can no longer do its job. It is usually permanent.

efficiency 10

The share of the energy put into a process that ends up where it is wanted, rather than as heat.

endotherms 10

Animals that keep a constant body temperature, above that of their surroundings, by generating heat from their own metabolism.

energy diagram 03

A graph with energy on the vertical axis and the progress of a reaction across, showing the hill of activation energy and the levels of substrate and products.

enzyme specificity 02

An enzyme catalyses only one reaction, or a few very similar ones, because only certain substrates fit its active site.

enzyme-substrate complex 04

The enzyme with its substrate bound in the active site.

enzyme-substrate specificity 06

Only a substrate whose shape and charges match the active site can bind, so each enzyme acts on one substrate, or a few similar ones.

enzymes 01

The catalysts of living things. Nearly all of them are proteins.

extracellular 09

Outside the cells that made the enzymes. Chemical digestion in the gut is the example.

feedback inhibition 13

The last product of a pathway acts as an inhibitor of an enzyme near the start of the pathway, usually the first, by binding to its allosteric site. Also called end-product inhibition.

globular proteins 04

Proteins whose polypeptide chains are folded into a compact, roughly round shape. Most dissolve in water.

glycolysis 09

The first stage of respiration: a linear pathway of about ten steps in the cytoplasm that converts glucose to pyruvate.

heat 10

The form of energy that is given off by every metabolic reaction, because no energy transfer is completely efficient.

HMG-CoA reductase 12

The liver enzyme that converts HMG-CoA to mevalonate, an early step on the pathway that makes cholesterol.

hydrolysis 02

A reaction that breaks a bond by adding a water molecule, one for every bond broken.

immobilised enzyme 05

Here, an enzyme held in place, for example embedded in a membrane, so that the substrate moves to it.

induced fit 04

The change in shape of both the active site and the substrate as they bind, which strains the substrate's bonds.

inhibitor 11

A molecule that binds to an enzyme and slows or stops its reaction.

initial rate 08

The rate at the very start of a reaction, found as the gradient of a tangent to the curve at time zero, before the substrate runs low.

intracellular 09

Inside a cell: in the cytoplasm or inside an organelle.

irreversible 14

Not able to be undone: the inhibitor stays bound, and the enzyme molecule is out of action for good.

isoleucine 13

An amino acid that plants and bacteria make from threonine. Humans cannot make it, so they need it in their diet.

Krebs cycle 09

A cyclical pathway in the matrix of the mitochondrion, part of aerobic respiration (C1.2).

linear pathway 09

A pathway in which the first substrate is converted step by step into a different end product.

mechanism-based inhibition 14

Inhibition in which the inhibitor enters the active site as if it were a substrate and the enzyme starts to act on it, but the reaction stops part way, with the inhibitor held by a covalent bond.

metabolic pathway 02

A series of enzyme-catalysed reactions in which the product of one is the substrate of the next.

metabolism 02

All the chemical reactions in an organism: a complex network of interdependent, interacting reactions.

molecular motion 05

The constant random movement of molecules in a liquid or gas, caused by their energy and by collisions with other molecules.

non-competitive inhibition 11

Inhibition by a molecule that binds an allosteric site, changing the active site, so it does not compete with the substrate for the active site.

optimum 07

The value of temperature or pH at which an enzyme's rate is highest.

orientation 05

The way a molecule faces when it collides. A substrate must meet the active site the right way round to bind.

oxidation 02

A reaction in which a substance loses electrons or hydrogen, or gains oxygen. In respiration, glucose is oxidised.

products 04

The molecules made from the substrate in an enzyme-catalysed reaction.

rate of reaction 01

How much substrate is used up, or how much product is made, in a given time.

reversible 11

Able to be undone: the molecule can leave again, and the enzyme returns to its working shape.

saturation 07

With nearly every active site occupied at any moment, so that more substrate barely raises the rate.

secondary data 08

Data collected by someone else, such as results in a table or a graph in a paper, that you analyse yourself.

sketch graphs 07

Generalised graphs of a relationship. They are models in biology: they show the general pattern, not the data of any one enzyme.

statins 12

Drugs taken to lower blood cholesterol. They are competitive inhibitors of HMG-CoA reductase.

substrate 04

The molecule an enzyme acts on.

tangent 08

A straight line that touches a curve at one point and has the same gradient as the curve there.

threonine 13

An amino acid. Plants and bacteria convert it to isoleucine in five steps.

threonine deaminase 13

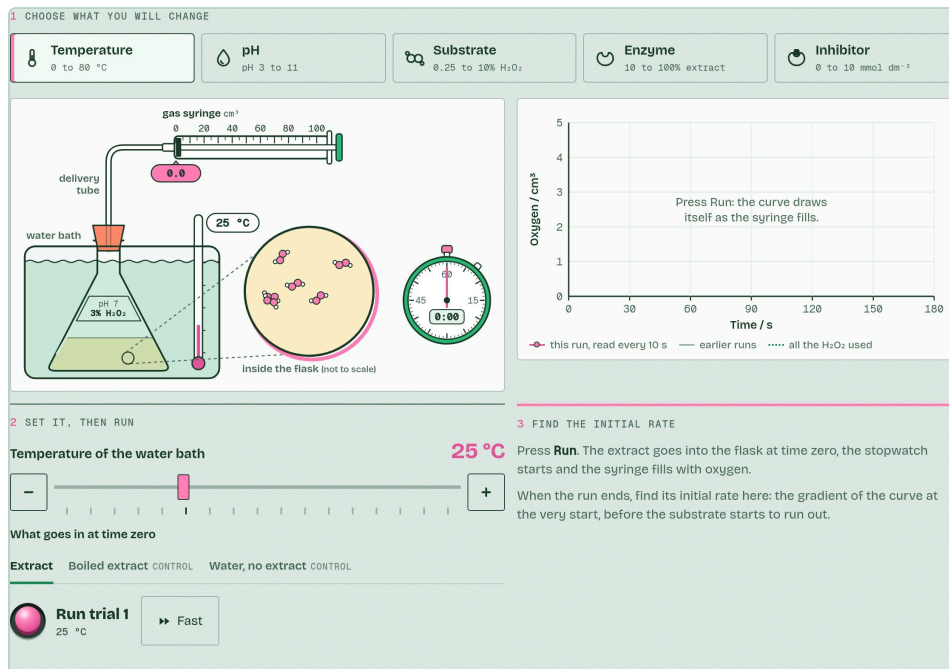
The first enzyme of the pathway from threonine to isoleucine. Isoleucine binds its allosteric site and inhibits it.

transpeptidase 14

The bacterial enzyme that makes the cross-links between the sugar chains of the cell wall.

Dry lab: *Catalase and hydrogen peroxide*

Catalase in a potato extract breaks hydrogen peroxide down to water and oxygen. Collect the oxygen in a gas syringe, find the initial rate, then plan and write it up as an investigation with the coach under the bench.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. biologybybradford.com/guides/ib-biology-c1-1-enzymes-and-metabolism#lab

Your question

How does one factor change the initial rate at which catalase breaks down hydrogen peroxide? Start with temperature: where is the optimum, and what happens beyond it?

What you can change

One independent variable at a time: temperature, pH, hydrogen peroxide concentration or extract concentration (and at higher level an inhibitor, competitive or non-competitive). Everything else stays fixed unless you change it on purpose.

What to record

The volume of oxygen every 10 seconds, then the initial rate in cm³ min⁻¹: the gradient at the very start. At least three trials at each value (the bench allows five), a mean and a standard deviation, and a graph of the means with error bars. The coach under the bench helps you plan, process and evaluate.

Find out

- **Where is the optimum?** Temperature, 0 to 80 °C in 10 °C steps, three trials each; then every 5 °C around the peak. Record the optimum to the nearest 5 °C and what a run at 70 °C does after its first 20 seconds.
- **When does more peroxide stop helping?** Substrate, 0.25% to 10%. Then halve the extract and run it again. Where does each curve level off?
- **Which pH suits catalase?** pH 3 to 11, three trials each.
- **Run the controls.** Boiled extract and water, no extract, beside a normal run at 25 °C.
- **Beat the inhibitor.** A substrate series with no inhibitor, then a competitive inhibitor at 1 mmol dm⁻³, then a non-competitive one at 1 mmol dm⁻³. Compare the runs at 0.5% and at 10%.

Record

- For every run: the settings, and which one you changed.
- Change one setting at a time and keep the rest fixed.
- Three to five repeats at each value, with a mean and its standard deviation.
- Use **Graph your results** under the bench, or download the CSV and plot it yourself.
- When you are done, the coach under the bench helps you write it up as an investigation.

QUESTIONS ON THE LAB

QUESTION 1

At 70 °C the oxygen collected rises for the first 20 seconds and then hardly at all, far short of what the peroxide could give. Why?

- (A) The hot peroxide breaks down on its own before catalase acts
- (B) The catalase unfolds during the run and stays unfolded
- (C) Hot oxygen expands and escapes past the syringe's plunger
- (D) The water bath cools the flask as the run goes on

Answer on page 48.

QUESTION 2

What does the boiled extract tube rule out?

- (A) That the peroxide was too concentrated for the catalase to cope
- (B) That the syringe was leaking gas during the runs
- (C) That the water bath was at the wrong temperature
- (D) That something other than working catalase made the gas

Answer on page 49.

QUESTION 3

At 10% peroxide, the run with the competitive inhibitor is almost as fast as the run with none, but the non-competitive run is still at about half. Why?

- (A) Peroxide wins the active site, not the allosteric site
- (B) More peroxide breaks down the competitive inhibitor
- (C) The non-competitive inhibitor has denatured the catalase
- (D) At 10% the catalase makes more of itself

Answer on page 49.

WRITE IT UP AS AN INVESTIGATION

Your results from this dry lab can be written up the way an IB scientific investigation is: four criteria, each worth 6 marks. Tick each line as your write-up does it. The coach on the page checks these as you go; it never gives a mark.

1 Research design

A focused question set in its biology; your choices of what to measure, how, over what range and how often, explained rather than listed; what you kept the same and how; safety, ethics and the environment; a method someone else could follow and repeat.

- ☐ My question names what I changed.
- ☐ It gives the range I used, with units.
- ☐ It names what I measured and how.
- ☐ It names the organism or system.
- ☐ My background explains, with the biology, why the two should be linked.
- ☐ I cite my sources, and each reference can be traced.
- ☐ If I give a hypothesis, it predicts and explains.
- ☐ Every variable has its How, Why and Units.
- ☐ For each thing kept the same, I say how I kept it so.
- ☐ I list at least three things I kept the same.
- ☐ I name the apparatus that set what I changed, and the instrument that measured.
- ☐ I test enough values.
- ☐ My values spread wide enough.
- ☐ I run at least three trials at every value.
- ☐ I run a control.
- ☐ I explain why these values, this many and this often.
- ☐ Someone else could repeat my method.
- ☐ I deal with safety, ethics and the environment.

3 Conclusion

Your question answered from the processed data, with numbers quoted and the spread taken into account; the biology that explains the pattern; a comparison with published work; no claim bigger than the data.

- ☐ I answer my question in a sentence, naming both variables.
- ☐ I quote my processed numbers.
- ☐ I say how sure the spread lets me be.
- ☐ I say whether my hypothesis is supported.
- ☐ I explain the pattern with biology.
- ☐ I compare my result with published work, and cite it.
- ☐ I claim no more than my data show.

2 Data analysis

Raw data recorded clearly, with titles, units, uncertainties and the same decimal places down a column; what you saw as well as what you measured; processing that suits the question, shown with a worked example; the spread shown; a graph a reader can trust.

- ☐ Each table has a numbered title that says what it shows.
- ☐ Every heading has its quantity and its unit.
- ☐ Every raw data heading has its uncertainty.
- ☐ Each uncertainty is realistic for the instrument.
- ☐ Each uncertainty has the same decimal places as its readings.
- ☐ I record what I saw as well as what I measured.
- ☐ I show one worked example of my processing, and it is right.
- ☐ I say why I left out any trial.
- ☐ My error bars show a spread my repeats can support.
- ☐ My graph has a numbered title and labelled axes with units.
- ☐ I say what the error bars show.
- ☐ A straight line, if I draw one, has its R^2 .
- ☐ A statistical test, if I run one, has its hypotheses and suits the data.

4 Evaluation

Weaknesses and limitations of this method (not slips in carrying it out), with evidence from your own data, the effect each had on the results, which mattered most and why, and a realistic improvement for each.

- ☐ I give at least three weaknesses or limitations.
- ☐ Every row is filled in.
- ☐ No slips in carrying it out: weaknesses of the method itself.
- ☐ Each improvement is specific: which instrument, how many, what changes.
- ☐ Each effect says what it did to my data.
- ☐ At least two rows point to evidence in my own data.
- ☐ At least one limitation: what this experiment cannot tell me.
- ☐ I say which mattered most, and why.
- ☐ I deal with what stands out in my data.
- ☐ My improvements improve this investigation, not a new one.

Variables

Variable	How?	Why?	Units
Independent: temperature			
Dependent: initial rate of oxygen production			
Kept the same: pH of the buffer			
Kept the same: concentration of hydrogen peroxide			
Kept the same: volume of hydrogen peroxide			
Kept the same: concentration of the extract			
Kept the same: the same potato extract for every run			
Kept the same: inhibitor (none)			

Evaluation

Weakness or limitation	Which?	Evidence in my data	Effect on my results	Improvement

Data generated with the catalase dry lab, biologybybradford.com (a simulation). These checks catch what is missing. They cannot judge how good it is: that is what your teacher does.

**Check yourself**

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on C1.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=C1.1&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

- 01** With no enzyme at all, how long would water at room temperature take to break half the bonds between the glucose units in starch?
- C About five million years**
- About five million years, by one careful measurement. The reaction is possible, but so slow it might as well not happen. Amylase in your saliva does the same job in a fraction of a second. That gap, repeated across thousands of reactions, is why life needs enzymes.
-
- 02** A liver cell makes thousands of different enzymes. Why so many?
- A Each enzyme catalyses one kind of reaction**
- Each enzyme fits one substrate, or one kind of substrate, so it catalyses one kind of reaction. Thousands of reactions need thousands of enzymes, and having a separate enzyme for each step is also what lets the cell control each step on its own.
-
- 03** An enzyme lowers the activation energy of a reaction that releases energy. What happens to the energy released overall?
- D Nothing: the start and end levels stay put**
- Nothing changes it. The energy released overall is the difference between the substrate and the products, and the enzyme changes neither. It lowers only the hill between them, so the reaction gets going more easily and runs faster.
-
- 04** An enzyme has 300 amino acids, and only about six touch the substrate. A mutation changes one amino acid far from the active site, and the enzyme stops working. How?
- B It changed how the chain folds, so the site lost its shape**
- The active site's shape and chemistry depend on the whole fold, and the fold is held by interactions between amino acids all through the chain. Change one, and the fold can shift enough to change the site, so the substrate no longer binds well or no longer reacts.
-
- 05** Lactase sits fixed in the membrane of cells lining your small intestine. It cannot move. How does lactose reach its active site?
- D Lactose molecules move at random and collide with it**
- Lactose molecules in the gut contents move at random, like every dissolved molecule. Some collide with the membrane, a few of those with a lactase active site the right way round, and those bind. Only one partner has to move for a collision.
-
- 06** Pepsin digests protein in the stomach at about pH 2. Carried on into the small intestine at about pH 8, what happens to it?
- A It denatures: its active site changes shape and charge**
- Pepsin's shape is held partly by ionic bonds that suit pH 2. At pH 8 its R groups lose hydrogen ions, the charges change, the bonds break and the active site changes shape. Pepsin stops working in the intestine, where other proteases suited to pH 8 take over.
-
- 07** On a graph of rate against substrate concentration, the curve levels off. Why?
- C Nearly every active site is already busy**
- At high substrate concentration nearly every active site is occupied at any moment. A substrate molecule arriving at a busy enzyme has to wait, so adding more substrate barely raises the rate. This is **saturation**. The substrate has not run out: there is more of it than ever. Only more enzyme can raise the maximum.
-

- 08** A drop of a starch and amylase mixture stops turning iodine blue-black after 40 s at 30 °C and after 80 s at 20 °C. Compare the rates.

B The rate at 30 °C is double: rate is $1 \div \text{time}$

Rate = $1 \div \text{time}$: $1 \div 40 \text{ s} = 0.025 \text{ s}^{-1}$ at 30 °C and $1 \div 80 \text{ s} = 0.0125 \text{ s}^{-1}$ at 20 °C. Half the time means twice the rate.

- 09** Glycolysis runs in the cytoplasm, the Krebs cycle inside mitochondria, and protein digestion in your stomach. Which are intracellular?

D Glycolysis and the Krebs cycle: both inside cells

Intracellular means inside a cell, in any part of it, so glycolysis and the Krebs cycle both count. The stomach's contents are outside every cell, even though they are inside your body: digestion there is extracellular.

- 10** A mouse and a lizard of the same mass sit at 20 °C for a day. Which needs more food, and why?

C The mouse: heat from respiration keeps it at 37 °C

The mouse. To stay at 37 °C in air at 20 °C it loses heat all the time and replaces it from respiration, so it respire faster and needs several times the food. The lizard's body cools to near 20 °C, its reactions slow, and it needs much less.

- 11** An allosteric inhibitor binds nowhere near the active site. How can it stop the enzyme?

A Binding changes the enzyme's shape, active site included

Binding at the allosteric site changes interactions between amino acids within the enzyme, so the whole protein shifts shape, the active site with it. The substrate no longer fits. Nothing is broken: when the inhibitor leaves, the shape returns.

- 12** Two samples of an enzyme: one with a competitive inhibitor, one with a non-competitive inhibitor. You add far more substrate to both. In which does the inhibitor's effect fade?

D The competitive one: substrate wins the site back

With far more substrate than competitive inhibitor, substrate molecules win almost every active site, so the rate climbs back towards its maximum. The non-competitive inhibitor binds elsewhere; substrate cannot compete for that site, so the enzyme molecules holding it stay off, however much substrate you add.

- 13** Isoleucine inhibits the first enzyme of its five-step pathway, not the last. Why the first?

B So no threonine is spent on intermediates nobody needs

Stopping the first step stops the whole pathway at its entrance. If the last enzyme were inhibited instead, the first four would keep using threonine and filling the cell with intermediates that go nowhere. Untick "Allosteric site working" to see what happens without the brake.

- 14** A strain of bacteria keeps building strong walls in penicillin. Its transpeptidase still makes cross-links. What has most likely changed?

C Its transpeptidase's active site binds penicillin poorly

The strain has a changed transpeptidase. Its active site still joins the peptide ends, but its shape no longer lets penicillin bind well, so the trap never springs. A mutation made the change; using penicillin selects the bacteria that carry it.

QUESTIONS ON THE DRY LAB

- Q1** At 70 °C the oxygen collected rises for the first 20 seconds and then hardly at all, far short of what the peroxide could give. Why?

B The catalase unfolds during the run and stays unfolded

At 70 °C the enzyme denatures within seconds, and denatured catalase does not refold. Fewer active sites are left every second, so the gas stops long before the peroxide runs out.

Q2 What does the boiled extract tube rule out?

D That something other than working catalase made the gas

Boiling denatures the catalase but leaves everything else in the extract. Almost no gas from the boiled tube shows that the oxygen in the real runs came from active enzyme, not from some other substance in the potato extract or from peroxide breaking down by itself.

Q3 At 10% peroxide, the run with the competitive inhibitor is almost as fast as the run with none, but the non-competitive run is still at about half. Why?

A Peroxide wins the active site, not the allosteric site

The competitive inhibitor takes turns with peroxide at the active site, so a flood of peroxide takes nearly every turn. The non-competitive inhibitor binds an allosteric site that peroxide does not compete for, so the enzyme molecules holding it stay off however much peroxide there is.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.