IB / A-Level Biology Revision Notes

C1.1 Enzymes and Metabolism

Exam-focused, picture-free notes for rapid revision and written-response practice.

Guiding questions

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

You must be able to explain

enzyme specificity; active site; induced fit; activation energy; anabolic vs catabolic reactions; ATP as energy currency; effects of temperature, pH and substrate concentration; competitive vs non-competitive inhibition; feedback inhibition.

You must be able to interpret

enzyme activity graphs; activation-energy diagrams; inhibition curves; the reason for a plateau at high substrate concentration; why extremes of pH or temperature reduce rate; how pathway control prevents waste.

Core idea

Metabolism is the complete network of enzyme-controlled reactions inside living organisms. Enzymes speed up reactions by lowering activation energy, while cells regulate these reactions to conserve resources, maintain homeostasis and make ATP available for cellular work.

Fast memory checklist

- Enzymes are usually **globular proteins** with a specific **active site**.
- The enzyme is **not used up**; substrate becomes product.
- Induced fit means **both enzyme and substrate can change shape** during binding.
- Higher temperature increases collisions **until denaturation begins**.
- Changing pH alters charges and can disturb the active site and intramolecular bonds.
- Increasing substrate concentration raises rate **until active sites are saturated**.
- Competitive inhibitors bind the **active site**; non-competitive inhibitors bind an **allosteric site**.
- Feedback inhibition usually switches off the **first enzyme** in a pathway.

Exam language to use

Specificity = only certain substrates fit an active site.
Denaturation = change in three-dimensional structure that alters function.
Activation energy = minimum energy needed to start a reaction.
Metabolic pathway = sequence of enzyme-controlled reactions where the product of one step becomes the substrate of the next.

1. Enzymes, catalysis and metabolism

Cells rely on thousands of reactions that would otherwise occur too slowly. Enzymes are biological catalysts that increase reaction rate to life-sustaining levels.

Term	Meaning	What to remember in exams
Catalyst	A substance that increases reaction rate without being used up.	State that catalysts lower activation energy rather than 'adding energy' to reactants.
Enzyme	A biological catalyst, usually a protein.	Most are proteins; some RNA catalysts exist and are called ribozymes.
Metabolism	The complete network of interacting chemical reactions in an organism.	Include both anabolic and catabolic reactions.
Reactants / substrates	Starting substances in a reaction.	In enzyme questions, the reactant is often called the substrate.
Products	Substances formed by the reaction.	Product release leaves the enzyme unchanged and ready to catalyse again.

Anabolism and catabolism

Feature	Anabolic reactions	Catabolic reactions
Main role	Build larger molecules from smaller ones.	Break larger molecules into smaller ones.
Water	Often produced in condensation reactions.	Often used in hydrolysis reactions.
Energy	Require energy input.	Release energy.
Examples	Protein synthesis; glycogen formation; photosynthesis.	Digestion; oxidation of substrates in respiration.

High-yield link

Metabolism is **interdependent**: products of one reaction become substrates in another. Because each step is enzyme-specific, changing one enzyme can change the output of a whole pathway.

ATP: the energy currency of the cell

ATP stores chemical potential energy in phosphate bonds and transfers usable energy to cellular processes. Hydrolysis of ATP to ADP + Pi releases energy for biosynthesis, active transport and movement.

ATP is used for...	Example
Building macromolecules	Protein synthesis and other anabolic reactions
Mechanical work	Muscle contraction; chromosome movement; cilia/flagella movement
Active transport	Sodium-potassium pump and other membrane transport processes

2. Enzyme structure, active sites and induced fit

Almost all enzymes are globular proteins folded into a precise three-dimensional conformation. Only a few amino acids form the active site, but the entire protein structure positions these amino acids correctly for catalysis.

Concept sketch: enzyme action

```
E + S  <=>  ES  <=>  E + P

E  = enzyme
S  = substrate
ES = enzyme-substrate complex
P  = product

Key sequence:
1. substrate collides with active site
2. binding occurs
3. enzyme and substrate adjust shape (induced fit)
4. activation energy is lowered
5. substrate is converted to product
6. product leaves; enzyme can be reused
```

Lock-and-key model

Useful for showing specificity, but too rigid. It suggests the active site is already a perfect fixed match for the substrate.

Induced-fit model

More accurate. Substrate binding causes small conformational changes in **both** enzyme and substrate. This stresses substrate bonds and favours reaction.

Activation energy

Activation energy is the minimum energy needed to destabilize existing bonds so a reaction can proceed. Enzymes **lower** activation energy. They do **not** supply energy, do **not** change the final equilibrium position, and do **not** make an impossible reaction possible.

Exergonic vs endergonic

Type	Energy change	Exam phrasing
Exergonic	Releases energy; products have less energy than reactants.	Useful when energy is transferred to ATP or lost as heat.
Endergonic	Requires net energy input; products have more energy than reactants.	Useful for building molecules and storing energy, e.g. photosynthesis.

3. Why reaction rate changes

Collision theory states that reactant molecules must collide with sufficient energy and in a suitable orientation for reaction to occur. Enzymes improve the chance of successful collisions by binding substrates at an active site and lowering activation energy.

Role of molecular motion

Substrate and active site must come together physically. Greater molecular motion increases collision frequency. In some systems, enzymes or substrates are immobilized in membranes so collisions happen more efficiently and pathway products do not diffuse away.

Examples of immobilized or localized enzyme action

Enzymes in **photosynthesis** and **cellular respiration** are embedded in membranes. Industrially, immobilized enzymes are used in food production, biofuel generation, diagnostics and antibiotic manufacture.

Effect of temperature

- As temperature rises, molecules move faster and collisions become more frequent and energetic.
- Rate increases up to an **optimum temperature**.
- Above the optimum, intramolecular bonds in the enzyme are disrupted, the active site changes shape, and rate falls.
- Mild denaturation may be reversible; severe denaturation may be permanent if structural damage is too great.

How to describe the temperature graph

```
x-axis: temperature
y-axis: rate of enzyme activity

low temp   -> low kinetic energy -> fewer effective collisions
rising temp -> more collisions -> faster rate
optimum    -> highest rate
above optimum -> active site starts changing shape
far above optimum -> denaturation -> sharp fall in rate
```

Effect of pH

- Each enzyme has an **optimum pH**.
- Changes in pH alter the concentration of H+ or OH- ions.
- These ions interfere with charges on amino acid side chains or substrate groups.
- Incorrect charge matching reduces binding and may disrupt bonds that maintain shape.
- Extreme pH can denature the enzyme.

How to describe the pH graph

```
x-axis: pH from acidic -> neutral -> basic
y-axis: rate of enzyme activity

Each enzyme shows a peak at its own optimum pH.
Many human enzymes peak near pH 7.
Specialized enzymes may peak in acidic or alkaline conditions.
Away from the optimum, binding and catalysis decrease.
At very unsuitable pH, denaturation may occur.
```

Effect of substrate concentration

- With enzyme concentration fixed, increasing substrate concentration initially increases rate because collisions with active sites become more frequent.
- Eventually all active sites are occupied.
- At this point the reaction reaches a maximum rate (Vmax) and further substrate does not increase rate.

How to describe the substrate concentration graph

```
low [S]    -> many free active sites -> rate rises quickly
higher [S]  -> more frequent binding -> rate still rises
very high [S] -> enzymes saturated -> plateau at Vmax

Reason for plateau:
every enzyme molecule is working as fast as possible.
```

4. Measuring enzyme-catalysed reactions

Reaction rate can be measured by tracking either substrate disappearance or product formation over time. In practice, you often calculate an initial rate from the steepest part of a graph.

What can be measured?	Example
Product appearing	Glucose produced when lactase digests lactose
Substrate disappearing	A reactant concentration decreasing with time
Rate	Change in concentration, mass, volume or absorbance per unit time

Exam tip: graph interpretation

Always link a changed rate to a cause. For example: *'Rate increased because higher temperature raised kinetic energy, so enzyme and substrate collided more often.'* If the rate falls at high temperature or extreme pH, mention **change in active-site shape** and **denaturation**.

Common short-answer patterns

- Why does rate increase first? -> more successful collisions / more ES complexes.
- Why does rate then plateau? -> active sites saturated / enzyme concentration limiting.
- Why does rate fall after optimum temperature? -> denaturation changes active site.
- Why does non-optimal pH reduce rate? -> altered charges interfere with binding and catalysis.

5. HL extension: intracellular vs extracellular enzymes

Type	Where they act	Examples
Intracellular enzymes	Inside cells	Glycolysis in cytoplasm; Krebs cycle in mitochondrial matrix
Extracellular enzymes	Outside cells	Chemical digestion in the gut

Multienzyme complexes
Some pathways use groups of enzymes held close together. This improves efficiency because intermediate products are passed directly from one step to the next and are less likely to diffuse away or be used in side reactions.

6. HL extension: metabolic efficiency and heat production

Energy transfer in metabolism is not 100% efficient. A substantial proportion of energy is released as heat. In birds and mammals this heat helps maintain a relatively constant internal temperature.

Key idea	Why it matters
ATP transfer is not perfectly efficient	Some energy becomes heat during metabolic reactions.
Heat production is inevitable	Not all chemical energy can be captured as useful work.
Endotherms depend on this heat	Supports stable body temperature in mammals and birds.

7. HL extension: metabolic pathways

Metabolic pathways are linked sequences of enzyme-controlled reactions. The product of one step becomes the substrate for the next.

Pathway type	Pattern	Examples
Linear pathway	Start substance is converted step-by-step into a different end product.	Glycolysis
Cyclic pathway	The pathway begins and ends with the same substance.	Krebs cycle; Calvin cycle

Pathway logic

```
Linear:
substrate -> A -> B -> C -> final product

Cyclic:
starting compound -> A -> B -> C -> starting compound again

Why pathways are useful:
- release or use energy in small controlled steps
- allow regulation at each step
- connect to other pathways
```

High-yield pathway statement
Fine control matters because releasing too much energy at once could damage the cell. Pathways let cells regulate output and conserve materials.

8. HL extension: enzyme inhibition

Type	Where inhibitor binds	Effect on substrate binding	Effect of more substrate	Example
Competitive inhibition	Active site	Inhibitor blocks the substrate directly.	Can be overcome because substrate out-competes inhibitor at high concentration.	Statins inhibiting an enzyme in cholesterol synthesis
Non-competitive inhibition	Allosteric site	Binding changes the active site so substrate no longer fits properly.	Cannot be overcome fully by adding more substrate.	Metal ions such as mercury
Mechanism-based / irreversible inhibition	Usually active site or essential chemical group	Inhibitor binds permanently and inactivates the enzyme.	Not reversed by extra substrate.	Penicillin inhibiting bacterial transpeptidase

How to identify inhibition curves

```
competitive inhibition:
- reaction rate is lower at first
- with enough substrate, Vmax can still be reached

non-competitive inhibition:
- maximum rate is reduced
- adding more substrate does not restore the same Vmax

Exam clue:
If Vmax is eventually reached -> competitive.
If Vmax stays lower -> non-competitive.
```

Feedback inhibition (end-product inhibition)

When enough end product has accumulated, it binds allosterically to an early enzyme in the pathway, usually the **first enzyme**. This stops unnecessary synthesis, conserving energy and raw materials. When product concentration falls, inhibition is removed and the pathway restarts.

Isoleucine example

```
threonine --(enzyme 1: threonine deaminase)--> A --> B --> C --> D --> isoleucine

high [isoleucine]:
isoleucine binds allosteric site on enzyme 1
-> active site changes
-> threonine cannot bind
-> pathway stops

low [isoleucine]:
enzyme 1 remains active
-> pathway continues
```

Mechanism-based inhibition: penicillin

Penicillin irreversibly inhibits bacterial **transpeptidase**, blocking cell-wall formation. Human cells are unaffected because they do not make cell walls. Resistance can arise if bacteria produce **penicillinase** or if mutations alter the transpeptidase active site so penicillin no longer binds effectively.

9. Exam-ready answers and memory page

Model-answer skeletons

Question type	Answer structure
Explain why enzymes are specific.	Specificity depends on the three-dimensional shape and chemical properties of the active site. Only substrates with a complementary shape and suitable charge distribution can form the enzyme-substrate complex.
Explain how temperature affects enzyme activity.	At first, higher temperature increases kinetic energy and collision frequency, so rate rises. Above the optimum, bonds maintaining enzyme shape are disrupted, the active site changes shape, and rate falls due to denaturation.
Explain how pH affects enzyme activity.	Changes in pH alter H+ or OH- concentration, affecting charges on amino acids in the active site and sometimes the substrate. Binding becomes less effective and extreme pH may denature the enzyme.
Explain why substrate concentration gives a plateau.	Once all enzyme active sites are occupied, enzymes are saturated and working at maximum rate. More substrate cannot further increase the rate unless enzyme concentration also increases.
Differentiate competitive and non-competitive inhibition.	Competitive inhibitors bind the active site and can be out-competed by more substrate. Non-competitive inhibitors bind elsewhere, alter the active site, and lower the maximum reaction rate.

Common exam traps

- Do not say enzymes 'give energy' to reactions. They **lower activation energy**.
- Do not say enzymes change equilibrium. They speed up forward and reverse reactions but do not change the final equilibrium ratio.
- Do not confuse **denaturation** with simply 'slower movement'. Low temperature usually slows collisions; high temperature may denature.
- In competitive inhibition, the inhibitor does **not** bind allosterically.
- In non-competitive inhibition, adding more substrate does **not** restore the same Vmax.

One-minute recap

Enzyme = globular protein catalyst.
Active site = region where substrate binds and reaction is catalysed.
Induced fit = binding causes conformational change in enzyme and substrate.
Activation energy = minimum energy needed to start reaction.
Optimum temperature / pH = conditions giving highest rate.
Competitive inhibitor = binds active site.
Non-competitive inhibitor = binds allosteric site.
Feedback inhibition = end product inhibits an early enzyme in the pathway.

Rapid self-test

Prompt	Fast answer
Why are enzymes reusable?	They are not consumed by the reaction.
What happens to rate above the optimum temperature?	It falls because denaturation alters active-site shape.
Why does more substrate stop increasing rate?	All active sites are saturated.
Which inhibition can be overcome by extra substrate?	Competitive inhibition.
Which inhibition lowers Vmax?	Non-competitive inhibition.
Why is feedback inhibition useful?	Prevents waste of energy and raw materials.
Give one intracellular enzyme example.	Glycolysis or Krebs cycle enzymes.
Give one extracellular enzyme example.	Digestive enzymes in the gut.