AP Biology, *two pages* at a time.

AP Biology revision guide: each group of topics boiled down to the core you need to know, with the diagrams to draw and the mistakes to dodge.

30 SHEETS · UNITS 1 TO 8 · CED TOPIC CODES · 62 PAGES

What is *inside*

CONTENTS

One sheet a guide
Front: the ideas. Back: the detail, the mistakes and exam practice.

Codes from the framework
Each card carries the topic or learning objective it covers.

Then test yourself
Cover the sheet, write what you remember, check, repeat tomorrow.

1 Chemistry of life

Water, carbon and the four molecules cells are built from.

1.1 and 1.2	**Water and the elements of life**	3
1.3 and 1.4	**Macromolecules and carbohydrates**	5
1.5 and 1.6	**Lipids and nucleic acids**	7
1.7	**Proteins**	9

2 Cell structure and function

What is inside a cell, and what crosses its membrane.

2.1, 2.2	**Cell structure and size**	11
2.3, 2.4	**Membranes and permeability**	13
2.5, 2.6, 2.8	**Membrane transport**	15
2.7	**Tonicity and water potential**	17
2.9, 2.10	**Compartments and their origins**	19

3 Cellular energetics

Enzymes, photosynthesis and respiration.

3.1 to 3.3	**Enzymes and cellular energy**	21
3.4	**Photosynthesis**	23
3.5	**Cellular respiration**	25

4 Cell communication and cell cycle

How cells signal, keep steady and divide.

4.1 to 4.3	**Cell communication and signal transduction**	27
4.4	**Feedback**	29
4.5 and 4.6	**The cell cycle and its regulation**	31

5 Heredity

Meiosis, and how traits pass from parents to offspring.

5.1 and 5.2	**Meiosis and genetic diversity**	33
5.3	**Mendelian genetics**	35
5.4 and 5.5	**Non-Mendelian genetics and the environment**	37

6 Gene expression and regulation

From DNA to protein, and how genes are switched.

6.1 and 6.2	**DNA structure and replication**	39
6.3 and 6.4	**Transcription and translation**	41
6.5 and 6.6	**Regulation of gene expression**	43
6.7 and 6.8	**Mutations and biotechnology**	45

7 Natural selection

How populations change, and how species arise.

7.1 to 7.3	**Natural selection**	47
7.4, 7.5 and 7.11	**Population genetics**	49
7.6 to 7.9	**Evidence of evolution and phylogeny**	51
7.10 and 7.12	**Speciation and the origins of life**	53

8 Ecology

Energy, populations, communities and change.

8.1	**Responses to the environment**	55
8.2	**Energy flow and matter cycles**	57
8.3 to 8.5	**Populations and communities**	59
8.6 and 8.7	**Biodiversity and disruptions**	61

AP BIOLOGY | UNIT 1 | TOPICS 1.1 AND 1.2

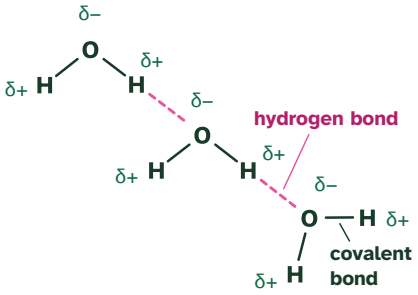
REVISION ON TWO PAGES

Water, carbon and *life*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Water is polar, so it forms hydrogen bonds: every property follows. Life builds its molecules on carbon, from six elements.



Draw it like this. Solid lines for covalent bonds, dashed for hydrogen bonds, δ+ and δ– on the atoms.

1.1.A START HERE

Polar bonds make *hydrogen bonds*

- Oxygen is more **electronegative** than hydrogen: it pulls the shared electrons toward itself. This **unequal sharing** makes each O–H bond a **polar covalent bond**, with a slightly negative oxygen (δ–) and slightly positive hydrogens (δ+).
- The δ+ hydrogen of one molecule is attracted to the δ– oxygen of a neighbor. That attraction is a **hydrogen bond**: it holds **one molecule to the next**, and is about 20 times weaker than a covalent bond.
- One hydrogen bond is weak and brief, but each molecule can make up to four, and there are vast numbers of them. Breaking them takes energy.

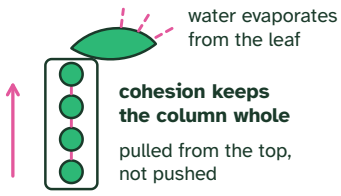
WHAT HYDROGEN BONDS GIVE WATER — *Cats Always Skip Hot Showers*

C	**Cohesion**	water sticks to water
A	**Adhesion**	water sticks to polar surfaces
S	**Solvent**	dissolves ions and polar molecules
H	**Heat**	slow to warm and to cool
S	**Surface tension**	a film at the surface

1.1.A WATER TO WATER

Cohesion

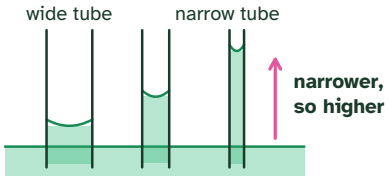
- **Cohesion**: hydrogen bonds hold water molecules to one another.
- **At a surface:** molecules have no neighbors above, so they are pulled sideways and inward. The surface acts like a stretched film: **surface tension**. A water strider stands on it.
- **In xylem: transpiration** from leaves pulls on the molecules behind, so a whole column is drawn up. No pump is needed.



1.1.A WATER TO OTHER THINGS

Adhesion

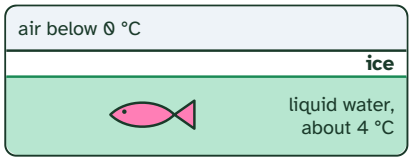
- **Adhesion**: water is attracted to surfaces that are **polar or charged**, such as glass, cellulose and soil particles.
- **Capillary action**: water adheres to the walls of a narrow space and climbs; cohesion drags the rest behind.
- It soaks water through soil and cell walls. On **nonpolar** wax, water beads up and runs off.



1.1.A THREE EFFECTS, ONE CAUSE

Water and *heat*

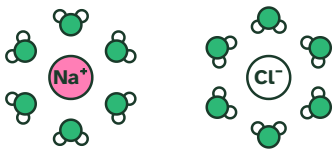
- **High specific heat**: energy breaks hydrogen bonds before molecules speed up, so water warms and cools slowly. Seas and cells hold a steady temperature.
- **Evaporative cooling**: the fastest molecules escape and take their energy with them. Sweat and transpiration cool this way.
- **Ice floats**: frozen molecules lock into four hydrogen bonds in an open lattice, so ice is less dense than liquid water.



1.1.A

The *solvent* a cell runs in

- **Ions dissolve:** the δ– oxygens of water turn toward positive ions and the δ+ hydrogens toward negative ions, and each ion leaves **wrapped in a shell of water**.
- **Polar molecules dissolve:** sugars and amino acids **form hydrogen bonds with water**.
- **Why it matters:** cytoplasm is a water solution where enzymes and their substrates meet; blood and xylem carry dissolved substances.



Oxygens face the positive ion; hydrogens face the negative ion

Hydrophilic polar or charged
Ions (Na^+, Cl^-), glucose, amino acids. They dissolve, so they can react and be carried.

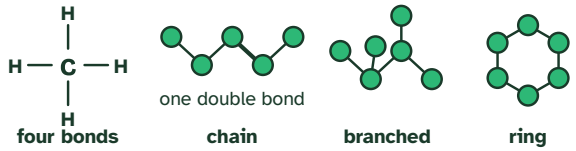
Hydrophobic nonpolar
Wax keeps water in a leaf. **Fat** stores energy. The nonpolar middle of a **membrane** keeps a cell's contents in.

Carbon skeletons and the *six elements* of life

1.2.A

Why life is built on *carbon*

- The molecules of life are **organic molecules**: carbon skeletons with other atoms attached.
- A carbon atom has four electrons to share, so it forms **four covalent bonds**. A double bond uses two of the four.
- Carbon bonds strongly to carbon, building **chains, branches and rings**. Shape decides what a molecule can do.



1.2.A FOUR TO KNOW

Functional groups

- A **functional group** is a small group of atoms on the skeleton that decides how the molecule reacts.

–OH **Hydroxyl** Polar: sugars dissolve.	–COOH **Carboxyl** Acidic: amino and fatty acids.
$-NH_2$ **Amino** Brings in nitrogen.	$-PO_4$ **Phosphate** Brings in phosphorus.

1.2.A LEARN THE PATTERN

Which *elements* are in which molecule

CLASS	ALWAYS CONTAINS	ALSO, IN SOME	SO THE ORGANISM NEEDS
Carbohydrates sugars, starch, cellulose	**C, H, O**	Nothing else.	Carbon, for every class and for every energy store.
Lipids fats, oils, phospholipids	**C, H, O**	**P** in phospholipids.	Phosphorus to build the phospholipids of every membrane.
Proteins chains of amino acids	**C, H, O, N**	**S** in some amino acids.	Nitrogen: every amino acid has an amino group.
Nucleic acids DNA and RNA	**C, H, O, N, P**	Nothing else.	Nitrogen for every base, and phosphorus for every nucleotide.

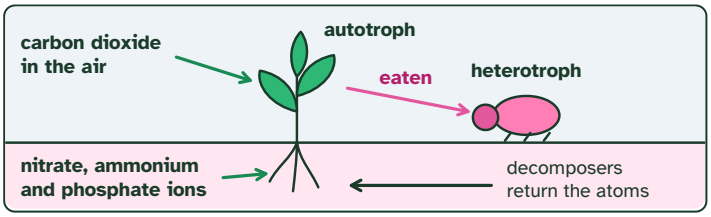
Six elements make up almost all the mass of a living thing.

Remember the six: *Cows Have Odd Names, Personally Speaking*

1.2.A

Where the atoms *come from*

- No organism makes its own atoms. To grow, repair and reproduce, it must **exchange matter with its environment**.
- A plant takes **carbon** as carbon dioxide from the air, and **nitrogen** and **phosphorus** as ions from the soil.
- An animal takes in all three by eating. Decomposers return them, so the atoms cycle.



WATCH OUT

Five mistakes that *cost points*

- ✕ **A hydrogen bond is between molecules.** The O–H bonds inside one molecule are covalent.
- ✕ **Write δ+ and δ–, never a bare + or –.** Water is neutral.
- ✕ **Water is pulled up a tree, not pushed.** Capillary action alone lifts it only a short way.
- ✕ **Sweat cools only as it evaporates.** On a humid day it drips off and cools very little.
- ✕ **A plant's mass comes mostly from the air.** Soil gives minerals; carbon dioxide gives the carbon.

COVER THE SHEET

Can you *answer these?*

1. Draw a hydrogen bond between two water molecules.
2. Explain how water reaches the top of a 100 m tree.
3. Describe capillary action and one place it matters.
4. Explain why salt dissolves in water but oil does not.
5. Explain why a lake warms more slowly than the air.
6. Predict what would happen to pond life if ice sank.
7. Describe why carbon can build so many molecules.
8. Identify two classes of molecule that need nitrogen.

IN THE EXAM

Name the bond, then the result: "hydrogen bonds between water molecules" earns the point, "water is sticky" does not. Then say what the property does for the organism.

GO FURTHER

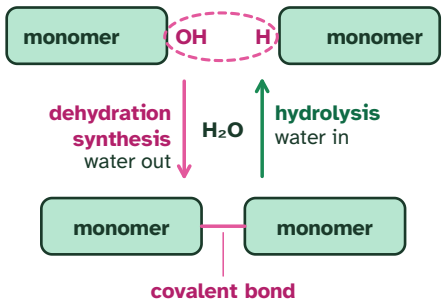
Animated figures, a dry lab and a marked Check are in the full guide online.

Big molecules from *small parts*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Cells build polymers from monomers by taking water out, and break them by putting water back. How the monomers join decides the job.



Follow the water. It leaves when a bond forms and is used up when a bond breaks.

1.3.A START HERE

Water out to *build*, water in to *break*

- **Dehydration synthesis**: a cell removes an OH from one monomer and an H from the other. They leave together as water, and a **covalent bond** forms between the monomers.
- **Hydrolysis** runs it backward: a water molecule is **split**, its H joins one monomer and its OH the other, and the bond between them breaks.
- **One water for every bond**, made or broken. Enzymes speed up both reactions, and building costs the cell energy.
- **Order matters:** the same few monomers, joined in another order or another way, make a different polymer with a different job.

WHICH WAY THE WATER GOES

D Dehydration synthesis water out: a bond is built	**H** Hydrolysis water in: a bond is broken

1.3.A THREE OF THE FOUR CLASSES ARE CHAINS

Monomers, bonds and *polymers*

CLASS	MONOMER	BOND BETWEEN MONOMERS	POLYMER
Carbohydrates	**Monosaccharides** such as glucose	Glycosidic bond	Polysaccharides: starch, glycogen, cellulose.
Proteins	**Amino acids** 20 kinds	Peptide bond	Polypeptides, which fold into proteins.
Nucleic acids	**Nucleotides** 4 kinds in each	Phosphodiester bond	DNA and RNA.
Lipids the odd one out	**None** a fat is glycerol and three fatty acids	Built by dehydration synthesis all the same	**Not a polymer:** large, but not a chain of repeating units.

All four classes are macromolecules. Three are polymers.

Order and joining decide what a polymer is

1.3.A

Digest, then *rebuild*

- **Digestion is hydrolysis.** Starch, protein and DNA in food are too big to be absorbed, so enzymes split them into glucose, amino acids and nucleotides.
- Cells then **rebuild the monomers into their own polymers** by dehydration synthesis: glucose from a potato can become glycogen in your liver.
- Breaking large molecules down is **catabolism**; building them up is **anabolism**. Each reaction has its own enzyme.



1.3.A A FAVORITE CALCULATION

Count the *waters*

- A chain of **n** monomers has **n – 1** bonds.
- So building it releases n – 1 water molecules, and digesting it completely uses the same number.

9 waters released joining 10 glucose	**299** waters used to digest a chain of 300

1.4.A

One unit, two units, *many*

- Carbohydrates contain C, H and O, usually **1:2:1**. Their monomers are **monosaccharides**, joined by **glycosidic bonds**.
- Glucose, fructose and galactose are all $C_6H_{12}O_6$ with the atoms arranged differently: they are **isomers**.



one unit | two units | many units

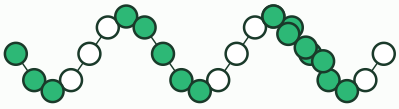
ONE UNIT
Monosaccharides
Glucose, fructose, galactose. Ribose and deoxyribose have five carbons.

TWO UNITS
Disaccharides
Sucrose: glucose and fructose. Lactose: glucose and galactose. Maltose: two glucose.

MANY UNITS
Polysaccharides
Starch, glycogen, cellulose, chitin. Too large to dissolve or to taste sweet.

1.4.A THE STRUCTURE OF THE MONOMER DECIDES THE PROPERTIES OF THE POLYMER

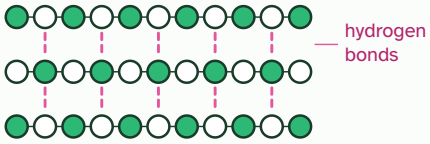
Same glucose, *different jobs*



starch: a coil, few branches



glycogen: many branches



cellulose: straight chains

	STARCH	GLYCOGEN	CELLULOSE
Found in	Plants: grains in a potato or a seed.	Animals and fungi: liver and muscle cells.	The cell wall of every plant cell.
Built from	**Alpha glucose**	**Alpha glucose**	**Beta glucose** Every other unit is turned over.
Shape	Coiled chains, some with occasional branches.	Coiled, and branched far more often.	Straight chains that lie side by side in bundles called microfibrils.
Job	**Energy store**	**Energy store** More branches mean more ends for enzymes, so glucose comes off fast.	**Structure** Holds the plant up and stops its cells bursting.
Why it suits	**Compact**, and too large to dissolve, so it does not **draw water into the cell**.	Enzymes hydrolyze glucose from the **ends of the chains**, one unit at a time.	One hydrogen bond is weak; **thousands between chains** are strong. Humans cannot hydrolyze it: fiber.

Each bead is one glucose unit.

Chitin, a structural polysaccharide with nitrogen, makes fungal cell walls and insect exoskeletons

WATCH OUT

Five mistakes that *cost points*

- ✕ **A fat is not a polymer.** It is large, but not a chain of repeating monomers.
- ✕ **Dehydration is not drying out.** The water is made from atoms of the two monomers.
- ✕ **In hydrolysis the water is split.** Its H and its OH end up on the two new ends.
- ✕ **Insoluble does not mean hydrophobic.** Starch is polar, but too large to dissolve.
- ✕ **Cellulose is structure, not a store.** Plants store glucose as starch.

COVER THE SHEET

Can you *answer these?*

1. Identify the monomer and the bond of a protein.
2. Describe what happens in dehydration synthesis.
3. Calculate the waters released as 50 amino acids join.
4. Explain why digestion is called hydrolysis.
5. Explain why a fat is not a polymer.
6. Describe how lactose differs from starch.
7. Explain why glycogen releases glucose faster than starch.
8. Explain how beta glucose makes cellulose strong.

IN THE EXAM

Say where the water goes ("a water molecule is released as a covalent bond forms"), then **link structure to function**: branched, so many ends, so glucose comes off fast.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

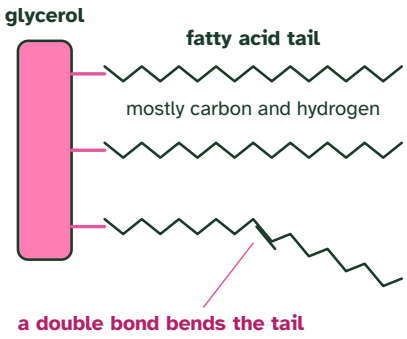
AP BIOLOGY | UNIT 1 | TOPICS 1.5 AND 1.6 | REVISION ON TWO PAGES

Fats, oils and the *code*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Lipids are nonpolar, so water pushes them together. Nucleic acids are chains of nucleotides whose bases pair and carry information.



A triglyceride. Each zigzag is a chain of carbons; hydrogens are left out.

1.5.A START HERE

The molecules water *will not touch*

- Lipids are grouped by how they behave, not by a shared monomer: they are **nonpolar**. Their C–H bonds share electrons almost evenly, so water has nothing to attract and they are **hydrophobic**.
- Fats and oils are mostly **triglycerides**: one glycerol joined to three fatty acids by dehydration synthesis, **releasing three waters**.
- A triglyceride is large but **not a polymer**: four parts joined, not a chain of repeats.

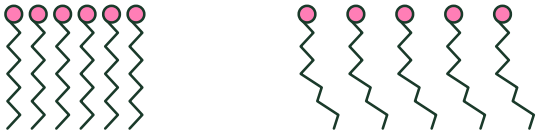
WHAT LIPIDS DO

E	**Energy** the long-term store	**I**	**Insulation** fat under the skin	**W**	**Wax** keeps water off a leaf	**M**	**Membranes** phospholipids

1.5.A STRUCTURE SETS THE MELTING POINT

Saturated and *unsaturated*

- **Saturated:** every bond between carbons is single, so the tail is **straight** and holds as many hydrogens as it can.
- **Unsaturated:** one or more C=C double bonds, each putting a **kink** in the tail.
- Straight tails pack closely and attract each other more, so the fat has a **higher melting point**. The more double bonds, the lower it is.



saturated tails | unsaturated tails

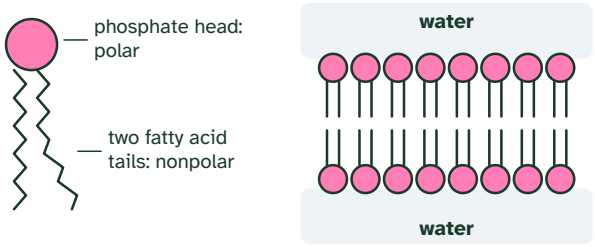
Saturated fat solid at room temperature
Butter, lard. Mammals, at about 37 °C, can store harder fats.

Unsaturated oil liquid at room temperature
Olive oil, sunflower oil. Plants and cold-water fish store oils that stay liquid.

1.5.A HALF LOVES WATER, HALF DOES NOT

Phospholipids make membranes

- A phospholipid is built like a triglyceride, but a **phosphate group** replaces one fatty acid.
- The charged phosphate is a **hydrophilic head**; the two tails stay **hydrophobic**. A molecule with both is **amphipathic**.
- In water, phospholipids form a **bilayer** by themselves: heads out, tails in. Ions and most polar molecules cannot cross its nonpolar core.
- Kinked unsaturated tails keep a bilayer fluid.



1.5.A SAME CLASS, THREE SHAPES

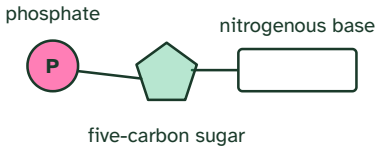
Three lipids to *tell apart*

	TRIGLYCERIDE	PHOSPHOLIPID	STEROID
Built from	Glycerol and **three** fatty acids.	Glycerol, **two** fatty acids and a phosphate group.	Four carbon rings joined together.
In water	**Hydrophobic** Gathers into droplets.	**Amphipathic** Forms a bilayer.	**Mostly nonpolar** Can pass through a bilayer.
Job	Stores about **twice the energy** of a carbohydrate, gram for gram, with no water held. Insulates.	Makes **every membrane**: a barrier that holds a cell's dissolved contents in.	**Cholesterol** sits among the tails of animal membranes. Testosterone and estrogen are hormones made from it.

All three are nonpolar, at least in part: that is what makes them lipids.

1.6.A

A sugar, a phosphate and a *base*



- Nucleic acids carry the instructions for every protein. Their monomers are **nucleotides**.
- Nucleotides join by dehydration synthesis into a **sugar-phosphate backbone** of covalent bonds. The bases stick out: they are the message.
- New nucleotides are added **only to the 3′ end**, so a strand always grows 5′ to 3′.

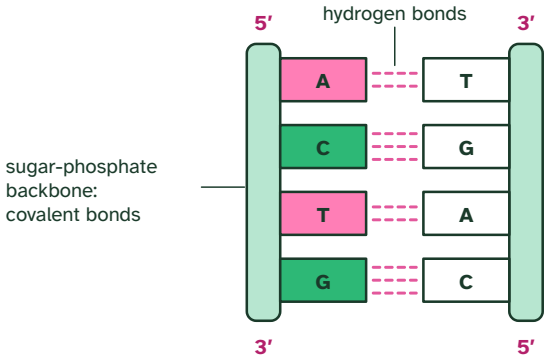
5′ END
A free phosphate
on the 5′ carbon of the sugar.

3′ END
A free OH
on the 3′ carbon. The next nucleotide joins here.

1.6.A

Two strands, running *opposite ways*

- **Complementary base pairing**: A with T, and C with G, held by **hydrogen bonds**. A and T share two; C and G share three.
- The strands are **antiparallel**: one runs 5′ to 3′, its partner 3′ to 5′. Together they twist into a double helix.
- Separated, each strand is a **template**: its bases decide which nucleotide joins opposite.



1.6.A BUILT THE SAME WAY, FOR TWO JOBS

DNA and RNA: *three differences*

	DNA	RNA
Sugar	**Deoxyribose** One oxygen fewer than ribose.	**Ribose**
Bases	**A, T, C and G**	**A, U, C and G** Uracil replaces thymine, and pairs with A.
Strands	**Usually two** Antiparallel, in a double helix, the bases tucked inside.	**Usually one** It can fold back on itself into shapes that do jobs.
Job	**The long-term store** Each strand can repair or copy the other.	**A working copy** Made from one gene when needed, used, then broken down.

Both are strands of nucleotides with a 5′ and a 3′ end.

Each difference fits the job

WATCH OUT

Six mistakes that *cost points*

- ✕ **Melting a fat breaks no covalent bonds.** It only separates whole molecules from each other.
- ✕ **A bilayer is not held by covalent bonds.** Water keeps pushing the tails together, so a membrane can flow.
- ✕ **5′ and 3′ are carbons of the sugar,** not the first and last bases.
- ✕ **The two strands are complementary, not identical.**
- ✕ **Hydrogen bonds join the base pairs;** the bonds along each backbone are covalent.
- ✕ **Uracil replaces thymine, not adenine.** U pairs with A.

COVER THE SHEET

Can you *answer these?*

1. Explain why lipids do not dissolve in water.
2. Describe how a triglyceride is built.
3. Explain why olive oil is liquid when butter is solid.
4. Explain why phospholipids form a bilayer in water.
5. Identify the three parts of a nucleotide.
6. Determine the strand that pairs with 5′-ATGC-3′.
7. Describe what antiparallel means.
8. Describe three ways RNA differs from DNA.

IN THE EXAM

For a lipid, start from polarity: nonpolar tails, polar head. **For DNA, mark 5′ and 3′ on both strands**, and say which bonds are hydrogen bonds and which are covalent.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

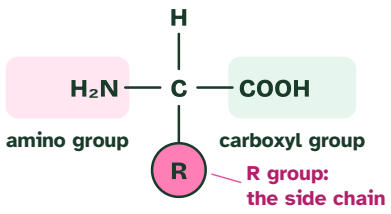
Proteins: shape is *function*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

The sequence of amino acids decides how a chain folds, and the folded shape decides what the protein can do.

the same in all twenty



Draw it like this. A central carbon with four things on it. Only the R group changes.

1.7.A START HERE

Twenty monomers, *one pattern*

- Every protein is built from **amino acids**. All twenty kinds share one pattern: a central carbon carrying an **amino group**, a **carboxyl group**, a hydrogen atom and a side chain.
- The side chain, the **R group**, is the only part that differs. It gives each amino acid its chemistry, and it decides how a chain folds.
- You do not need the structure of any particular amino acid: know the pattern, and the kinds of R group.

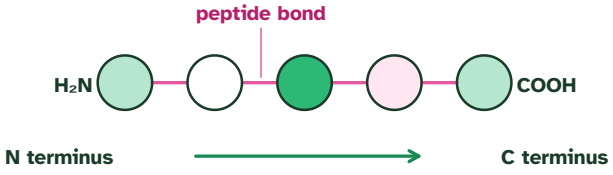
WHAT PROTEINS DO

E Enzymes	speed up reactions
C Channels	and pumps cross membranes
A Antibodies	defend the body
F Fibers	collagen and keratin

1.7.A PEPTIDE BONDS AND DIRECTION

A chain with a *beginning* and an end

- Amino acids join by dehydration synthesis: the carboxyl group of one meets the amino group of the next, and an OH and an H leave as water. The covalent bond is a **peptide bond**.
- Many amino acids joined make a **polypeptide**. It has direction: a free amino group at the **N terminus** and a free carboxyl group at the **C terminus**.
- Each new amino acid is added at the carboxyl end, so a chain grows from N to C. The order along it is the **sequence**.
- R groups are not part of the bond: they hang off the backbone.



Each circle is one amino acid. The arrow shows the way the chain grows.

20
kinds of amino acid

20^{10}
ways to order a chain of only ten

1.7.A WHAT DECIDES THE FOLD

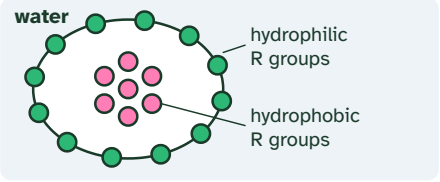
R groups: three kinds

NONPOLAR
Hydrophobic
Mostly carbon and hydrogen. In water they cluster together, away from it.

POLAR
Hydrophilic
Carry OH or other partial charges. They hydrogen bond with water and each other.

CHARGED
Ionic
Acidic ones become negative, basic ones positive. Opposite charges attract.

- In water, a protein's surface is mostly hydrophilic and charged R groups; its **core is mostly hydrophobic**.



1.7.A SEQUENCE, SHAPE, FUNCTION

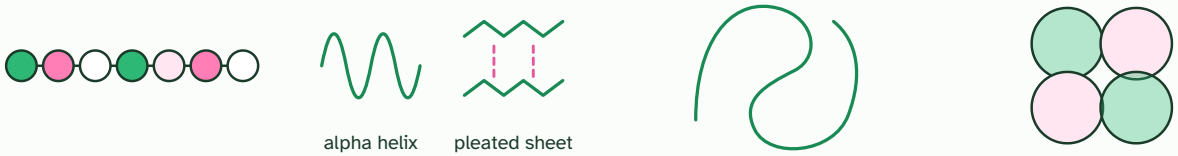
One amino acid can *change everything*

- Change the sequence and the chain may fold differently: a new shape, and a changed or lost function.
- **Sickle cell disease:** one charged amino acid in a chain of hemoglobin is swapped for a hydrophobic one. The molecules stick together when oxygen is low and distort the red blood cell.
- **Shape is function**: an enzyme's active site, a receptor's binding site and a channel's pore are all pockets made by folding.

Four levels of *structure*, and how to lose them

1.7.A FOUR LEVELS OF STRUCTURE

Each level is built on the *one before*



	PRIMARY	SECONDARY	TERTIARY	QUATERNARY
What it is	The **sequence** of amino acids. It decides everything that follows.	Local folding of the backbone into an **alpha helix** or a **beta pleated sheet**.	The whole chain's **three-dimensional shape**, set by its R groups.	How the chains fit together in a protein of **two or more polypeptides**.
Held by	**Peptide bonds** Covalent.	**Hydrogen bonds** Between C=O and N–H of the backbone, not between R groups.	**R group interactions** A hydrophobic core, hydrogen bonds, ionic bonds and disulfide bridges.	**The same interactions** This time between chains.
Denatured	Kept: only hydrolysis breaks peptide bonds.	Lost.	Lost.	Lost.

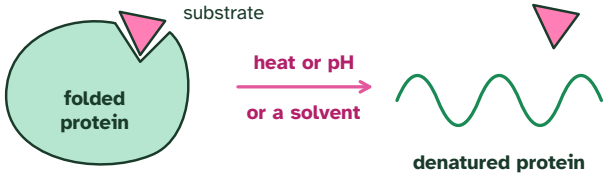
Hemoglobin has four chains; collagen has three, wound into a rope.

A **disulfide bridge** is a covalent bond between the sulfur atoms of two cysteines

1.7.A

Denaturing: unfold it and it stops working

- The interactions that hold the shape are weak. Break them and the protein unfolds: it is **denatured**.
- It **keeps its full sequence** but loses its shape, so an enzyme's active site no longer fits its substrate.
- Unfolded chains expose their hydrophobic R groups and clump, as egg white does in a pan. Clumped protein rarely refolds.
- Each protein works best where it evolved: most human proteins near 37 °C and pH 7, the enzymes of the stomach near pH 2.



CAUSE 1
Heat
The chain vibrates until hydrogen bonds snap.

CAUSE 2
Acid or alkali
Charges on R groups change, so ionic and hydrogen bonds fail.

CAUSE 3
Solvents
Ethanol and other solvents loosen the hydrophobic core.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Peptide bonds join the backbone.** R groups are not part of the bond: they hang off the chain.
- ✕ **Secondary structure is hydrogen bonds in the backbone.** Bonds between R groups are tertiary.
- ✕ **Not every protein has quaternary structure.** Only those made of two or more polypeptides.
- ✕ **Denaturing is not hydrolysis.** The peptide bonds and the sequence stay; only the shape goes.
- ✕ **Amino acids are not only C, H, O and N.** Two of the twenty carry sulfur in their R groups.

COVER THE SHEET

Can you *answer these?*

1. Draw an amino acid and label its four parts.
2. Describe how a peptide bond forms.
3. Identify the two ends of a polypeptide.
4. Predict where hydrophobic R groups lie in water.
5. Describe what holds an alpha helix in shape.
6. Explain how one changed amino acid can alter function.
7. Explain why a denatured enzyme stops working.
8. Explain why boiling does not hydrolyze a protein.

IN THE EXAM

Follow the chain of cause: sequence, then R group interactions, then shape, then function. Name the level of structure and the bond that holds it.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

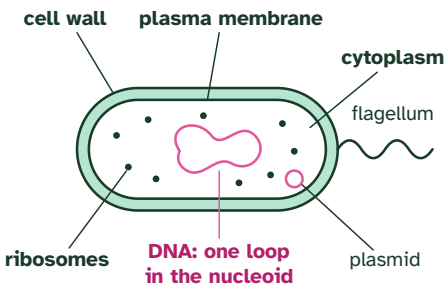
AP BIOLOGY | UNIT 2 | TOPICS 2.1, 2.2 | REVISION ON TWO PAGES

The parts of a *cell*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Every cell shares four parts. Eukaryotes add membrane-bound organelles, each built for its job. Cells stay small to keep surface high for their volume.



A bacterium. One open space: every reaction shares it, which works because the cell is tiny.

2.1.A START HERE

Every cell, the same *four parts*

- **Prokaryotes** (bacteria and archaea) are small, with **no membrane-bound organelles**. **Eukaryotes** (animals, plants, fungi, protists) are usually ten times wider and divided into compartments.
- A prokaryote's DNA is one loop in the **nucleoid**, a region of cytoplasm with no membrane around it. Most have a cell wall (peptidoglycan in bacteria); many have plasmids, some a flagellum.
- Every cell has the same four parts, with the same genetic code: evidence that all cells share a **common ancestor**.

IN EVERY CELL EVER FOUND

M Membrane controls what crosses	**C** Cytoplasm mostly water; fills the cell	**D** DNA carries the instructions	**R** Ribosomes read them to make proteins

2.1.A IN ALL LIFE

Ribosomes

- Made of **rRNA and protein**, in two subunits, with no membrane. They read mRNA and join amino acids in order: they **make proteins**.
- All life has them, working so alike that they must be inherited from **one common ancestor**.
- They are assembled in the nucleus, at the **nucleolus**, not in the ER.

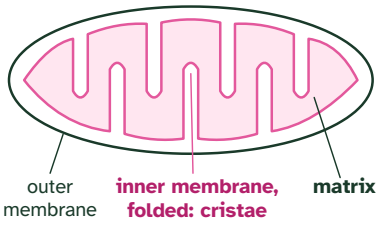
Free in the cytoplasm
Make proteins that stay in the cytoplasm.

Bound on the rough ER
Make proteins for membranes, for lysosomes or for export.

2.1.A USES ENERGY

The *mitochondrion*

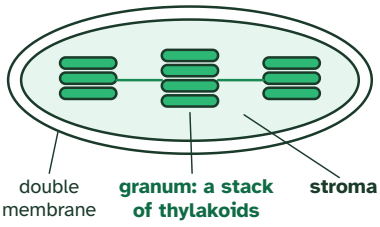
- Double membrane: a smooth outer one and an inner one **folded into cristae**.
- The **Krebs cycle** runs in the matrix. The **electron transport chain** and **ATP synthase** sit in the inner membrane.
- Folding gives **more surface area**, so more of both fit in and the cell makes more ATP.



2.1.A CAPTURES ENERGY

The *chloroplast*

- In plants and photosynthetic algae. A double membrane around a fluid, the **stroma**.
- **Thylakoid** membranes hold chlorophyll and electron transport proteins: the **light-dependent reactions** happen in the grana.
- The **Calvin cycle** fixes carbon dioxide into sugar in the **stroma**.



2.1.A EACH WITH ITS OWN JOB

A eukaryotic cell, *room by room*

ORGANELLE	WHAT IT LOOKS LIKE	WHAT IT DOES
Nucleus	A double membrane with pores.	Holds the DNA, the cell's instructions.
Rough ER	Membrane sacs studded with ribosomes.	Makes proteins and sends them on to the Golgi.
Smooth ER	Membrane with no ribosomes.	Makes lipids and breaks down toxins: liver cells have a lot.
Golgi complex	A stack of flattened sacs.	Folds and modifies proteins, then sorts them into vesicles.
Lysosome	A sac of hydrolytic enzymes.	Breaks down worn-out parts and what the cell takes in; apoptosis.
Vacuole	A membrane sac.	Stores water, food or waste.

2.1.A BOTH EUKARYOTIC

Plant cell, *animal* cell

	PLANT CELL	ANIMAL CELL
Cell wall	**Cellulose**	None: cytoskeleton holds shape.
Vacuole	**One, large**	Often many, small.
Chloroplasts	**Yes**	None.
Lysosomes	The vacuole does much of that job.	**Common**
Centrioles	None.	**Yes**

Both: nucleus, ER, Golgi, mitochondria, ribosomes, plasma membrane.

2.1.A SHADES OF GRAY, NO LABELS

Name it from a *micrograph*

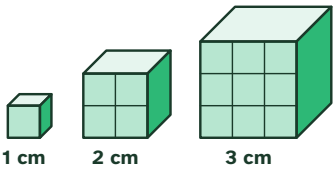
STRUCTURE	WHAT TO LOOK FOR
Nucleus	Largest round body: double membrane, pores.
Mitochondrion	Small, with a folded inner membrane.
Chloroplast	An oval with stacks of membrane inside.
Rough ER	Parallel sacs dotted with ribosomes.
Golgi	A curved stack with vesicles, no dots.

Wall, no nucleus: prokaryote. Wall, vacuole, chloroplasts: plant.

2.2.A

Why cells *stay small*

- Everything a cell exchanges crosses its membrane, so **supply** depends on **surface area**. **Demand** depends on **volume**.
- As a cell grows, volume rises faster than surface area, so the **surface area-to-volume ratio falls**.
- A large cell has too little membrane for its volume and a middle far from any surface. So cells stay small, and **divide** rather than keep growing.



SA = $6s^2$, V = s^3, so SA:V = 6 ÷ s

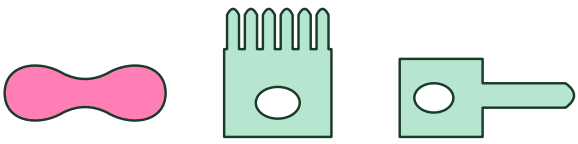
SIDE, CM	SA, CM²	V, CM³	SA:V
1	6	1	**6**
2	24	8	**3**
3	54	27	**2**

Sphere, cylinder and box formulas are on the AP formula sheet.

2.2.A

More surface: *flatten, fold, fringe*

- Cells that exchange a lot raise their surface area. **Flattening:** a red blood cell is a thin disc, so no hemoglobin is far from the surface.
- **Microvilli**, tiny fingers of membrane, multiply the area for absorption in the small intestine and kidney. A **root hair** does it for water and minerals.
- SA:V also sets heat exchange: a small animal **loses heat fast** for its size. Large animals need lungs, guts and blood to bring exchange surfaces close to every cell.



red blood cell
flattened disc

gut cell
microvilli

root hair cell
long extension

WATCH OUT

Five mistakes that *cost points*

- ✕ **Prokaryotes do have DNA.** It is a loop in the nucleoid, with no membrane around it.
- ✕ **The Golgi does not make proteins.** Ribosomes make them; the Golgi modifies and ships them.
- ✕ **Plant cells have mitochondria too.** Chloroplasts make sugar; mitochondria turn it into ATP.
- ✕ **A bigger cell has more surface area, not less.** It is the area for each unit of volume that falls.
- ✕ **Microvilli are not cilia.** They do not beat: they only add surface.

COVER THE SHEET

Can you *answer these?*

1. Identify the four structures every cell has.
2. Explain why ribosomes are evidence of common ancestry.
3. Describe one difference between rough and smooth ER.
4. Explain how cristae let a cell make more ATP.
5. Identify where the Calvin cycle runs in a chloroplast.
6. Describe three ways plant and animal cells differ.
7. Calculate SA:V for a cube of side 4 cm.
8. Predict which cools faster for its size: mouse or elephant.

IN THE EXAM

Link structure to function: name the feature (folded inner membrane), say what it adds (surface area), then what that allows (more ATP synthase, more ATP).

GO FURTHER

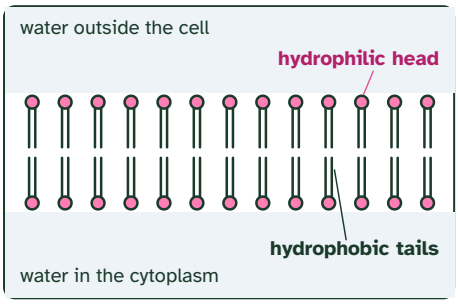
Animated figures, a dry lab and a marked Check are in the full guide online.

The membrane: a *fluid* barrier

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Phospholipids form a bilayer with a hydrophobic core. That core decides what crosses; proteins let through the rest.



Draw it like this. A circle for each head, two lines for its tails, water on both sides.

2.3.A START HERE

A barrier that *builds itself*

- A phospholipid has two ends. Its charged phosphate head is **hydrophilic**: it mixes with water. Its two nonpolar fatty acid tails are **hydrophobic**: water pushes them out.
- A cell has water on both sides, so phospholipids settle into a **bilayer**: heads facing the water on each side, tails facing each other in the middle.
- Nothing arranges them. Water hydrogen bonds with itself and squeezes the tails together: the **hydrophobic effect**. That is why a torn membrane seals itself.

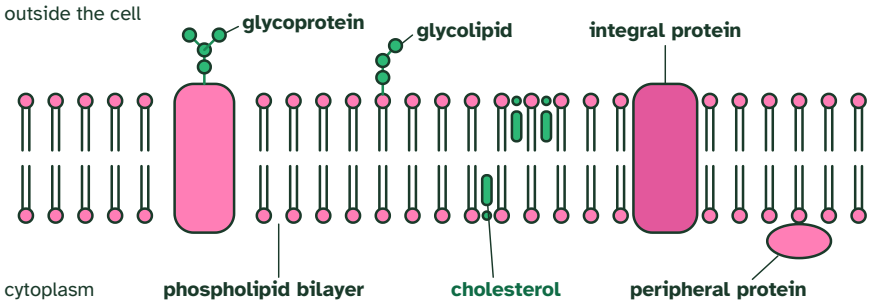
WHAT THE PROTEINS IN A MEMBRANE DO

T Transport: carry substances across	**S** Signals: receive them	**J** Joining: cell to cell	**E** Enzymes: speed up reactions

2.3.B

The *fluid mosaic* model

- **Mosaic:** a framework of phospholipids with other molecules set in it like tiles: **proteins, cholesterol** (in eukaryotes), **glycoproteins and glycolipids**.
- **Fluid:** nothing is fixed. Phospholipids and most proteins **move sideways** within the membrane, like a film of oil.
- Fluidity lets a membrane seal itself, and bud off or take in vesicles.



2.3.A PLACED BY R GROUPS

Proteins in the bilayer

- Where a protein sits depends on its **amino acids**. Nonpolar R groups are hydrophobic and stay **among the tails**; charged and polar R groups face the water.
- An integral protein has both: a hydrophobic region in the core and hydrophilic regions out in the water.

Integral in the bilayer
Set into it; many span it from one side to the other. One set in a single layer still counts.

Peripheral on the surface
Hydrophilic all over. Held to the heads or to an integral protein.

2.3.B THREE CONTROLS

Not too stiff, *not too runny*

- **Temperature:** warmer is more fluid, colder is stiffer.
- **Tails:** saturated tails pack tightly; the kinks in **unsaturated tails** keep them apart. Cold-water fish and plants in the cold make more of these.
- **Cholesterol** steadies fluidity: it holds phospholipids back when warm and stops tails packing when cold.



saturated
straight: stiffer

unsaturated
kinked: more fluid

2.3.B CELL RECOGNITION

Sugar *name tags*

- A **glycoprotein** is a protein with sugar chains; a **glycolipid** is a lipid with them.
- The sugars face **outward only**. The side of the membrane facing the cytoplasm has none.
- Each cell type has its own pattern, so cells **recognize each other** and the immune system tells your cells from invaders.

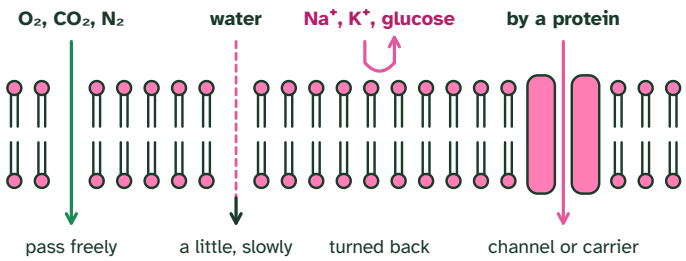
A, B, O
blood groups are differences in the sugar chains on red blood cells

What *gets through*, and the wall outside

2.4.A

Selectively permeable

- A membrane lets only some things across: it is **selectively permeable**, and its structure decides which.
- To cross unaided, a molecule must pass the **hydrophobic core** of tails. Small nonpolar molecules dissolve in it and pass straight through.
- Charged and strongly polar molecules are turned back. They cross through **channel and carrier proteins**, each fitting only some substances, so the cell chooses what comes in.



2.4.A SIZE AND CHARGE DECIDE

What crosses the *bilayer itself*

KIND OF MOLECULE	EXAMPLES	CROSSES UNAIDED?	WHY
Small, nonpolar	O_2, CO_2, N_2	**Yes, freely**	It dissolves in the hydrophobic core.
Small, polar, uncharged	Water	**In small amounts**	Polar, but small enough to slip between the phospholipids.
Ions	Na^+, K^+	**No**	Charge holds a shell of water around the ion; the core will not let it in.
Large, polar	Glucose	**No**	Too polar and too large for the core.

Size is not the whole story: Na^+ is smaller than O_2, yet cannot cross.

Ions and large polar molecules need a transport protein

2.4.B

A *wall* outside the membrane

- Plants, fungi and most prokaryotes have a **cell wall** outside the plasma membrane, made of complex carbohydrates.
- It is a **structural boundary**: it gives the cell its shape, supports the plant and stops the cell bursting when water rushes in.
- It is a barrier only to some substances: very large molecules and many viruses.

2.4.B ALL COMPLEX CARBOHYDRATES

Three walls, *three carbohydrates*

CELLS	WALL OF	MADE FROM
Plants	**Cellulose**	Long chains of glucose lying side by side.
Fungi	**Chitin**	Chains of glucose units that carry nitrogen.
Bacteria	**Peptidoglycan**	Sugar chains cross-linked by short peptides.

Animal cells have no wall: the cytoskeleton and materials such as collagen support them.

WATCH OUT

Five mistakes that *cost points*

- ✕ **No bonds hold the tails together.** Water pushes them together, because it bonds with itself and not with them.
- ✕ **Cholesterol does not always stiffen.** It firms a warm membrane and keeps a cold one fluid.
- ✕ **Sugar chains are on the outside only.** None face the cytoplasm.
- ✕ **Small does not mean it crosses.** An ion is tiny, but its charge keeps it out of the core.
- ✕ **A wall is not a second membrane.** Water, ions and small molecules pass through it; the membrane does the choosing.

COVER THE SHEET

Can you *answer these?*

1. Explain why phospholipids form a bilayer in water.
2. Describe where an integral and a peripheral protein sit.
3. Explain why a membrane-spanning region has nonpolar R groups.
4. Describe what "fluid" and "mosaic" each mean.
5. Predict how a cold-water fish's tails differ from a reef fish's.
6. Explain how cholesterol steadies fluidity.
7. Identify which crosses a bilayer fastest: CO_2, K^+ or glucose.
8. Identify the wall material of plants, fungi and bacteria.

IN THE EXAM

Give the property, then the consequence: "K^+ is charged, so it cannot pass the hydrophobic core and needs a channel protein" earns the point. "It is too big" does not.

GO FURTHER

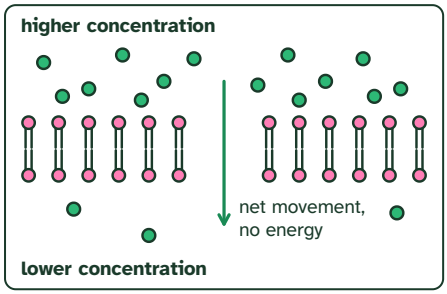
Animated figures, a dry lab and a marked Check are in the full guide online.

Across the *membrane*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Down a gradient is free, with or without a protein. Against it needs a pump and energy. Large cargo travels in vesicles.



Net movement, not all movement. At equal concentrations molecules still cross, as many each way.

2.5.A START HERE

Downhill, *for free*

- Molecules move at random. Where one side is more crowded, more wander away from it than come back: a net movement from higher to lower concentration, **diffusion**. The difference is a **concentration gradient**.
- Moving down a gradient takes no energy from the cell: **passive transport**. It imports materials and exports wastes: oxygen in, carbon dioxide out of every cell that respires.
- A membrane can keep up a gradient only because it is **selectively permeable**.

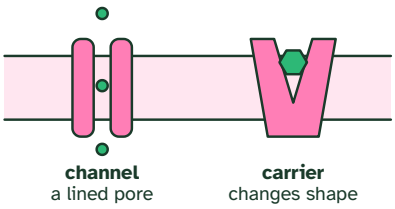
THREE QUESTIONS NAME ANY MECHANISM

1. **Which way?** down the gradient or against it
2. **A protein?** none, channel, carrier or pump
3. **Energy?** none, or ATP

2.6.A A DOOR THROUGH

Facilitated diffusion

- Ions and large polar molecules cannot cross the hydrophobic core, but move down their gradients **through proteins**. Still passive: no energy.
- A **channel protein** is a tunnel with a hydrophilic lining, often gated. A **carrier protein** binds its molecule, such as glucose, and changes shape.
- Each is **specific**: a potassium channel passes K^+ but not Na^+.



2.6.A WATER IN SINGLE FILE

Aquaporins

- **Aquaporins** are channel proteins for water: large quantities of water cross membranes through them.
- They are passive and specific: the pore blocks ions, even H^+. Water moves only down its own gradient, toward more solute.
- A cell sets its water permeability by its **number of aquaporins**: kidney cells add more when the body is short of water.

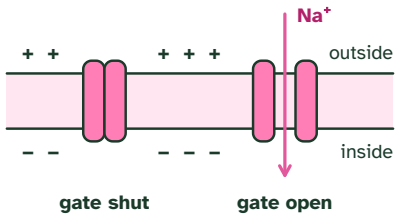
Bilayer a little
Water is polar but small: some slips between the phospholipids, slowly.

Aquaporin a lot
Single file through a narrow pore, billions of molecules a second.

2.6.A GATED CHANNELS

Gates and *charge*

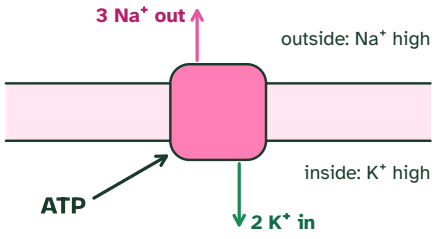
- Na^+ and K^+ cross only through channels, many of them gated. **Ligand-gated:** opens when a signal molecule binds. **Voltage-gated:** opens when the charge across the membrane changes.
- Moving ions separates charge. Most cells keep the inside negative: the **membrane potential**. The membrane is **polarized**.
- Open the Na^+ gates and Na^+ floods in: a neuron signals.



2.5.A

Uphill, *for a price*

- **Active transport** moves a substance **against its gradient**, from low to high concentration. It always needs a pump protein and a direct input of energy, usually **ATP**.
- The **sodium-potassium pump** (Na^+/K^+ ATPase) moves **3 Na^+ out and 2 K^+ in** for each ATP. Pumps make and keep gradients, and help keep the inside negative.
- Root cells take in mineral ions from dilute soil water this way.



STEP 1
Bind
Three Na^+ bind inside.

STEP 2
Phosphate on
A phosphate from ATP changes the pump's shape.

STEP 3
Swap
Na^+ leaves outside; two K^+ bind.

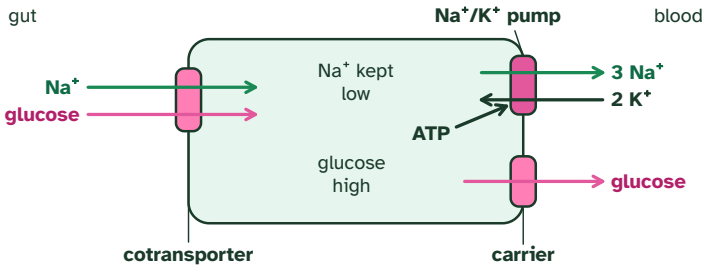
STEP 4
Phosphate off
The pump resets; K^+ leaves inside.

Cotransport, *bulk transport* and naming the mechanism

2.8.A

Cotransport: riding a gradient

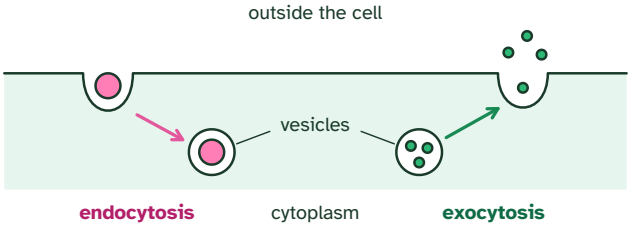
- A gradient made by a pump is **stored energy**. A **cotransporter** lets an ion flow down its gradient and uses that flow to carry another substance **against its own gradient**.
- **In the gut lining:** the pump keeps Na^+ low inside the cell. On the gut side Na^+ flows in and glucose comes with it. Glucose then leaves on the blood side by facilitated diffusion.
- It is still active transport: the ATP is spent by the pump, **one step removed**. Stop the pump and the glucose stops too.



2.5.B

Moving it *in bulk*

- Proteins, polysaccharides and whole cells are too large for any channel or pump. Cells move them wrapped in membrane. **Both ways need energy**.
- **Endocytosis**: the plasma membrane folds in around material and pinches off as a vesicle. Taking in a large particle, such as a bacterium, is **phagocytosis**.
- **Exocytosis**: a vesicle fuses with the plasma membrane and releases its contents outside: insulin, neurotransmitters, mucus.



2.8.A PLACE ANY EXAMPLE

Four ways *across a membrane*

MECHANISM	DIRECTION	PROTEIN	ENERGY	FOR EXAMPLE
Simple diffusion	Down the gradient	None	**None**	O_2, CO_2, a little water
Facilitated diffusion	Down the gradient	Channel or carrier	**None**	Water by aquaporins, ions, glucose
Active transport	**Against the gradient**	Pump	**ATP, or another gradient**	Na^+ out and K^+ in
Endocytosis, exocytosis	In or out, in bulk	None crossing: vesicles	**ATP**	A bacterium in, insulin out

An ion also feels the charge across the membrane: a positive ion can be drawn into a negative cell.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Diffusion does not stop at equal concentrations.** Molecules still cross both ways; only the net movement ends.
- ✕ **Facilitated diffusion is not active transport.** A protein helps, but movement is down the gradient and uses no ATP.
- ✕ **Aquaporins do not pump water.** Water passes through them only down its own gradient.
- ✕ **ATP does not push the ions.** Its phosphate changes the pump's shape, and the shape change moves them.
- ✕ **Nothing in endocytosis crosses the membrane.** The cargo stays inside a vesicle, apart from the cytoplasm.

COVER THE SHEET

Can you *answer these?*

1. Describe diffusion in terms of net movement.
2. Explain why Na^+ needs a channel but O_2 does not.
3. Describe how a carrier differs from a channel.
4. Explain how a cell changes its permeability to water.
5. Explain what makes a membrane polarized.
6. Describe one cycle of the sodium-potassium pump.
7. Identify how insulin leaves a cell. Justify your answer.
8. Predict the effect on glucose uptake in the gut if the Na^+/K^+ pump stops.

IN THE EXAM

Name the mechanism, then justify it with direction, protein and energy: "active transport, because the ion moves against its gradient, which needs a pump and ATP".

GO FURTHER

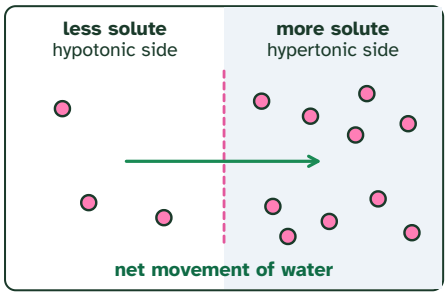
Animated figures, a dry lab and a marked Check are in the full guide online.

Water goes where the *solute* is

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Water moves by osmosis toward more solute: from higher water potential to lower. A wall turns that into pressure.



Always say "to what". A solution is hypertonic only compared with another, such as a cell's cytoplasm.

2.7.A START HERE

Osmosis and tonicity

- **Osmosis** is the diffusion of water across a selectively permeable membrane: one that lets water through but not the solute.
- Water crosses both ways all the time. Where there is more solute, more of the water is held around the dissolved particles and is less free to move, so the **net movement** is from lower solute concentration to higher.
- Tonicity compares two solutions. Water moves from the **hypotonic** side to the **hypertonic** side. Between isotonic solutions it crosses as fast each way: a dynamic equilibrium.

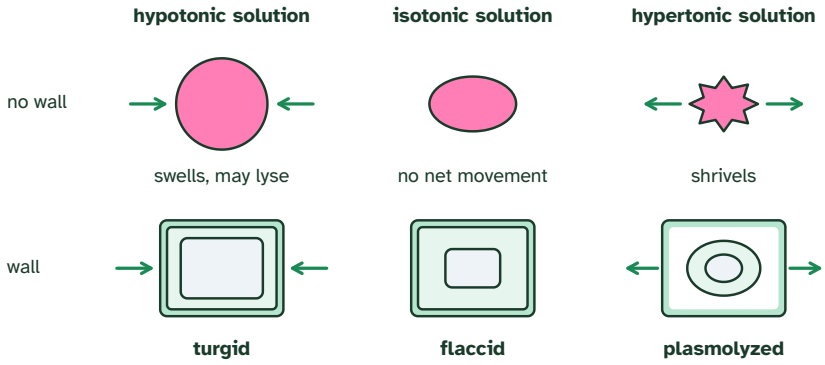
THREE WORDS THAT COMPARE TWO SOLUTIONS

− **Hypotonic** less solute	= **Isotonic** the same	+ **Hypertonic** more solute

2.7.A

Cells in *three solutions*

- **No wall** (animal cells, many protists). In a hypotonic solution the cell swells and can **lyse**: burst. In a hypertonic one it loses water and shrivels.
- **With a wall** (plants, fungi, bacteria). In a hypotonic solution water enters until **turgor pressure**, the wall pressing back, stops it. The cell is turgid, and turgid cells hold a plant up.
- Isotonic: the plant cell is **flaccid**. Hypertonic: the membrane pulls away from the wall, **plasmolysis**, and the plant wilts.



2.7.A STAYING IN BALANCE

Osmoregulation

- **Osmoregulation** keeps an organism's water and solutes in balance, whatever its surroundings.
- A plant cell stores solutes in its **central vacuole**. That lowers its water potential, so it keeps drawing water in and stays turgid.

Contractile vacuole freshwater protists
Collects the water that keeps entering a *Paramecium* and expels it, using ATP.

Kidneys or gills animals
Adjust the water and salt that leave, so body fluids stay isotonic with the cells.

2.7.A IN MEDICINE

Keeping cells *as they are*

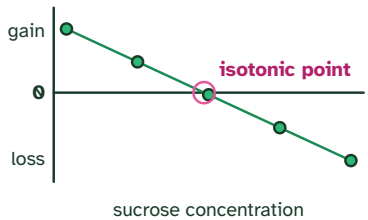
- Fluid run into a vein must be **isotonic** with the blood cells. Pure water would make red blood cells swell and lyse; strong salt solution would shrivel them.
- A donor organ is flushed and bathed in a **cold isotonic solution**: its cells neither gain nor lose water, and the cold slows their metabolism.
- Isotonic means the same total solute concentration, not the same substance.

0.9%
sodium chloride: normal saline, isotonic with blood cells

2.7.A THE POTATO LAB

Cores in *sugar*

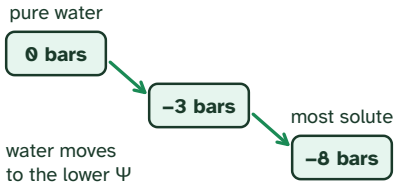
- Potato cores are weighed, soaked in a range of sucrose solutions, blotted and reweighed.
- In a hypotonic solution they gain mass; in a hypertonic one they lose it. Use **percentage change in mass**, as cores start at different sizes.
- Where the line crosses zero, the solution is isotonic with the cells.



2.7.B

Water runs *downhill*: Ψ = Ψp + Ψs

- **Water potential**, Ψ (psi), measures how free water is to move. Its unit is a unit of pressure: **bars**.
- Pure water in an open container is the reference: **Ψ = 0**. Solute lowers Ψ; pressure raises it.
- Water moves from **higher Ψ to lower Ψ**: toward the more negative value.
- Two things set it. Add them before comparing: Ψs alone can give the wrong direction.



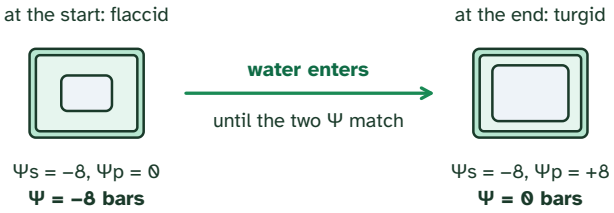
Ψs solute potential
Zero for pure water, negative for any solution. The more solute, the more negative.

Ψp pressure potential
Zero in an open container. Positive in a turgid cell pressing on its wall.

2.7.B

A cell in *pure water*

- A flaccid cell with Ψs = −8 bars goes into pure water. Its Ψ is 0 + (−8) = **−8 bars**, lower than the water's 0, so water enters.
- The cell presses on its wall, and Ψp rises until the cell's Ψ reaches 0. Ψp is then about **+8 bars**: the cell is turgid.
- In a solution of −12 bars instead, water leaves the cell and it plasmolyzes.



2.7.B CALCULATE A SOLUTE POTENTIAL

$\Psi s = -iCRT$

	STANDS FOR	USE
i	Ionization constant	Particles per unit in water: 1 for sucrose, 2 for NaCl.
C	Molar concentration	In mol/L.
R	Pressure constant	0.0831 L·bar/(mol·K).
T	Temperature in kelvin	°C + 273.

Particles count, not their kind: 0.1 M NaCl has the same Ψs as 0.2 M sucrose.

WORKED EXAMPLE

0.20 M sucrose at 22 °C
Ψs = −(1)(0.20)(0.0831)(295) = −4.9 bars.

THEN

In an open beaker
Ψp = 0, so Ψ = Ψs = −4.9 bars.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Water does not stop at isotonic.** It crosses equally both ways.
- ✕ **A plasmolyzed cell's gap is not empty.** The outside solution fills it, passing freely through the wall.
- ✕ **−8 bars is lower than −3 bars.** Water moves toward the more negative value.
- ✕ **A turgid cell in pure water has Ψ = 0.** Its Ψp just cancels its Ψs.
- ✕ **T is in kelvin.** At 22 °C use 295, never 22.

COVER THE SHEET

Can you *answer these?*

1. Describe osmosis in terms of solute concentration.
2. Predict the fate of a red blood cell in pure water.
3. Explain why a plant cell in pure water does not burst.
4. Describe how a *Paramecium* osmoregulates.
5. Explain why percentage change in mass is used.
6. Calculate Ψ for a cell: Ψs = −7 bars, Ψp = +2 bars.
7. Predict where water moves if it sits in a −4 bar solution.
8. Calculate Ψs of 0.30 M sucrose at 27 °C.

IN THE EXAM

Show the working: write the equation, substitute with T in kelvin, then state the direction: "from −4 to −6.5 bars, higher water potential to lower".

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 2 | TOPICS 2.9, 2.10

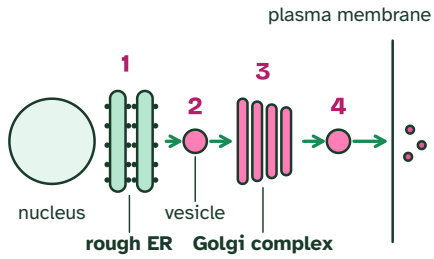
REVISION ON TWO PAGES

A cell of *compartments*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Internal membranes keep reactions apart and add surface for them. Mitochondria and chloroplasts began as free-living prokaryotes.



A protein for export. Once inside the ER it never crosses another membrane.

2.9.A START HERE

Membranes make *compartments*

- Membranes inside a eukaryotic cell divide it into compartments, each with its own enzymes and conditions: **compartmentalization**.
- Compartments **keep apart** reactions that would interfere, and hold enzymes and substrates **close together**, so they meet more often and reactions run faster.
- The **endomembrane system** passes membrane and cargo between its parts: the nuclear envelope, ER, Golgi complex, lysosomes, vacuoles and plasma membrane.

THE ROUTE OF A SECRETED PROTEIN

1. **Rough ER** makes it, threads it inside
2. **Vesicle** carries it to the Golgi
3. **Golgi** modifies it, sorts it
4. **Vesicle** fuses: exocytosis

2.9.A THE LYSOSOME

A safe place to *digest*

- A **lysosome** holds hydrolytic enzymes that digest proteins, fats, nucleic acids and carbohydrates, in an acid interior.
- Loose in the cytoplasm they would digest the cell. Inside membrane they break down a captured bacterium or a worn-out organelle, and the products go back to the cell.
- One compartment, two jobs: it keeps the enzymes apart and gives them the pH they need.

pH 5 inside a lysosome

pH 7.2 in the cytoplasm

2.9.A THE NUCLEUS

Genes behind an *envelope*

- The **nuclear envelope**, a double membrane, separates the DNA from the cytoplasm, where proteins are made.
- **Nuclear pores** let mRNA out and proteins in. Only finished mRNA leaves for the ribosomes.
- So in a eukaryote, making mRNA and making protein happen in turn, in two places.

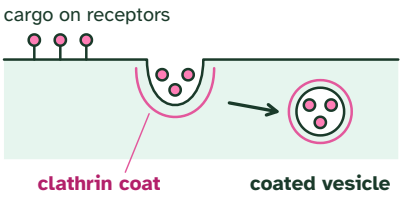
Prokaryote no nucleus
Ribosomes start translating an mRNA while it is still being made.

Eukaryote nucleus
mRNA is made and edited first, so the message is checked before any protein is made.

2.9.A VESICLES

Bubbles that *carry*

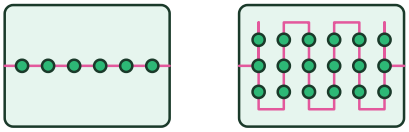
- A **vesicle** is a small sac of membrane. It buds off one compartment and fuses with another, so its cargo is never loose in the cytoplasm.
- Budding is not random: cargo binds receptors, and a coat protein bends the membrane into a pit.
- Vesicles leave the plasma membrane in endocytosis and join it in exocytosis.



2.9.B

Folded for *surface*

- Many reactions happen **on membranes**, because their enzymes are built into the membrane. The amount of membrane then limits the rate.
- Folding packs more membrane, and more enzymes, into the same volume: **more surface area**.
- Internal membranes help in two ways: they **minimize competing interactions** and give reactions more surface to happen on.



MITOCHONDRION
Cristae
Carry the proteins that make most of the cell's ATP.

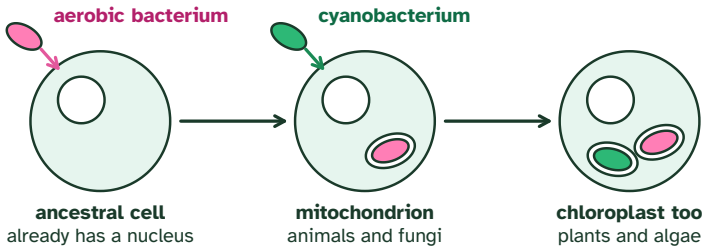
CHLOROPLAST
Thylakoids
Carry the pigments and proteins of the light reactions.

ENDOPLASMIC RETICULUM
Folded sheets
A large surface for making proteins and lipids.

2.10.A

The cell that *swallowed a bacterium*

- The theory of **endosymbiosis**: mitochondria and chloroplasts were once **free-living prokaryotes**.
- An ancestral cell, already with a nucleus, engulfed an **aerobic bacterium** and did not digest it. It used its host's food and supplied ATP: both gained. Over many generations it became the mitochondrion.
- Later some of these cells took in a photosynthetic **cyanobacterium** the same way: the chloroplast.



2.10.A THE EVIDENCE

Still *bacteria* inside

EVIDENCE	A FREE-LIVING BACTERIUM	A MITOCHONDRION OR CHLOROPLAST
Membranes	One plasma membrane.	**Two:** its own inner one, and an outer one from the vesicle that engulfed it.
DNA	One circular loop.	**Its own DNA:** a small circular loop, like a bacterium's.
Ribosomes	Small, prokaryote type.	**Its own ribosomes:** small, like a prokaryote's.
New ones	By binary fission.	**Only by dividing in two:** a cell cannot build one from scratch.
Job	Aerobic respiration; photosynthesis on the thylakoids of cyanobacteria.	**The same:** respiration on the inner membrane; photosynthesis on thylakoids.

Most of their genes have since moved to the nucleus, so neither can live on its own today.

One theory explains many separate observations

2.10.A

Two ways to *divide up the work*

- Prokaryotes generally have no membrane-bound organelles, but they are organized: they have **internal regions** with their own jobs.
- Eukaryotes partition the whole cell with **internal membranes**: one reason they can be so much larger.

Prokaryote by region
DNA gathers in the nucleoid. Ribosomes cluster where proteins are made. Some have internal membranes: folds of plasma membrane for respiration, thylakoids in cyanobacteria.

Eukaryote by membrane
A nucleus, an endomembrane system, mitochondria and, in plants and algae, chloroplasts: specialized compartments, each with its own conditions.

WATCH OUT

Five mistakes that *cost points*

- ✕ **The Golgi does not make proteins.** It receives them from the rough ER, modifies them and sends them on.
- ✕ **Compartments are not sealed boxes.** Membranes let some substances through and vesicles link them.
- ✕ **Folding does not make an organelle bigger.** It fits more membrane into the same volume.
- ✕ **Endosymbiosis is not about the nucleus or the ER.** It explains mitochondria and chloroplasts only.
- ✕ **A nucleoid is not a nucleus.** It is a region where the DNA gathers, with no membrane around it.

COVER THE SHEET

Can you *answer these?*

1. Describe two ways compartments help a cell.
2. Explain why lysosomal enzymes are kept inside a membrane.
3. Describe the route of a secreted protein out of a cell.
4. Explain why a bacterium can translate an unfinished mRNA.
5. Explain how cristae raise the rate of ATP production.
6. Describe how mitochondria are thought to have arisen.
7. Identify three features mitochondria share with bacteria.
8. Predict where a protein builds up if vesicles cannot fuse with the Golgi.

IN THE EXAM

Evidence, not the story: for endosymbiosis give a feature the organelle shares with bacteria (own circular DNA, own small ribosomes, division in two) and say what it shows.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 3 | TOPICS 3.1 TO 3.3

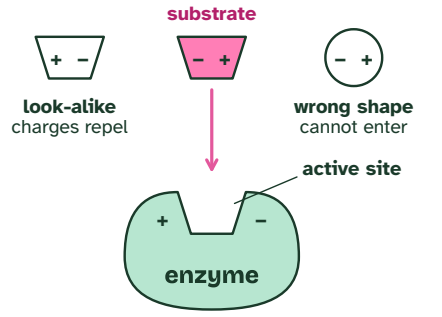
REVISION ON TWO PAGES

Enzymes and *energy*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

An enzyme's shape lowers the activation energy of one reaction. Change the shape and the rate changes. ATP pays for order.



Draw it like this. Site and substrate are complementary, like a mold and what fills it: never "the same shape".

3.1.A START HERE

The active site fits *one substrate*

- An **enzyme** is a biological catalyst: a protein that speeds up one reaction and is **not used up**. It lets go of the products unchanged and binds the next substrate.
- The **active site** is a small pocket in the folded 3D shape, lined by a few R groups. The molecule the enzyme works on is its **substrate**.
- A substrate binds only if its **shape fits** the site and its **charges are compatible** with those R groups. That double check makes an enzyme **specific**: lactase splits lactose and leaves sucrose alone.
- **Induced fit**: as the substrate settles in, the site shifts to grip it more tightly.

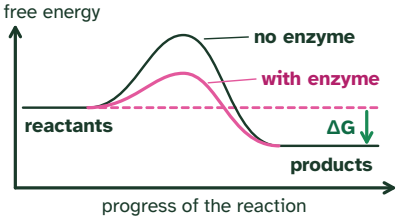
HOW THE SITE LOWERS THE ACTIVATION ENERGY

1. **Holds** the substrate in exactly the right position
2. **Strains** the bond that has to break
3. **Pulls** electrons, with charged R groups

3.1.A CATALYSIS

Lower *activation energy*, same ΔG

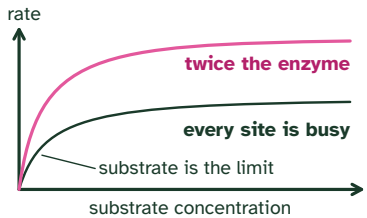
- Breaking a bond takes energy in. So even a reaction that releases energy must first be pushed over a hump: the **activation energy**.
- An enzyme **lowers the activation energy**, so far more molecules get over each second. It supplies no energy of its own.
- The free energy of the reactants and of the products, and so **ΔG, stays the same**. An enzyme cannot make an uphill reaction go, and it speeds the reverse reaction just as much.



3.2.B

Substrate: up to a limit

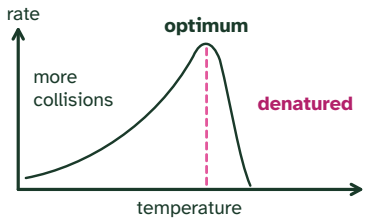
- More substrate means more collisions between substrate and free active sites, so the rate climbs.
- When every site is refilled the moment it empties, the enzyme is **saturated** and the rate levels off. Only **more enzyme** raises it.
- As substrate is used up and **product builds up**, the rate falls. An enzyme speeds a reversible reaction whichever way the concentrations favor.



3.2.A, 3.2.B

Temperature

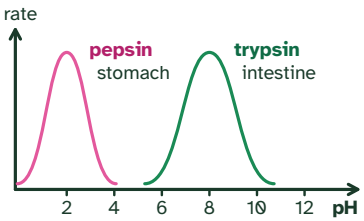
- **Rising side:** molecules move faster, so collisions are more frequent and carry more energy. Most human enzymes peak near 37 to 40 °C.
- **Falling side:** past the **optimum**, the weak bonds that hold the shape break. The active site changes shape and the substrate no longer fits: **denatured**.
- Denaturing breaks bonds between R groups, **not peptide bonds**. It can reverse, but after heat the chains tangle: usually permanent.



3.2.A, 3.2.B

pH

- The pH scale is logarithmic: **each step down is ten times more H^+**.
- **A little off the optimum:** R groups in the site gain or lose H^+, their charges change and the substrate is held less well. This reverses when the pH returns.
- **Far off it:** the ionic and hydrogen bonds that hold the fold break too, and the enzyme **denatures**.
- Each optimum suits the place: pepsin near pH 2 in the stomach, trypsin near pH 8 in the small intestine.

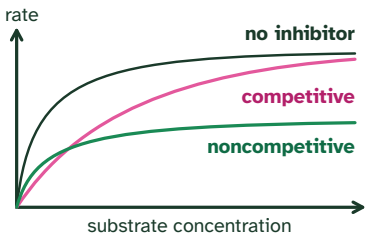


Five things change the rate, SPITE: Substrate, pH, Inhibitors, Temperature, Enzyme. *Spicy Peppers Irritate Tired Eyes.*

3.2.B

Inhibitors: block the site, or bend it

- An **inhibitor** binds to an enzyme and slows it down. A graph of rate against substrate concentration tells the two kinds apart.
- A **competitive inhibitor** fits the active site, so the substrate cannot bind. The two take turns: add enough substrate and the rate climbs back to nearly its normal maximum.
- A **noncompetitive inhibitor** binds an **allosteric site** (any site that is not the active site) and changes the enzyme's shape, active site included. No amount of substrate wins those enzymes back.
- Most inhibitors bind reversibly. Some bond for good: penicillin, on a bacterial cell wall enzyme.



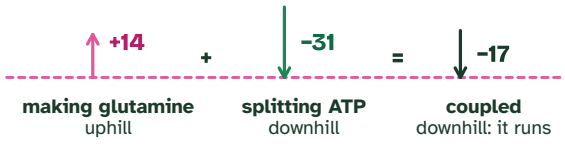
Competitive the active site
Same maximum rate, but more substrate is needed to reach it. Zanamivir, a flu drug, fills the active site of the virus's neuraminidase.

Noncompetitive an allosteric site
Lower maximum rate, whatever the substrate concentration. Isoleucine does this to the first enzyme of its own pathway.

3.3.A

Staying alive takes *constant energy*

- A cell is highly ordered. It keeps that order only by taking in energy, from food or light, **faster than it loses energy**. Cut off the flow, or lose the order, and the cell dies.
- **Second law of thermodynamics:** every energy transfer turns some energy into heat, and the disorder of the universe increases. A cell pays for its order with the heat and disorder it releases.
- A cell runs an endergonic reaction by **coupling** it to an exergonic one, usually the hydrolysis of **ATP**, its energy currency.
- **Exergonic** reactions release free energy (ΔG negative): breaking down glucose. **Endergonic** ones need it put in (ΔG positive): building a protein.

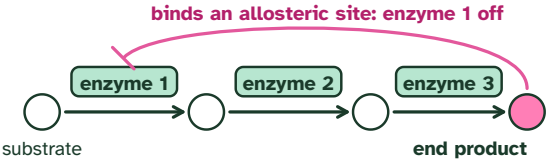


ΔG in kJ/mol. EXergonic: energy EXits. ENdergonic: energy ENters.

3.3.B

Pathways run in *small steps*

- A **metabolic pathway** is a chain of reactions, each with its own enzyme: the product of one step is the substrate of the next.
- Small steps release energy a little at a time, so the cell can capture it as ATP and control it. Burned, glucose gives it all up at once as heat and light.
- **Feedback inhibition**: the end product binds an allosteric site on the pathway's **first enzyme** and switches it off. It binds reversibly: as the product is used up it lets go and the enzyme works again. This is negative feedback, so nothing is wasted.
- Bacteria, archaea and eukaryotes all run on ATP and on versions of glycolysis. Pathways **conserved** in every domain are evidence of **common ancestry**.



WATCH OUT

Five mistakes that *cost points*

- ✕ **Breaking bonds takes energy in.** Energy is released when new, more stable bonds form.
- ✕ **An enzyme never changes ΔG.** It lowers the activation energy: the route, not the destination.
- ✕ **A plateau is not denaturing.** Every enzyme is still working, flat out. Add more and the rate climbs.
- ✕ **Cold does not denature.** At 5 °C an enzyme is slow but whole, and works normally once warmed.
- ✕ **ATP is not a spring.** Its hydrolysis releases energy because ADP and phosphate are more stable than ATP and water were.

COVER THE SHEET

Can you *answer these?*

1. Explain why lactase splits lactose but not sucrose.
2. Describe what an enzyme does to ΔG.
3. Explain why rate levels off at high substrate.
4. Explain why rate falls above the optimum temperature.
5. Predict the rate of pepsin once it reaches pH 8. Justify it.
6. Identify the inhibitor that excess substrate can overcome.
7. Calculate ΔG: a +20 kJ/mol step coupled to ATP hydrolysis.
8. Explain how an end product switches off its own pathway.

IN THE EXAM

Chain the cause: the condition, the bonds or charges it changes, the shape of the active site, whether the substrate binds, then the rate. "It denatures" alone explains nothing.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

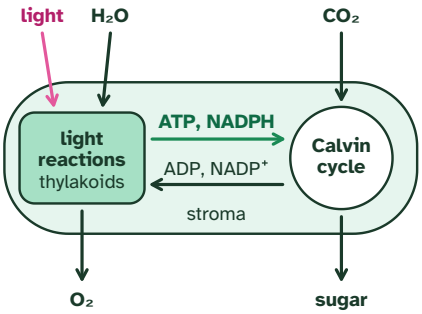
REVISION ON TWO PAGES

Light into *sugar*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Light reactions in the thylakoids make ATP and NADPH. The Calvin cycle in the stroma spends them to build sugar from carbon dioxide.



Draw it like this. Two stages in one chloroplast, each handing the other what it needs.

3.4.A START HERE

Light energy becomes *chemical energy*

- Photosynthesis **transforms light energy into chemical energy** in the bonds of carbon compounds. It does not make energy.
- $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$, with light energy and chlorophyll over the arrow.
- Water is split using light energy: **photolysis**. Its hydrogen is added to carbon dioxide to build glucose, and its **oxygen is given off** as a by-product.
- **Producers** (plants, algae, cyanobacteria) make the carbon compounds every consumer depends on. Energy flows from light to sugar to ATP to work and heat: it is not recycled.

WHERE THE ATOMS OF GLUCOSE COME FROM

C Carbon	**H** Hydrogen	**O** Oxygen
in glucose: from carbon dioxide	in glucose: from water	in glucose: from carbon dioxide

3.4.A ABSORBING LIGHT

Pigments: why a leaf is *green*

- Visible light runs from about 400 nm (violet) to 700 nm (red). The shorter the wavelength, the more energy in each photon.
- A pigment absorbs a photon only if its energy **matches a jump an electron can make**. The electron is then **excited**: that is the energy photosynthesis captures.
- Chlorophyll absorbs **blue and red** strongly and **reflects green**. The carotenoids, accessory pigments, absorb blue and blue-green and widen the range a leaf can use.
- **Chromatography** separates the pigments: the more soluble a pigment is in the solvent, the further it travels.

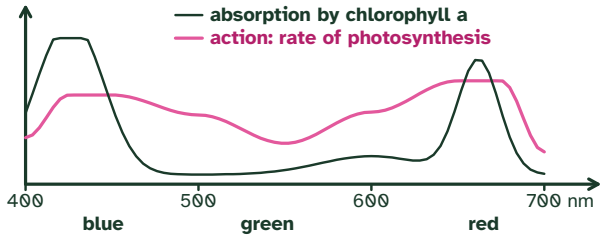
Rf
= pigment distance ÷ solvent front distance, both from the origin

< 1
always, with no units

3.4.A READING THE GRAPHS

Absorption and *action spectra*

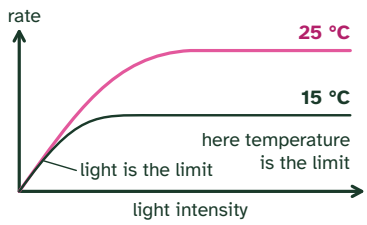
- An **absorption spectrum** shows how much light a pigment takes in at each wavelength.
- An **action spectrum** plots the **rate of photosynthesis** (oxygen produced ÷ time) against wavelength.
- **Similar:** both peak in blue and red and dip in green, because the light a leaf uses is the light its pigments absorb.
- **Different:** the action spectrum's green dip is shallower: chlorophyll b and the carotenoids absorb there and pass the energy on.



3.4.A LAZY CATS TOAST

Limiting factors: whatever runs short sets the pace

- The **limiting factor** is the factor in shortest supply. It sets the rate: raising any other factor does nothing.
- Raise the limiting factor and the rate rises, until another factor takes over and the curve **levels off**. Raise that one and the plateau rises.
- **To test one:** change it alone, then measure the oxygen pondweed gives off or the time leaf disks take to float.
- A hypothesis names the **independent**, the **dependent** and the **controlled** variables.



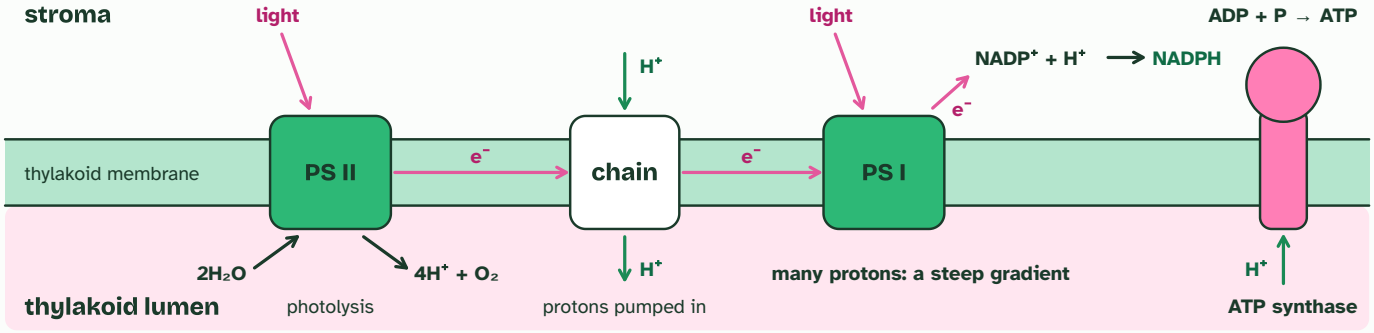
L
Light intensity
Energy for splitting water.

C
Carbon dioxide
The carbon to fix.

T
Temperature
Enzymes: an optimum, then denaturing.

3.4.B IN THE THYLAKOID MEMBRANE

The *light-dependent reactions* make ATP and NADPH



1 **Photosystem II**
An array of pigments passes light energy to its reaction center, which emits an excited electron.

2 **Photolysis**
Photosystem II takes electrons from water: $2H_2O$ give 4 electrons, 4 protons and one O_2.

3 **Electron transport**
Electrons give up energy along the chain. It pumps protons from the stroma into the lumen.

4 **Photosystem I**
Light excites the electrons again. $NADP^+$ takes two, and a proton, and is reduced to NADPH.

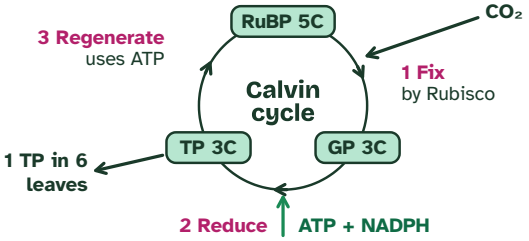
5 **ATP synthase**
Protons flow back down their gradient and drive ADP + phosphate to ATP: chemiosmosis.

Prokaryotes came first. Cyanobacteria were the first to split water, and chloroplasts descend from them. Their oxygen built up in the air about 2.4 billion years ago and made aerobic respiration possible.

3.4.B LIGHT-INDEPENDENT, BUT NOT IN THE DARK

The *Calvin cycle* builds sugar in the stroma

- **Carbon fixation**: the enzyme **Rubisco** joins carbon dioxide to a 5-carbon acceptor (RuBP), which splits into two 3-carbon molecules.
- **Reduction:** NADPH gives the hydrogen and ATP the energy to turn them into a 3-carbon sugar. ADP and $NADP^+$ go back to the thylakoid.
- **Regeneration:** five of every six sugars remake the acceptor, using more ATP. One turn fixes one carbon dioxide, so **six turns make one glucose**.
- Rubisco is slow, and poor at low carbon dioxide, so the stroma holds a great deal of it. Each half needs the other:



NO LIGHT
The cycle stops
No ATP or NADPH is made, so the Calvin cycle stops a few seconds later. "Light-independent" does not mean it runs in the dark.

NO CARBON DIOXIDE
The chain backs up
NADPH is not used, so no $NADP^+$ returns. Photosystem I has nowhere to pass its electrons, the chain fills and photolysis stops.

WATCH OUT

Five mistakes that *cost points*

- ✕ **The oxygen gas comes from water**, not from carbon dioxide. Photosystem II splits the water.
- ✕ **Pigments pass on energy, not electrons.** Only the reaction center emits an electron.
- ✕ **Protons build up in the thylakoid lumen**, not an intermembrane space. ATP is made in the stroma.
- ✕ **Electrons go through photosystem II first.** $NADP^+$ is reduced at photosystem I.
- ✕ **Green is the light a leaf did not absorb.** Chlorophyll does not make green light.

COVER THE SHEET

Can you *answer these?*

1. Identify the source of each atom in glucose.
2. Explain why chlorophyll absorbs little green light.
3. Calculate Rf: pigment 5.7 cm, solvent front 8.0 cm.
4. Describe how an action spectrum differs from an absorption spectrum.
5. Predict the rate if a plant on a light plateau is warmed.
6. Explain how the proton gradient makes ATP.
7. Describe what the Calvin cycle uses and makes.
8. Predict what happens to photolysis with no carbon dioxide. Justify it.

IN THE EXAM

Say where: lumen or stroma, photosystem II or I. Then follow the electrons in order: water, photosystem II, the chain, photosystem I, $NADP^+$.

GO FURTHER

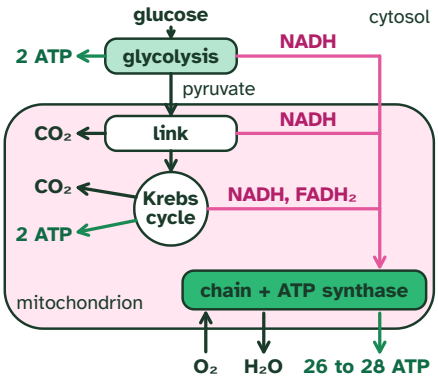
Animated figures, a dry lab and a marked Check are in the full guide online.

Fuel into *ATP*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Respiration takes hydrogen off the fuel a step at a time. Its electrons build a proton gradient, and the gradient makes ATP.



Draw it like this. Glycolysis in the cytosol; everything after it in the mitochondrion.

3.5.A START HERE

Four stages, *one map*

- **Cellular respiration** makes ATP with energy released from carbon compounds, in every living cell, all the time. Energy is transferred to ATP: none is made.
- **Aerobic:** glucose + oxygen → carbon dioxide + water. The energy comes out a step at a time, each step with its own enzyme. Burning releases it all at once, and makes no ATP.
- Energy is released by taking hydrogen off the fuel. **NAD^+** accepts the hydrogen and is reduced to **NADH**, a hydrogen carrier that takes it to the chain.
- A cell has only a little NAD^+, so NADH must keep being turned back into it.

THEY ALWAYS HAPPEN TOGETHER: REDOX — *OIL RIG*

O **Oxidation** Is Loss of electrons: hydrogen removed

R **Reduction** Is Gain of electrons: hydrogen accepted

3.5.A LEARN THE LEDGER

What goes in, what comes out, *and where*

STAGE	WHERE	IN	OUT, FOR ONE GLUCOSE
1 **Glycolysis** needs no oxygen	Cytosol	Glucose (6 carbons). 2 ATP are spent to start it.	**2 pyruvate, net 2 ATP, 2 NADH** 4 ATP are made, so 2 are gained.
2 **Pyruvate oxidation** the link	Matrix of the mitochondrion	2 pyruvate (3 carbons each)	**2 acetyl groups, 2 CO_2, 2 NADH** A carbon leaves each pyruvate as carbon dioxide.
3 **Krebs cycle** two turns	Matrix	2 acetyl groups (2 carbons each)	**4 CO_2, 6 NADH, 2 $FADH_2$, 2 ATP** Its main product is the carriers, not ATP.
4 **Oxidative phosphorylation** chain and ATP synthase	Inner membrane	NADH, $FADH_2$ and oxygen	**Water, about 26 to 28 ATP** NAD^+ and FAD go back for more hydrogen.

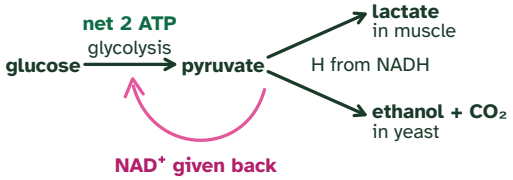
All six carbons of glucose leave as carbon dioxide: two in the link, four in the Krebs cycle.

In all: about **30 to 32 ATP** for one glucose

3.5.A WITHOUT OXYGEN

Fermentation gives NAD^+ back

- Glycolysis turns two NAD^+ into NADH for every glucose. Without the **regeneration of NAD^+**, glycolysis stops very quickly.
- Without oxygen, NADH cannot be unloaded at the chain. **In muscle**, pyruvate takes the hydrogen from NADH and becomes **lactate**.
- **In yeast**, each pyruvate loses a carbon as carbon dioxide, and what is left takes the hydrogen to become **ethanol**.
- Glycolysis goes on, at a net **2 ATP per glucose**. The last step makes no ATP: its whole point is the NAD^+.



3.5.A COMPARE

With oxygen and *without*

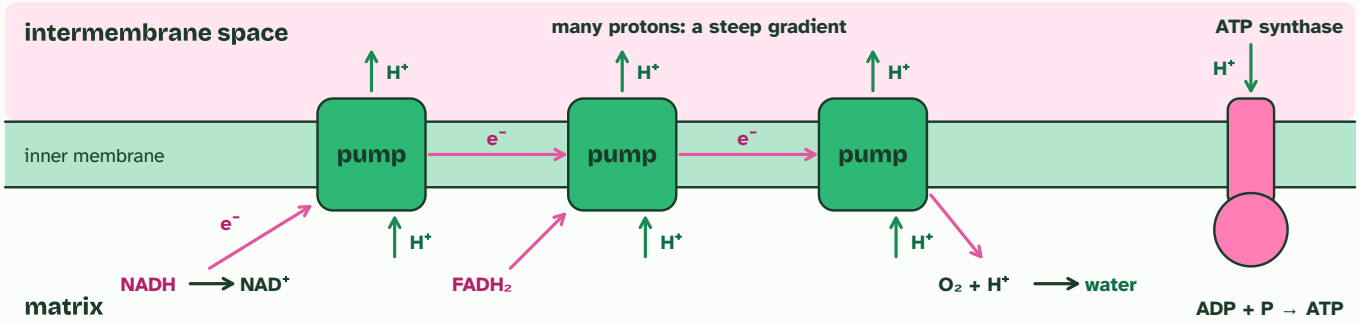
- Both routes start with glycolysis. Muscles ferment when the blood cannot bring oxygen fast enough, as in a sprint: fermentation adds to aerobic respiration, it does not replace it.

	AEROBIC	FERMENTATION
Oxygen	Needed	Not needed
Where	Cytosol, then mitochondria	Cytosol only
ATP	**About 30 to 32**	**2**
Waste	Carbon dioxide and water	Lactate; or ethanol and carbon dioxide
Fuels	Glucose, fatty acids and others	Glucose only

Fermentation in humans is LOW: Lactate, Only 2 ATP, Without oxygen.

3.5.B IN THE INNER MITOCHONDRIAL MEMBRANE

The *electron transport chain* and chemiosmosis



1
Carriers unload
NADH and $FADH_2$ pass electrons to the chain and become NAD^+ and FAD again.

2
Electrons step down
Each carrier holds them more tightly than the last, so a little energy is released at every step.

3
Protons are pumped
The pumps use that energy to move protons from the matrix into the intermembrane space.

4
Oxygen
The terminal electron acceptor: it takes the electrons, and protons from the matrix, and becomes water.

5
ATP synthase
Protons flow back through it, down their gradient. The flow joins ADP and phosphate: chemiosmosis.

3.5.B WHAT STOPS

No oxygen, or a *leak*

- The chain with ATP synthase is **oxidative phosphorylation**. The same machinery works in thylakoid membranes and in the plasma membrane of prokaryotes.

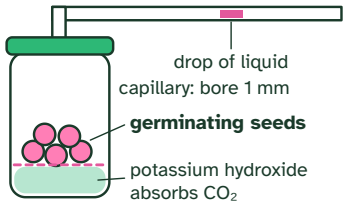
No oxygen the chain backs up
Nothing takes the electrons at the end, so every carrier stays full. Pumping stops, the gradient runs down, ATP synthase stops and NADH cannot be unloaded.

Uncoupling heat, not ATP
Protons leak back without passing through ATP synthase. The chain still runs, but the energy of the gradient is released as heat: brown fat in newborns and hibernating mammals.

3.5.A RESPIROMETER

Measuring the *rate*

- In a **respirometer**, potassium hydroxide absorbs the carbon dioxide, so the drop's movement shows **oxygen uptake**.
- Volume = πr^2 × distance moved. Rate = volume ÷ time, and per gram to compare samples.
- A **control** tube holds glass beads: its movement is not respiration, so subtract it.



3.5.A FUELS

Fat or *sugar*?

- Lipids release about **twice the energy per gram** of carbohydrates.
- Carbohydrate goes through glycolysis, so it can be respired with oxygen or without.
- A fatty acid is cut into 2-carbon acetyl groups that enter the Krebs cycle, so **fat needs oxygen**.
- Proteins can be used too: amino acids lose their nitrogen and join as pyruvate or acetyl groups.

37 kJ in a gram of lipid

17 kJ in a gram of carbohydrate

WATCH OUT

Five mistakes that *cost points*

- ✕ **Respiration is not breathing.** It is the chemistry that makes ATP in every cell: plants too, day and night.
- ✕ **Glycolysis is in the cytosol and needs no oxygen.** Only what follows it is in the mitochondrion.
- ✕ **The chain makes a proton gradient, not ATP.** ATP synthase makes the ATP, and it is not a pump.
- ✕ **Oxygen becomes water, not carbon dioxide.** The carbon dioxide comes from the carbons of the fuel.
- ✕ **Muscle makes lactate; yeast makes ethanol and carbon dioxide.** Never the other way around.

COVER THE SHEET

Can you *answer these?*

1. Describe what glycolysis takes in and gives out.
2. Identify where each stage of aerobic respiration happens.
3. Explain why a muscle cell turns pyruvate into lactate.
4. Calculate the oxygen used if the drop moves 20 mm.
5. Explain how the chain builds a proton gradient.
6. Predict what happens to the chain with no oxygen. Justify it.
7. Explain how uncoupling makes heat.
8. Explain why fat cannot be respired without oxygen.

IN THE EXAM

Follow the hydrogen: off the fuel, onto NAD^+, to the chain, onto oxygen. Say where each step happens, and write "proton gradient" before you write "ATP".

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 4 | TOPICS 4.1 TO 4.3

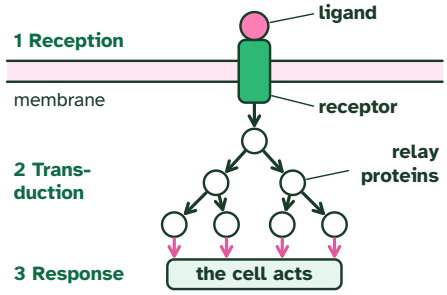
REVISION ON TWO PAGES

THE ONE IDEA

A ligand binds the receptor that fits it. The receptor changes shape, relays inside pass the message on and amplify it, and the cell responds.

How cells *signal*

What to know, what to draw and what to say. Nothing else.



Read it like this. One ligand outside, more active molecules at each step inside: the signal is amplified.

4.2.A START HERE

Reception, transduction, *response*

- A **signal transduction pathway** links what a receptor senses to what the cell does. In **reception** the ligand binds its receptor, and the receptor **changes shape**.
- In **transduction** that change passes along a chain of relay molecules, mostly proteins, each switching on the next. In the **response** the last ones act: an enzyme starts work, a channel opens, a gene is read.
- Most relays are switched by a phosphate group. Its negative charges change how the protein folds, and so what it does. In a **phosphorylation cascade**, kinase switches on kinase, each one acting on many of the next.

THE ON AND OFF SWITCH

a Kinase Kicks, a Phosphatase Peels

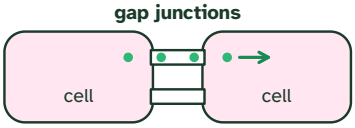
K Kinase
kicks a phosphate on, taken from ATP

P Phosphatase
peels it off, so the relay rests again

4.1.A DIRECT CONTACT

Cells that *touch*

- **Gap junctions**: protein tunnels that join the cytoplasm of two animal cells. Ions and small molecules pass; proteins are too big. Heart muscle beats as one this way.
- **Plasmodesmata**: channels through plant cell walls, lined with plasma membrane, so cytoplasm runs on from cell to cell.
- **Surface contact:** a molecule on one cell binds a receptor on the other, as when an antigen-presenting cell switches on a helper T cell.



ions and small molecules pass

4.1.B ACROSS THE FLUID

Near or far

- A **local regulator** acts on cells near the one that released it, then is broken down or taken up.
- **Paracrine:** it diffuses to neighbors, as a growth factor does. **Synaptic:** a neurotransmitter crosses the cleft between a neuron and the next cell.
- **Endocrine:** a gland releases a **hormone** into the blood. It reaches nearly every cell, but only **target cells**, those with its receptor, respond.
- Hormones to know: insulin, human growth hormone, thyroid hormones, testosterone, estrogen.

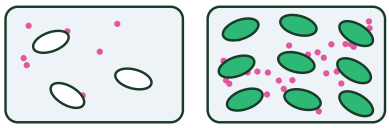
20 nm
a synaptic cleft: crossed in under a millisecond

1 min
about how long blood takes around the body

4.1.A, 4.3.A QUORUM SENSING

Bacteria that *count heads*

- **Quorum sensing** is signaling that measures population density.
- Each cell releases a small signaling molecule, an **autoinducer**, and carries receptors for it: more cells, a higher concentration.
- Above a **threshold** it binds the receptors and switches genes on in every cell: a change in gene expression.
- *Vibrio fischeri* glows only when crowded inside a squid. Other bacteria time biofilms and toxins this way.

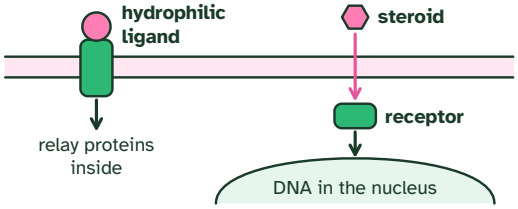


few cells | many cells

4.2.B

A receptor fits *one ligand*

- A signaling molecule is a **ligand**, and the protein it binds is its **receptor**. The **ligand-binding domain** has a shape and a pattern of charges that fit one ligand: one to one.
- Binding is weak and reversible: the more ligand there is, the more receptors are filled at any moment.
- A cell with no receptor for a ligand cannot respond, however much is around.



The core of the membrane is hydrophobic, so where a receptor sits depends on its ligand

In the membrane hydrophilic or large
Proteins such as insulin, peptides, epinephrine. The ligand **never enters**: the receptor carries the message across by changing shape.

Inside the cell hydrophobic
Steroids such as testosterone and estrogen slip through the bilayer to a receptor in the cytoplasm or nucleus.

Four receptors, one cascade and *broken pathways*

4.2.B LEARN THE PATTERN

Four *receptors*, four speeds

RECEPTOR	ITS LIGAND	WHAT BINDING DOES	THE RESPONSE	HOW FAST
G protein-coupled GPCR: crosses the membrane 7 times	Epinephrine	A **G protein** swaps its GDP for GTP, then switches on an enzyme.	A second messenger, then a kinase cascade.	**Seconds**
Ligand-gated ion channel receptor and channel in one	Acetylcholine	The channel opens. In a muscle fiber, Na^+ rushes in down its gradient.	The membrane depolarizes: no second messenger.	**A millisecond**
Receptor tyrosine kinase its inner domain is a kinase	Insulin	It adds phosphates to its own tyrosines; relay proteins bind them.	Glucose transporters move to the membrane.	**Seconds to minutes**
Intracellular receptor in the cytoplasm or nucleus	Testosterone, estrogen	Hormone and receptor together bind DNA beside their target genes.	Transcription changes: new proteins are made.	**Hours, but it lasts**

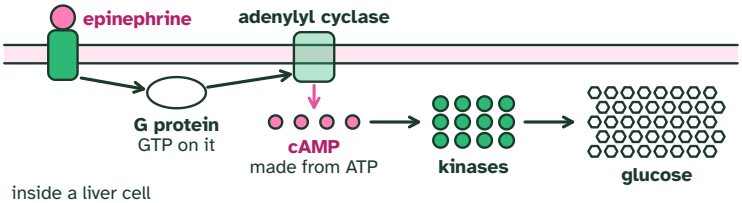
One signal can do different things in cells with different receptors and pathways.

A G protein is **off with GDP, on with GTP**

4.2.A, 4.2.B

Epinephrine: one hormone, *millions of glucose*

- **Cyclic AMP (cAMP)** is a **second messenger**: the cell makes it once the receptor is active. Epinephrine, the first messenger, stays outside.
- Each enzyme acts on many molecules, so the signal is **amplified** at every step, down to glycogen phosphorylase, which breaks glycogen down.
- **Off:** the G protein breaks down its GTP, **phosphodiesterase** turns cAMP into AMP, and phosphatases take the phosphates off.



In order: *Real Gamers Always Collect Keys* (receptor, G protein, adenylyl cyclase, cAMP, kinases)

4.3.A RESPONSES

What a signal makes a cell *do*

SLOW, LASTING
Gene expression
Ethylene ripens a fruit.

FAST, BRIEF
Cell function
An enzyme switches on.

MANY CELLS
Phenotype
An embryo grows testes.

THE END
Apoptosis
Programmed cell death.

4.3.B STUCK ON OR STUCK OFF

When a pathway *breaks*

STUCK OFF
Mutated receptor
The ligand cannot bind.

STUCK OFF
Beta blocker
Binds; switches nothing on.

STUCK ON
Cholera toxin
GTP is never broken down.

OFF SWITCH LOST
Caffeine, high dose
cAMP is not broken down.

WATCH OUT

Five mistakes that *cost points*

- ✕ **The ligand of a membrane receptor never enters the cell.** The receptor changes shape and relays carry the message.
- ✕ **GDP does not become GTP.** The G protein lets go of a GDP and picks up a new GTP.
- ✕ **cAMP is not the hormone, nor a piece of it.** The cell makes it from its own ATP.
- ✕ **A kinase's phosphate is a switch, not fuel.** It changes a protein's shape; no energy is stored there.
- ✕ **A target cell is set by its receptor, not its place.** Blood takes a hormone to nearly every cell.

COVER THE SHEET

Can you *answer these?*

1. Describe three ways cells signal by direct contact.
2. Explain why a hormone changes only its target cells.
3. Predict the glow of *V. fischeri* after a tenfold dilution.
4. Identify where a peptide's receptor sits, and justify it.
5. Describe what a protein kinase does to its target.
6. Explain how a cascade amplifies a signal.
7. Explain why a steroid acts more slowly than epinephrine.
8. Predict the response if a phosphatase is lost.

IN THE EXAM

One part changed? Find it, decide whether it is stuck on or stuck off, then follow every arrow after it to the response. Parts above the change carry on as normal.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 4 | TOPIC 4.4

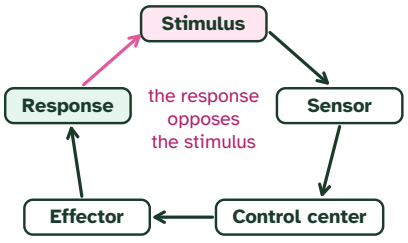
REVISION ON TWO PAGES

Feedback: holding *steady*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Negative feedback opposes a change and returns a variable to its set point. Positive feedback amplifies a change until an outside event ends it.



Draw it like this. Five parts in a ring. The last arrow closes the loop.

4.4.A START HERE

A loop that *undoes* a change

- **Homeostasis** is keeping the internal environment stable while the outside changes. Each controlled variable has a **set point**, the value the body steers toward, and a normal range around it.
- Cells run on enzymes and membranes that work well only in narrow conditions. Staying in range takes a way to detect a change and a way to reverse it: a **feedback loop**.
- In **negative feedback** the response **opposes the stimulus**: a rise brings about a fall, and a fall a rise. Back at the set point the stimulus has gone, so the loop switches itself off.

98.6 °F	70 to 100	7.4
core body temperature (37 °C)	mg/dL of glucose in fasting blood	the pH of blood

4.4.A LEARN THE ORDER

Every loop has the same *five parts*

THE PARTS, IN ORDER

Sly Snakes Can Eat Rats

S Stimulus: the change: a rise or fall from the set point	**S** Sensor: a receptor detects the change	**C** Control center: compares, then signals by nerve or hormone	**E** Effector: a muscle or gland acts	**R** Response: undoes the change

- **A thermostat:** the room cools (stimulus), the thermometer reads the fall (sensor), the circuit compares it with the dial (control center) and switches on the furnace (effector), and the room warms (response).
- **If one part fails,** every link after it is cut off: the effector never acts, and the variable is left to drift.

4.4.A THE AP EXAMPLE

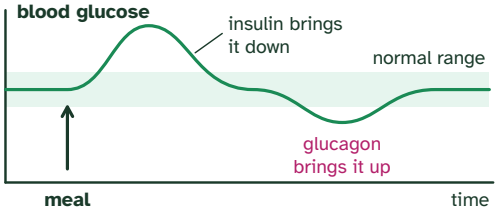
Blood glucose: *two hormones*, one level

- The sensor and the control center are one tissue: the **islets** of the pancreas, which detect glucose in the blood flowing past.

Glucose high after a meal
Beta cells release **insulin**. Liver and muscle cells take glucose in and store it as glycogen; fat cells take some in too.

Glucose low between meals
Alpha cells release **glucagon**. Liver cells break glycogen down and release glucose. Muscle has no glucagon receptors.

- Two hormones with opposite effects push the level back from either side, each switched off as it returns.



Insulin: glucose goes into cells. Gluca**gon**: glucose gone, so the liver releases some

4.4.A WHEN A PART FAILS

Diabetes: a *broken loop*

- **Diabetes mellitus** is a failed glucose loop. Where the loop breaks decides the type; either way the response fails and glucose stays above its normal range.

	TYPE 1	TYPE 2
The break	The immune system destroys the **beta cells**.	Target cells respond weakly: **insulin resistance**.
Insulin	None is released.	Released, often extra at first: the stimulus never goes away.
Inside the cell	Could respond, but no signal comes.	Insulin binds, but fewer glucose transporters reach the membrane.
Treated with	Insulin, injected or pumped.	Diet, exercise, and drugs that make cells more sensitive.

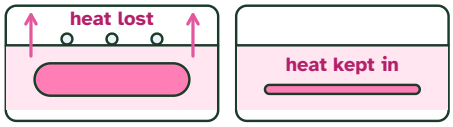
- Above about 180 mg/dL the kidneys cannot take back all the glucose they filter. It spills into the urine and pulls water with it: thirst and frequent urination.

Temperature, *positive feedback* and the two compared

4.4.A

Too hot, too cold: *body temperature*

- **Thermoreceptors** in the skin and the brain are the sensors. The **hypothalamus** is the control center, and signals the effectors along nerves.
- Negative feedback again, with nerves in place of hormones and a set of effectors for each direction.
- In the cold, tiny muscles also pull the hairs upright: goose bumps.



Circles: sweat on the surface. Pink band: an arteriole that supplies the skin

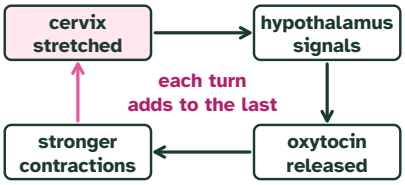
Too hot lose more heat
Sweating: sweat carries heat away as it evaporates. **Vasodilation:** more warm blood flows near the surface.

Too cold keep heat, release more
Vasoconstriction: warm blood stays deeper. **Shivering:** respiration in skeletal muscle releases heat.

4.4.A

Positive feedback: a loop that *runs away*

- In **positive feedback** the response **adds to the stimulus**, so the change grows, and grows faster.
- It would wreck homeostasis, so it is kept for events that must finish fast and completely.
- Nothing inside the loop can stop it. An **event outside the loop** ends it: the birth takes the pressure off the cervix.



BABIES
Birth
The stretched cervix signals the hypothalamus; oxytocin from the posterior pituitary makes the uterus contract harder.

LIKE
Lactation
Suckling releases prolactin (milk is made) and oxytocin (milk is let out). It stops when the baby stops feeding.

RIPE
Ripening
Ethylene, a gas, ripens a fruit and makes it release more ethylene. One ripe fruit sets off its neighbors.

4.4.A COMPARE

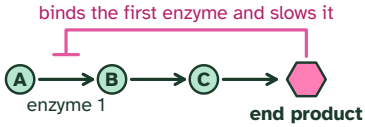
Back to the set point, or *on to the end*

	NEGATIVE FEEDBACK	POSITIVE FEEDBACK
Response	**Opposes the change**	**Adds to the change**
Variable	Returns to its set point.	Moves ever farther from it.
Stopped by	The loop itself.	An event outside the loop.
Job	Keeps conditions steady.	Finishes a process fast.
Examples	Blood glucose, temperature, feedback inhibition.	Labor, lactation, fruit ripening.

4.4.A MOLECULE BY MOLECULE

Feedback *inside a cell*

- **Feedback inhibition**: the end product of a pathway binds the first enzyme at an **allosteric site**. The more product, the less is made.
- Genes too: lactose switches on the *lac* operon, which switches off again once the lactose is used up.



WATCH OUT

Five mistakes that *cost points*

- ✕ **Negative is not bad:** the response opposes the change.
- ✕ **Positive is not good:** it pushes a variable farther from where it started.
- ✕ **Glucagon is not glycogen.** Glucagon is a hormone; glycogen is the polysaccharide it tells the liver to break down.
- ✕ **Blood vessels do not move.** Arterioles widen or narrow, changing how much blood flows near the surface.
- ✕ **Type 1 diabetes is not caused by eating sugar.** It is an immune attack on the beta cells.

COVER THE SHEET

Can you *answer these?*

1. Describe homeostasis, using the term set point.
2. Identify the five parts of a feedback loop, in order.
3. Explain how blood glucose falls after a meal.
4. Predict blood glucose after a meal in type 1 diabetes.
5. Explain why insulin can be high early in type 2 diabetes.
6. Explain how vasodilation cools the body.
7. Describe what ends the feedback loop of labor.
8. Predict what happens when a cell uses up an end product.

IN THE EXAM

Say which way the response goes: against the change (negative) or with it (positive). If a part of a loop fails, trace it link by link: every link after the break is cut off.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 4 | TOPICS 4.5 AND 4.6

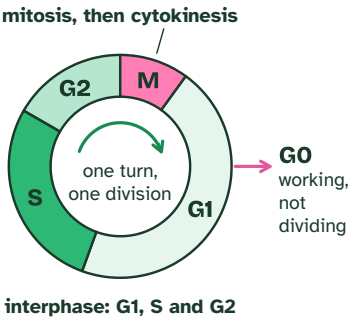
REVISION ON TWO PAGES

The cell cycle and *mitosis*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

A cell copies its DNA, then mitosis hands one complete copy to each of two identical daughter cells. Checkpoints decide whether it goes on.



Draw it like this. A ring read clockwise, with G1 the longest stage and M the shortest.

4.5.A START HERE

Around the *cell cycle*

- The **cell cycle** is the sequence a dividing cell goes through again and again. **Interphase** is G1, S and G2. It is about nine tenths of the cycle, and it is not a rest.
- Then **mitosis** divides the nucleus and **cytokinesis** divides the cytoplasm. Each daughter cell starts again in G1.
- A cell can leave G1 for **G0**: alive and working, but not dividing. Most nerve cells and mature muscle cells stay there for life; liver cells reenter the cycle after damage. A cell can also be held at a stage until conditions are right.

THE ORDER OF THE CYCLE

Giraffes Sing, Gorillas Make Chili

G G1 grows: proteins and organelles	**S** S the DNA is copied	**G** G2 grows more, ready to divide	**M** Mitosis the nucleus divides	**C** Cytokinesis the cytoplasm divides

4.5.B WHY CELLS DIVIDE

One cell, *two copies*

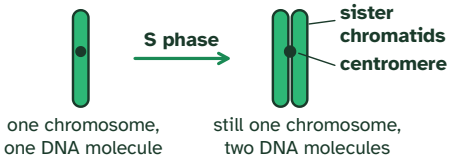
- New cells come only from existing cells dividing: a parent cell ends as two daughter cells.
- In eukaryotes, **mitosis** hands a complete copy of the genome, every chromosome, to each daughter cell. So the daughters are **genetically identical** to each other and to the parent.
- It alternates with interphase: copy the DNA, divide, copy, divide.

JOB 1	JOB 2	JOB 3
Growth One cell becomes tens of trillions.	**Tissue repair** Cells around a wound replace those lost.	**Asexual reproduction** A yeast buds; a strawberry sends out runners.

4.5.B CHROMOSOMES AND CHROMATIDS

Copied, then *coiled*

- A **chromosome** is one long DNA molecule wound around proteins called histones. DNA with its histones is **chromatin**.
- Before a cell divides it copies every chromosome. The two copies stay joined as **sister chromatids**, held together at the **centromere**.
- As division begins the chromatin **condenses**: short, thick chromosomes can be moved without tangling.



4.5.B THE PHASES

Mitosis: four phases, *one smooth process*



	PROPHASE	METAPHASE	ANAPHASE	TELOPHASE
What happens	Chromosomes **condense**, each as two sister chromatids. The nuclear envelope breaks down and the spindle starts to grow.	Microtubules from both poles attach at each centromere. Chromosomes line up in **one row across the middle**.	The **centromeres split**. Sister chromatids are pulled to opposite poles: one copy of each chromosome to each end.	A nuclear envelope forms around each group: **two nuclei** in one cell. Chromosomes uncoil and the spindle breaks down.
Spot it	Thick threads; the envelope going.	A line across the middle.	Two groups moving apart.	Two nuclei, still one cell.

Each chromosome lines up on its own: matching chromosomes pair only in meiosis.

In order: *Penguins March Across Town*

Counting, cytokinesis and the *controls* on the cycle

4.5.B COUNT CENTROMERES

Keep *count* through the cycle

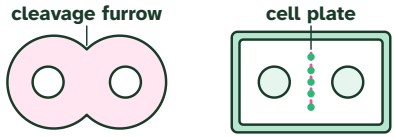
A HUMAN BODY CELL	CHROMOSOMES	CHROMATIDS	DNA MOLECULES
G1	**46**	Not copied yet.	**46**
G2 to metaphase	**46**	**92**	**92**
Anaphase	**92**	Separated.	**92**
Each daughter cell	**46**	Not copied yet.	**46**

Count **centromeres** to count chromosomes. From anaphase, each chromatid is a chromosome of its own.

4.5.A STARTS IN TELOPHASE

Cytokinesis splits the cytoplasm

- **Animal cells:** a ring of actin and myosin tightens and pulls the membrane into a **cleavage furrow**.
- **Plant cells:** the wall cannot bend, so Golgi vesicles fuse into a **cell plate** that becomes a new wall.

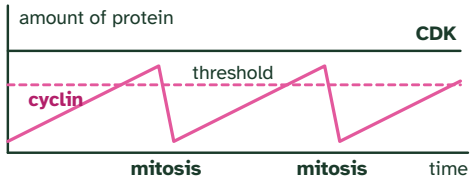


animal cell plant cell

4.6.A

Checkpoints: *stop*, or go

- At **checkpoints** a cell checks its own state and goes on only if all is well.
- **Cyclin-dependent kinases (CDKs)** are always present, but inactive alone. **Cyclins** come and go: once enough of one has built up, it binds and activates its CDK.
- The active CDK **phosphorylates** proteins that start the next stage. Then the cyclin is broken down and the CDK falls quiet.



GROWN?
G1 checkpoint
Big enough, with nutrients, signals and undamaged DNA? If not, the cell waits or enters G0.

GENOME COPIED?
G2 checkpoint
Has all the DNA been copied, without damage?

MOORED?
M checkpoint
No anaphase until the spindle holds every chromosome from both poles.

4.6.B

When cells *ignore the rules*

- **Cancer** is cells that divide when they should not and pass checkpoints they should fail. It usually takes several mutations, in both kinds of gene.
- A **benign** tumor stays where it formed; a **malignant** one invades nearby tissue and can spread in the blood.
- **Apoptosis**: a cell with damage it cannot repair takes itself apart in an orderly way. Many cancer cells cannot trigger it.

Proto-oncogenes the accelerator
Proteins that push a cell to divide when signaled. A mutation can make an **oncogene**, stuck on.

Tumor suppressor genes the brakes
Proteins that hold a damaged cell at a checkpoint. A mutation that breaks one removes a brake.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Copying DNA does not double the chromosome number:** a copied chromosome still has one centromere.
- ✕ **Interphase is not a rest:** the cell grows and copies its DNA.
- ✕ **Cytokinesis is not a phase of mitosis.** Mitosis divides the nucleus; cytokinesis divides the rest of the cell.
- ✕ **Cyclins come and go, not CDKs.** The CDK is always there.
- ✕ **Cancer is not one mutation.** One mutated gene seldom makes a cell cancerous.

COVER THE SHEET

Can you *answer these?*

1. Describe what a cell does in G1, S and G2.
2. Explain why mitosis gives genetically identical cells.
3. Calculate the chromatids made from 8 chromosomes.
4. Identify the phase in which the centromeres split.
5. Predict where a cell with no spindle stops in mitosis.
6. Explain why a plant cell cannot form a cleavage furrow.
7. Explain how a CDK is switched on and off.
8. Predict the effect of losing a tumor suppressor gene.

IN THE EXAM

Counting? Count centromeres; chromatids exist only from S phase to anaphase. **A broken control?** Name the checkpoint that fails, then what the cell does next.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

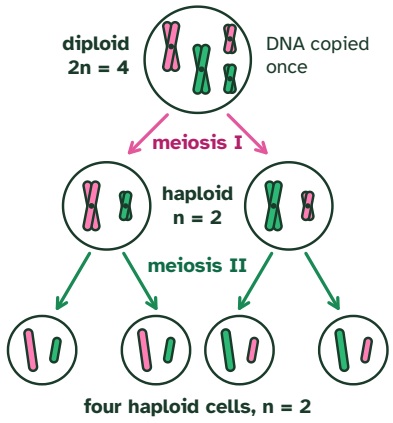
AP BIOLOGY | UNIT 5 | TOPICS 5.1 AND 5.2 | REVISION ON TWO PAGES

Meiosis halves and *shuffles*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Copy the DNA once, divide twice: one diploid cell gives four haploid cells, and crossing over and random assortment make each one different.



Draw it like this. Pink from one parent, green from the other. Count centromeres to count chromosomes.

5.1.A START HERE

Copy once, *divide twice*

- Before meiosis the cell copies its DNA **once**, in S phase. Each chromosome is then two **sister chromatids** joined at the centromere.
- **Meiosis I separates homologous chromosomes**: each cell gets one chromosome of every pair, so the number is halved here.
- **Meiosis II separates sister chromatids**, much as mitosis does. No DNA is copied between the two divisions.
- One diploid cell becomes **four haploid cells**, each genetically different. In animals this happens only in the cells of the ovaries and testes that make gametes.

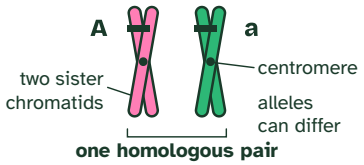
MEIOSIS I, IN ORDER — *Pairs Meet And Travel*

P Pairs: prophase I: homologs pair up	**M** Meet: metaphase I: pairs on the plate	**A** And: anaphase I: homologs separate	**T** Travel: telophase I: two haploid cells

5.1.A DIPLOID AND HAPLOID

Two sets in, *one set* out

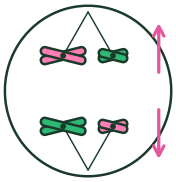
- A **diploid** cell (2n) has two sets of chromosomes, one from each parent. A **haploid** cell (n) has one set. In humans 2n = 46 and n = 23.
- The two chromosomes of a pair are **homologous**: the same length, the same genes at the same loci. Their alleles can differ.
- Gametes must be haploid so that **fertilization** gives a diploid zygote. If not, the number would double every generation.



5.1.A HOMOLOGS SEPARATE

Meiosis I: *pairs* part

- **Prophase I:** chromosomes condense and homologs pair along their length (**synapsis**); chiasmata may form. The spindle starts to form and the nuclear envelope breaks down.
- **Metaphase I:** spindle fibers line the **pairs** up on the metaphase plate.
- **Anaphase I: homologous chromosomes separate**.
- **Telophase I, cytokinesis:** two haploid cells.



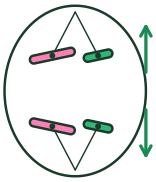
homologous chromosomes part

sister chromatids stay joined

5.1.A CHROMATIDS SEPARATE

Meiosis II: *chromatids* part

- **Prophase II:** no DNA is copied. A spindle forms in each cell and attaches at the centromeres.
- **Metaphase II:** chromosomes line up one by one, sister kinetochores held from opposite poles.
- **Anaphase II:** the proteins holding the centromere together break down and **sister chromatids separate**.
- **Telophase II, cytokinesis:** four haploid cells.



sister chromatids part

each is now a chromosome

5.1.A TRACKING THE NUMBERS

Count *centromeres*, not chromatids

- Chromosome number counts centromeres. Two joined sister chromatids are **one** chromosome; once they separate, each is a chromosome of its own.
- **Meiosis I halves the chromosome number** (2n to n). Meiosis II halves the chromatids in each chromosome.
- A cell is already haploid after meiosis I: it holds one chromosome of each pair, though each is still two chromatids.

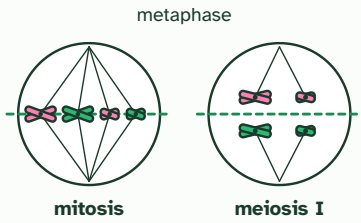
A HUMAN CELL	CELLS	CHROMOSOMES	CHROMATIDS
Before meiosis I DNA copied	1	46	92
After meiosis I	2	23	46
After meiosis II	4	23	23

Mitosis against meiosis, and where *variation* comes from

5.1.B MITOSIS AGAINST MEIOSIS

Same machinery, *different result*

	MITOSIS	MEIOSIS
Alike	DNA copied once. A spindle apparatus.	DNA copied once. A spindle apparatus.
Homologs	Do not pair.	**Pair, cross over and separate.**
Divisions	One: two cells, 2n to 2n.	Two: four cells, 2n to n.
Cells made	Identical to the parent.	Different from the parent and each other.
Role	Growth, repair, asexual reproduction.	Gametes for sexual reproduction.

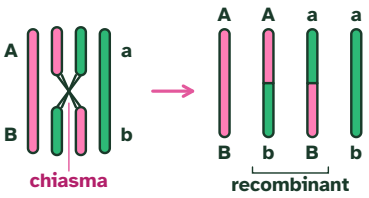


Meiosis II separates chromatids as mitosis does. Meiosis I is what sets meiosis apart.

5.2.A SHUFFLE 1: PROPHASE I

Crossing over

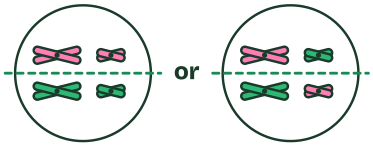
- In prophase I, **nonsister chromatids** of a homologous pair exchange matching segments at a **chiasma**: **crossing over**.
- No gene is lost or gained, but a **recombinant** chromatid carries a new combination of alleles.



5.2.A SHUFFLE 2: METAPHASE I

Random assortment

- At **metaphase I** each pair lines up **independently**, so a gamete gets one haploid set that mixes maternal and paternal chromosomes.
- With n pairs there are **2^n combinations**: 2^{23} is about 8.4 million in a human.



5.2.A SHUFFLE 3: AFTER MEIOSIS

Fertilization

- **Fertilization** fuses two haploid gametes into a diploid zygote, restoring 2n.
- Any sperm can meet any egg, so it multiplies the combinations. That is why siblings differ.
- Crossing over makes the true number far larger: each chromosome is itself a new mix.

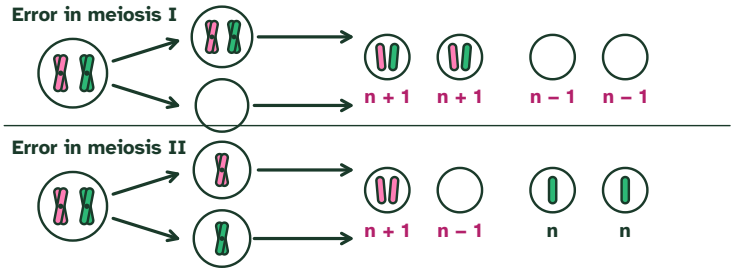
$2^{23} \times 2^{23}$
over 70 trillion possible zygotes from one couple, from assortment alone

The three shuffles: *Cats Avoid Fleas*

5.2.A INCORRECT SEPARATION

Nondisjunction: when a pair does not part

- **Nondisjunction**: homologous chromosomes (meiosis I) or sister chromatids (meiosis II) fail to separate, and both go to the same pole.
- The gametes are no longer haploid: one chromosome too many (**n + 1**) or one too few (**n – 1**).
- After fertilization by a normal gamete, the zygote has 2n + 1 or 2n – 1, copied into every cell by mitosis.



WATCH OUT

Five mistakes that *cost points*

- ✕ **Homologs are not identical.** Same genes, perhaps different alleles. Sister chromatids are the identical copies.
- ✕ **DNA is copied once, not twice.** Only before meiosis I.
- ✕ **The number halves in meiosis I, not II.** Count centromeres.
- ✕ **Crossing over is between nonsister chromatids of one pair.** Never sisters, never different pairs.
- ✕ **Meiosis makes no new alleles.** Mutation does. Meiosis makes new combinations of them.

COVER THE SHEET

Can you *answer these?*

1. Explain why gametes must be haploid.
2. Describe what separates in each division.
3. Calculate the chromatids at metaphase II if 2n = 8.
4. Identify two ways mitosis and meiosis are alike.
5. Explain how a recombinant chromatid forms.
6. Calculate the gamete combinations if 2n = 6.
7. Explain why siblings with the same parents differ.
8. Predict the zygote from an n + 1 gamete.

IN THE EXAM

Say what separates, and when: homologous chromosomes in anaphase I, sister chromatids in anaphase II. "The chromosomes split" earns nothing. In a count, give chromosomes and chromatids separately.

GO FURTHER

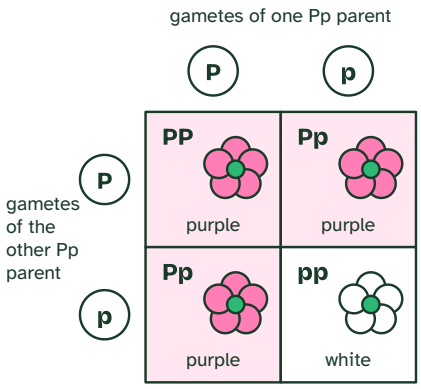
Animated figures, a dry lab and a marked Check are in the full guide online.

Predicting the *offspring*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Each parent passes on one of its two alleles of a gene, at random. So offspring come in ratios you can predict, and test.



Draw it like this. One parent's gametes along the top, the other's down the side. Each box is one equally likely offspring.

5.3.A THE LAW OF SEGREGATION

Two alleles in, *one allele out*

- A diploid organism has two alleles of each gene, one on each chromosome of a homologous pair.
- **Law of segregation**: the two alleles of a gene separate into different gametes, so each gamete carries one. The cause is meiosis: **homologous chromosomes separate in meiosis I**.
- Fertilization fuses two haploid gametes. It restores the diploid number and gives the zygote a new combination of alleles.
- Pp × Pp gives a **genotypic ratio** of 1 PP : 2 Pp : 1 pp and a **phenotypic ratio** of 3 purple : 1 white.

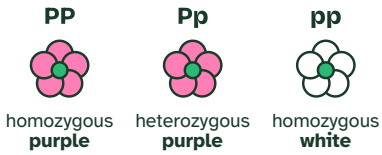
THE GENERATIONS OF A CROSS — *Parents First, Second Follows*

P Parents	**F** First	**S** Second
P: the true-breeding plants crossed	F1: their offspring	F2: offspring of two F1 plants

5.3.A GENES, ALLELES, TRAITS

The *words*

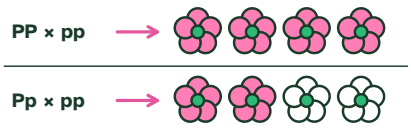
- A **gene** is a length of DNA at one **locus** on a chromosome. Its versions are **alleles**.
- **Genotype**: the alleles inherited. Two the same is **homozygous**; two different is **heterozygous**.
- **Phenotype**: the observable expression of the traits.
- By convention a capital letter is the dominant allele and a small letter the recessive one.
- A **dominant** allele shows in a heterozygote. A **recessive** allele shows only in a homozygote.



5.3.A A HIDDEN GENOTYPE

The *test cross*

- A purple plant could be PP or Pp. You cannot tell by looking.
- **Test cross**: cross it with a **homozygous recessive**, pp. That parent adds only p, so the offspring show the unknown parent's gametes.
- Any recessive offspring means the unknown parent was heterozygous.
- Which allele is dominant? Cross two true-breeding parents that differ: it is the trait every F1 shows.
- A square works backward too: from the offspring you can deduce the parents.



5.3.A RULES OF PROBABILITY

"And" multiplies, *"or" adds*

- **Multiplication rule:** for **independent** events, P(A and B) = P(A) × P(B). Aa × Aa gives aa with chance 1/2 × 1/2 = 1/4.
- **Addition rule:** for **mutually exclusive** events, P(A or B) = P(A) + P(B). Aa can form two ways: 1/4 + 1/4 = 1/2.
- **Several genes** on different chromosomes: one gene at a time, then multiply.

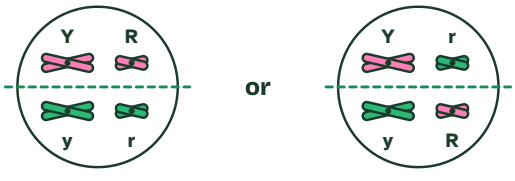
Worked AaBbDd × AaBbdd
Shows A, is bb and is Dd: 3/4 × 1/4 × 1/2 = **3/32**.

No memory
Each fertilization is independent: the chance is the same for every offspring.

5.3.A THE DIHYBRID CROSS

Two genes: *independent assortment*

- **Law of independent assortment**: the alleles of one gene pass into gametes independently of the alleles of another. It holds for genes on **different chromosomes**.
- The cause is meiosis: each homologous pair lines up on its own at **metaphase I**. So a YyRr plant makes four kinds of gamete in equal numbers.
- YyRr × YyRr gives **9 : 3 : 3 : 1**, which is two 3 : 1 ratios multiplied: 3/4 × 3/4 = 9/16 show both dominant traits. The test cross YyRr × yyrr gives **1 : 1 : 1 : 1**.



gametes YR and yr — **gametes Yr and yR**

Testing a ratio, reading a *pedigree*, giving the chance

5.3.A TESTING A RATIO

Chi-square: close enough, or too far to be chance?

FIVE STEPS

Hungry Elves Cook Delicious Cakes

H Hypothesis the null: the counts fit the ratio	**E** Expected total × each fraction of the ratio	**C** Calculate sum of $(o - e)^2 \div e$	**D** Degrees of freedom: outcomes minus one	**C** Compare with the critical value at $p = 0.05$

- **Null hypothesis**: there is no significant difference between the observed counts and the counts the ratio predicts.
- Chi-square **above** the critical value: **reject** the null hypothesis. At or below it: **fail to reject**.
- It is for **counts in categories**, not means, measurements or percentages. The formula and the critical values are on the AP equations sheet.

MENDEL'S F2 SEEDS	OBSERVED	EXPECTED	$(O - E)^2 \div E$
Round, yellow	315	312.75	0.02
Round, green	108	104.25	0.13
Wrinkled, yellow	101	104.25	0.10
Wrinkled, green	32	34.75	0.22

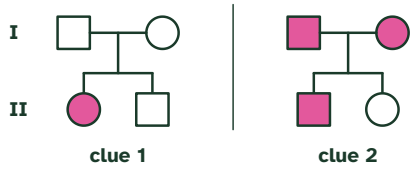
Expected from 9 : 3 : 3 : 1 of 556 seeds — Chi-square = **0.47**

Four outcomes, so 3 degrees of freedom: the critical value is 7.81. 0.47 is below it: fail to reject. Critical values at $p = 0.05$: 3.84 (1), 5.99 (2), 7.81 (3).

5.3.A READING A FAMILY

A *pedigree* is data

- Squares are males, circles are females and a filled symbol shows the trait. Generations are numbered I, II, III.
- **Clue 1:** unaffected parents with an affected child. The allele is **recessive**, and both parents are heterozygous **carriers**.
- **Clue 2:** affected parents with an unaffected child. The allele is **dominant**, and both parents are heterozygous.
- Then deduce genotypes from the people you are sure of: anyone who shows a recessive trait is aa. Where two genotypes fit, write A_.



5.3.A PATTERN, THEN CHANCE

From data to a *prediction*

- Ask two things. Dominant or recessive? And **autosomal** (not on a sex chromosome) or not? An autosomal trait affects males and females alike.
- A trait that vanishes in the F1 and returns in a quarter of the F2 is recessive.
- Sexes not affected alike: suspect a **sex-linked** gene. Two traits staying together more than 9 : 3 : 3 : 1 allows: suspect **linked** genes.
- With the pattern known, the rules of probability give the chance for the next offspring.

1/4 chance that each child of two carriers shows the recessive trait

2/3 chance that their unaffected child is a carrier: aa is ruled out

WATCH OUT

Five mistakes that *cost points*

- × **Dominant does not mean common, strong or better.** It only describes what shows in a heterozygote.
- × **1 : 2 : 1 counts genotypes; 3 : 1 counts phenotypes.** Give the one the question asks for.
- × **A gamete carries one allele of each gene.** YyRr makes YR, Yr, yR and yr: never Yy or Rr.
- × **A ratio is a chance, not a promise.** Four offspring need not be 3 and 1, and earlier ones change nothing.
- × **"Fail to reject" is not "proved".** Never write "accept" the null hypothesis.

COVER THE SHEET

Can you *answer these?*

1. Explain the law of segregation using meiosis.
2. Explain why a test cross uses a recessive parent.
3. Calculate the chance of aabb from AaBb × AaBb.
4. Explain why a YyRr plant makes four kinds of gamete.
5. Calculate chi-square for 290 and 110 against 3 : 1.
6. Justify the degrees of freedom for a 3 : 1 test.
7. Identify the pattern: affected parents, unaffected child.
8. Predict the chance two carriers' next child is affected.

IN THE EXAM

State the null hypothesis in terms of the cross: "no significant difference between the observed counts and those expected from 3 : 1". Show the expected counts, then end on "reject" or "fail to reject".

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

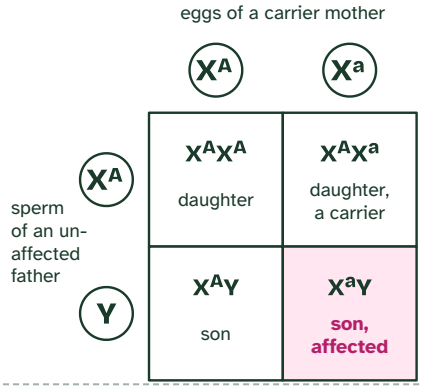
AP BIOLOGY | UNIT 5 | TOPICS 5.4 AND 5.5 | REVISION ON TWO PAGES

When the ratio *breaks*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

A ratio that fails chi-square is a clue: to how alleles show, where a gene sits, or what the environment does to its expression.



Draw it like this. Write the allele on the X and leave the Y bare: it has no copy of the gene.

5.4.A SEX-LINKED TRAITS

A gene on the *X chromosome*

- **Sex-linked** traits are set by genes on the sex chromosomes: X-linked or Y-linked.
- An XY individual has one X, so a single recessive allele on it shows. An XX individual needs the allele on both. So X-linked recessive traits appear at **higher rates in XY individuals**.
- A father gives his X to every daughter and his Y to every son, so he never passes an X-linked allele to a son. A Y-linked trait goes from a father to all his sons.
- In data, a ratio that **differs between sons and daughters** points to a sex-linked gene.

X-LINKED RECESSIVE IN A PEDIGREE: THREE SIGNS

M **Males** mostly males are affected

M **Mothers** unaffected carrier mother, affected son

N **Never** father to son: a son gets his Y

5.4.A SPOTTING A DEVIATION

A ratio that *will not fit*

- Mendel's ratios are a model. Many traits do not follow them.
- A deviation is found in data: the **observed ratio differs statistically** from the predicted one. The test is chi-square.
- The null hypothesis is the Mendelian ratio. Chi-square above the critical value: **reject** it.
- Rejecting does not name the cause. Alleles still segregate: something else is outside the model.

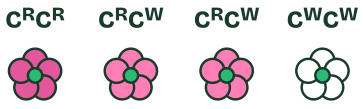
Worked 3 : 1 predicted
160 offspring: 100 tall and 60 short, against 120 and 40 expected. Chi-square = 3.33 + 10.00 = **13.33**.

Verdict 1 degree of freedom
13.33 is above 3.84: reject. These plants do not fit 3 : 1.

5.4.A KINDS OF DOMINANCE

In between, or *both at once*

- **Incomplete dominance**: neither allele masks the other, so the heterozygote is **in between**. Red × white four o'clocks give pink.
- **Codominance**: both alleles' phenotypes are expressed. A roan Shorthorn has red hairs and white hairs side by side.
- Either way, two heterozygotes give three phenotypes, **1 : 2 : 1**, not 3 : 1. Neither allele is recessive, so both take capitals: C^R and C^W.
- The alleles never blend: cross two pinks and red and white come back.



offspring of pink × pink

5.4.A BIRDS AND BEES

Sex without *X and Y*

- In some species sex is not set by X and Y chromosomes.

Birds Z and W
Males are ZZ and females are ZW, so a recessive allele on the Z shows more often in females.

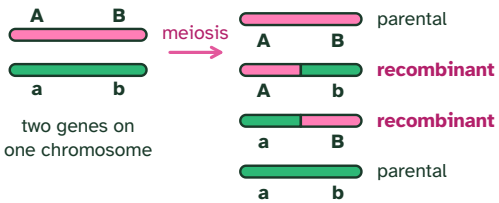
Bees haplodiploidy
Females grow from fertilized eggs and are diploid. Males grow from unfertilized eggs and are haploid.

- The rule to carry over is not "males show it more". It is: the sex with **one copy** of the gene shows a recessive allele more often.
- A male bee has one set of chromosomes, so every allele he carries shows.

5.4.A TWO GENES, ONE CHROMOSOME

Linked genes and map distance

- Genes on the same chromosome are **genetically linked**. They tend to segregate together, so they do not assort independently.
- Only **crossing over** between the two genes separates their alleles. A test cross gives two large parental classes and two small recombinant ones, not 1 : 1 : 1 : 1.
- **Recombination frequency** = recombinants ÷ total × 100, and 1% is **1 map unit**. Genes farther apart are separated more often.



Worked 1,000 offspring
430 and 420 parental, 70 and 80 recombinant. 150 ÷ 1,000 × 100 = 15%: **15 map units**.

Order three genes
A to B is 12, B to D is 5, A to D is 17. So B lies between A and D.

5.4.A TRAITS THAT NEVER PART

Pleiotropy: one gene, many effects

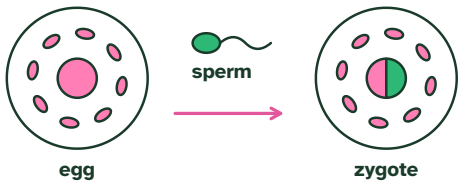
- **Pleiotropy**: the expression of a single gene results in multiple traits, because its product acts in more than one place or pathway.
- Those traits **do not segregate independently**. They are inherited as a set, and no crossover can part them: there is only one gene.
- In Mendel's peas one gene colors the flower, the seed coat and the leaf joints: it switches on the pathway for one purple pigment.

TWO TRAITS FROM	PHENOTYPE CLASSES IN A CROSS
Two genes on different chromosomes	Four: 9 : 3 : 3 : 1 from two heterozygotes.
Two linked genes	Four, with the two recombinant classes small.
One pleiotropic gene	Two only. The traits always go together.

5.4.A NON-NUCLEAR INHERITANCE

DNA *outside the nucleus*

- Mitochondria and chloroplasts have their own DNA. Traits set by it **do not follow Mendel's rules**.
- These organelles are **randomly assorted** to gametes and daughter cells, not lined up and shared out as chromosomes are. So there is no fixed ratio.
- **Animals:** mitochondria come from the egg, not the sperm, so mitochondrial traits are **maternally inherited**.
- **Plants:** mitochondria and chloroplasts come in the ovule, not the pollen, so their traits follow the mother plant too.

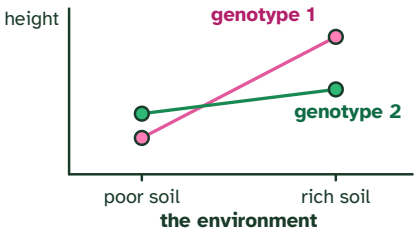


Nuclear DNA is half from each parent. The mitochondria, and their DNA, are all from the egg.

5.5.A PHENOTYPIC PLASTICITY

Same genotype, *different phenotype*

- **Environmental conditions influence gene expression**. So the same genotype can give different phenotypes in different conditions: **phenotypic plasticity**.
- The DNA sequence does not change. What changes is which genes are expressed, and how much. The change happens within one individual's life and is not passed on in its alleles.
- To explain a case, make three moves: the genotype is the same, an environmental condition differs, and the phenotype responds.
- On a graph each line is one genotype. A sloping line shows plasticity; different slopes show that genotypes respond differently.



NUTRITION	SOIL PH	SEASON	NEST HEAT	UV LIGHT	MATE NEARBY
Humans Height and weight.	**Some flowers** Blue or pink.	**Arctic animals** White or brown fur.	**Reptiles** Male or female.	**Animals** More melanin.	**Yeast** Pheromone made.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Incomplete dominance blends the phenotype, not the alleles.** Cross two pinks and red and white come back.
- ✕ **Linked is not sex-linked.** Linked genes share any one chromosome; sex-linked genes sit on a sex chromosome.
- ✕ **Add both recombinant classes before you divide.** One class alone gives half the true distance.
- ✕ **Maternal inheritance is not X-linked.** A father passes his X to daughters, but his mitochondria to no one.
- ✕ **The environment changes expression, not the genes.** Plasticity is not mutation, and it is not evolution.

COVER THE SHEET

Can you *answer these?*

1. Explain how a deviation from 3 : 1 is identified in data.
2. Describe the coat of a codominant heterozygote.
3. Predict the sons of an affected mother, X^aX^a.
4. Explain why linked genes do not assort independently.
5. Calculate the map distance: 104 recombinants in 800.
6. Explain why a pleiotropic gene gives no recombinants.
7. Predict the children of a man with a mitochondrial trait.
8. Justify: a fox's winter coat is not passed to its pups.

IN THE EXAM

Read the cause from the data: sexes differ, sex-linked; two large and two small classes, linked; three phenotypes in 1 : 2 : 1, incomplete dominance or codominance. Name it, then show the working.

GO FURTHER

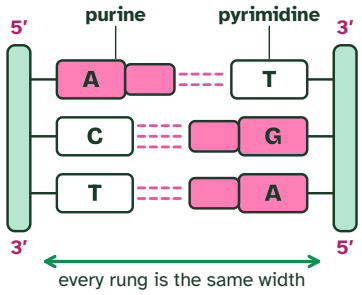
Animated figures, a dry lab and a marked Check are in the full guide online.

DNA: built to be *copied*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

DNA holds information in the order of its bases. Each strand fixes its partner, so each is the template for a new one.



Draw it like this. Two rings for a purine, one for a pyrimidine, dashes for hydrogen bonds, and the strands antiparallel.

6.1.B START HERE

A purine always pairs with a *pyrimidine*

- **Purines**, adenine (A) and guanine (G), have a **double ring**. **Pyrimidines**, cytosine (C), thymine (T) and uracil (U), have a **single ring**.
- Two purines are too wide for the helix and two pyrimidines too narrow. One of each fits, and only **A with T** and **G with C** line up their hydrogen bonds: two for A and T, three for G and C. In RNA, U replaces T and pairs with A.
- The pairing rule is the same in all living things: it has been **conserved through evolution**.
- Know one strand and you know the other, so **each strand can rebuild its partner**. That is why DNA can be hereditary material.

WHICH BASES ARE THE PURINES — *Pure As Gold*

P	**Purines** the big ones: a double ring
A	**Adenine** pairs with T, or U in RNA
G	**Guanine** pairs with C

6.1.A DNA, AND SOMETIMES RNA

What is *passed on*

- Hereditary information is stored in DNA, as the **order of its bases**.
- It passes from a cell to the cells it divides into, and from parents to offspring, because DNA is **copied and handed on**.
- Cells always use DNA. In **some viruses** the hereditary material is **RNA**: influenza and the coronaviruses.

Gene a stretch of DNA
It holds the information for one product, at one place on a chromosome.

Allele one version of a gene
Alleles of a gene differ in their base sequence.

6.1.B DATA TO REASON FROM

Counting *bases*

- In **double-stranded** DNA every A faces a T and every G faces a C, so the amounts match.
- **Worked example:** DNA is 31% A. Then T is 31%, together 62%. The other 38% is shared equally: **G = C = 19%**.
- A + T need not equal G + C: that share differs between species.
- A **single-stranded** molecule has no partner strand, so its A need not equal its T or U.

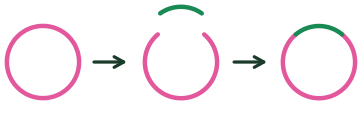
A = T in double-stranded DNA

G = C so purines are half the bases

6.1.A SMALL, CIRCULAR AND EXTRA

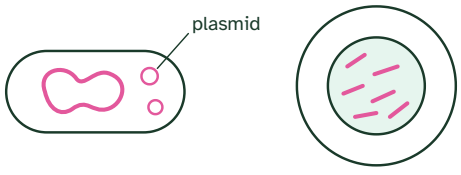
Plasmids

- A **plasmid** is a small, circular DNA molecule separate from the chromosome: **extra-chromosomal**.
- It carries only a few genes and is **copied apart from the chromosome**, so each new cell normally gets a copy.
- Prokaryotes and eukaryotes can both contain plasmids.
- A gene from another organism can be added to a plasmid, and the plasmid taken up by a bacterium.



6.1.A TWO WAYS TO ORGANIZE DNA

One circle, or several *lines*



prokaryote: circular chromosome — **eukaryote: linear chromosomes in a nucleus**

Not to scale. A bacterium is far smaller than an animal cell.

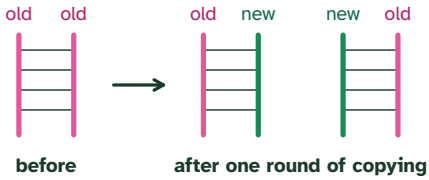
	PROKARYOTE	EUKARYOTE
Shape	**Typically circular** A closed loop. *E. coli*: about 4.6 million base pairs.	**Typically linear** Several, each with two ends. A human body cell has 46.
Where	In the **cytoplasm**: there is no nucleus.	Inside the **nucleus**.
Packing	No histones of the eukaryotic kind. Other proteins fold it.	Condensed with **histones** and associated proteins, so about 2 m of DNA fits in one human nucleus.

Replication: *semiconservative*, and always 5′ to 3′

6.2.A SEMICONSERVATIVE REPLICATION

Half old, *half new*

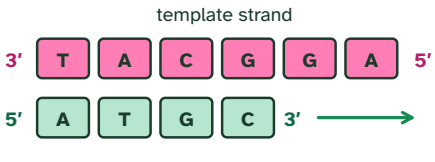
- Replication copies the DNA before a cell divides, keeping hereditary information **continuous between generations**.
- The two strands separate. Each is a **template**: new nucleotides pair with its bases and are joined into a **complementary strand**.
- **Semiconservative**: each new molecule has one old strand and one new strand. Both have the same base sequence as the original.



6.2.A DIRECTION

New DNA grows only *5′ to 3′*

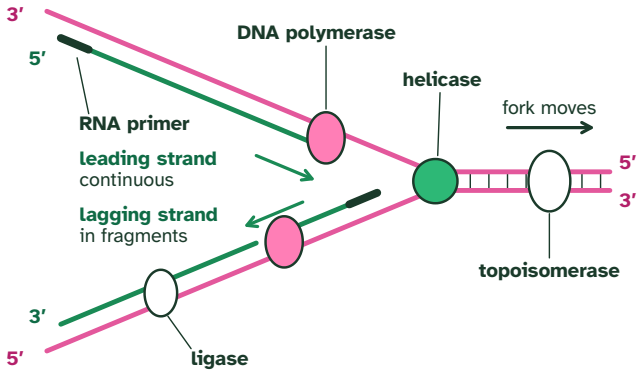
- A strand has a free phosphate at its **5′ end** and a free hydroxyl group at its **3′ end**.
- **DNA polymerase** adds nucleotides **only to a 3′ end**, so every new strand is built 5′ to 3′.
- The template is **read 3′ to 5′**. The two templates of a helix are antiparallel, so the two new strands **grow in opposite directions**.



new strand: nucleotides join only at the 3′ end

6.2.A FIVE PARTS, FIVE JOBS

At the *replication fork*



- Replication happens at a **replication fork**: the Y-shaped place where the helix is being opened.
- DNA polymerase **cannot start a strand**. Each one begins with a short **RNA primer**, which is later replaced with DNA.

Leading strand continuous
Its 3′ end points **toward the fork**, so DNA polymerase keeps adding as helicase opens the helix. One primer.

Lagging strand discontinuous
Here 5′ to 3′ points **away from the fork**, so it is built in fragments, each from its own primer. Ligase joins them.

UNWINDS
Helicase
separates the two strands of the helix.

RELAXES
Topoisomerase
relaxes supercoiling ahead of the fork.

STARTS
RNA primer
gives DNA polymerase a 3′ end to add to.

BUILDS
DNA polymerase
adds DNA nucleotides, always 5′ to 3′.

JOINS
Ligase
bonds the lagging fragments into one strand.

WATCH OUT

Five mistakes that *cost points*

- ✕ **A = T and G = C does not mean A + T = G + C.** In human DNA, A and T together are about 60% of the bases.
- ✕ **Semiconservative is not one old molecule and one new.** Both are half old, half new.
- ✕ **DNA polymerase builds 5′ to 3′.** To do that it moves along the template 3′ to 5′. Say which strand you mean.
- ✕ **The lagging strand is not made 3′ to 5′.** Each fragment is built 5′ to 3′, away from the fork.
- ✕ **Helicase only separates the strands.** It breaks hydrogen bonds, not the backbone, and copies nothing.

COVER THE SHEET

Can you *answer these?*

1. Describe how DNA stores hereditary information.
2. Explain why a purine never pairs with a purine.
3. Calculate the percent G in double-stranded DNA that is 22% A.
4. Describe two features of a prokaryote's chromosome.
5. Describe a plasmid.
6. Explain why replication is called semiconservative.
7. Explain why one new strand is made in fragments.
8. Predict the new DNA at a fork if ligase does not work.

IN THE EXAM

Name the strand and the direction: "the new strand is built 5′ to 3′", not just "5′ to 3′".
Give each enzyme its own job: helicase unwinds, DNA polymerase builds, ligase joins.

GO FURTHER

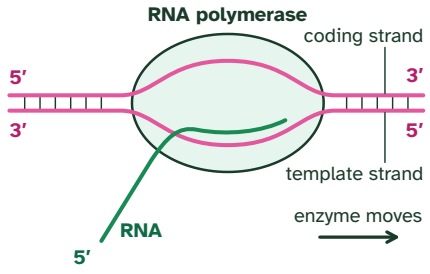
Animated figures, a dry lab and a marked Check are in the full guide online.

From gene to *protein*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

DNA to RNA to protein: a gene is transcribed into mRNA, and a ribosome translates its codons into a polypeptide.



Worked example. Template 3′ CAT GGC 5′ gives RNA 5′ GUA CCG 3′. The coding strand reads 5′ GTA CCG 3′.

6.3.A START HERE

Transcription copies one strand into *RNA*

- **RNA polymerase** binds at the start of a gene and separates the two DNA strands. It uses one, the **template strand**, to set the order of bases in the RNA.
- RNA nucleotides pair with the template: A takes U, T takes A, C takes G, G takes C. Each joins the 3′ end of the RNA, so the enzyme **reads the template 3′ to 5′** and **builds RNA 5′ to 3′**.
- The RNA is **complementary** to the template, so it matches the other strand, the **coding strand**, with U in place of T. Behind the enzyme the DNA closes up, unchanged.

PAIRING IN TRANSCRIPTION — *Apples Under Cars Garage*

A	**Apples** A on the template	**U**	**Under** takes U in the RNA	**C**	**Cars** C on the template	**G**	**Garage** takes G in the RNA

6.3.A 6.4.A THE FLOW OF INFORMATION

DNA to RNA to *protein*

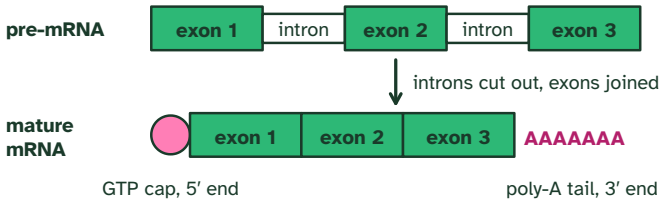
- A gene is a sequence of bases in DNA. Reading it and making its product is **gene expression**.
- The DNA is **copied, never used up**. In a eukaryote it stays in the nucleus, and mRNA carries the message out.
- Proteins do the work of the cell, so **genotype determines phenotype** through the proteins made.
- **Example:** one gene codes for the enzyme tyrosinase, which makes the dark pigment melanin.

Transcription DNA to RNA
The base sequence of a gene is copied into RNA.

Translation RNA to polypeptide
A ribosome reads the mRNA and joins amino acids in the order it sets.

6.3.A CAPPED, TAILED AND SPLICED

A eukaryotic transcript is *processed*



- Enzymes change the new transcript (pre-mRNA) in the nucleus. Only **mature mRNA** leaves.
- **Introns** are transcribed, then cut out of the RNA; the **exons** are joined and expressed.
- **Alternative splicing**: keeping different sets of exons gives different mature mRNAs, and so different polypeptides, from one gene.

THREE CHANGES — *Cats Take Showers*

C	**Cap** a GTP cap on the 5′ end helps a ribosome recognize the mRNA	**T**	**Tail** a poly-A tail on the 3′ end makes the mRNA more stable	**S**	**Splice** introns are cut out and the exons joined

6.3.A STRUCTURE FITS FUNCTION

Three RNAs meet at the *ribosome*

	SHAPE	JOB	WHY THE SHAPE FITS
mRNA messenger	One open strand.	Carries the information from the DNA to a ribosome.	A message has to be read in order, from one end to the other.
tRNA transfer	A short strand folded back on itself.	Each kind binds **one specific amino acid**. Its **anticodon** pairs with one codon of the mRNA.	A three-base tip matches one codon and nothing else.
rRNA ribosomal	Large folded strands, with proteins.	The **working building block of the ribosome**: it holds the mRNA and tRNAs, and joins the amino acids.	A big scaffold can grip several molecules at once.

All three are made by transcription. Only mRNA is translated.

Sequence sets the shape; shape sets the job

Translation: *codons*, ribosomes and a special case

6.4.A THE GENETIC CODE

A code read in *threes*

- mRNA is read three bases at a time. Each **codon** names one amino acid: read it from a genetic code chart.
- **Redundant**: most amino acids have several codons. Never ambiguous: no codon names two.
- **AUG** is the start codon and codes for methionine. UAA, UAG and UGA mean stop.
- Nearly all organisms use the same code: evidence of **common ancestry**.

64	61	3
codons	amino acids	stop

6.4.A PLACE AND TIMING

Where *ribosomes* work

- Translation happens on ribosomes in the **cytoplasm** of every cell, prokaryotic or eukaryotic.
- In eukaryotes some ribosomes sit on the cytoplasmic surface of the **rough endoplasmic reticulum**.

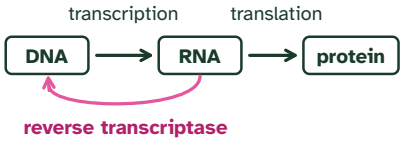
Prokaryote no nucleus
Ribosomes begin translating an mRNA **while it is still being transcribed**.

Eukaryote a nucleus
An mRNA is translated only after it is finished, processed and out of the nucleus.

6.4.A A SPECIAL CASE

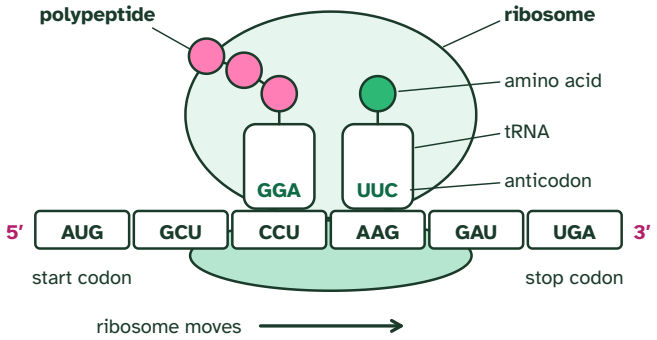
Retroviruses

- A retrovirus carries its genes as **RNA**. Its enzyme **reverse transcriptase** copies that RNA into DNA: information flows from **RNA to DNA**.
- The DNA copy **integrates into the host genome**. The host cell then transcribes and translates the viral genes, and new viruses are assembled.



6.4.A THREE STAGES: IN EVERY TALE

Translation: *start, grow, stop*



The order of codons sets the order of amino acids: the primary structure of the protein.

1 INITIATION
At the start codon
The rRNA of the ribosome interacts with the mRNA at AUG. A tRNA carrying methionine pairs with it.

2 ELONGATION
Codon by codon
A tRNA whose **anticodon pairs with the codon** brings the amino acid it names. It is joined to the chain, and the ribosome moves one codon on, 5′ to 3′.

3 TERMINATION
At a stop codon
No amino acid is added. The new polypeptide is released.

WATCH OUT

Five mistakes that *cost points*

- ✕ **mRNA is not a copy of the template.** It is complementary to it, and matches the coding strand with U for T.
- ✕ **Introns are cut out of the RNA, never the DNA.** They lie inside a gene and are transcribed every time.
- ✕ **The anticodon is on the tRNA; the codon is on the mRNA.** The chart is always in codons.
- ✕ **Redundant is not ambiguous.** One codon never names two amino acids.
- ✕ **A mutation does not denature a protein.** Denaturing is heat or pH unfolding a protein built correctly.

COVER THE SHEET

Can you *answer these?*

1. Describe the direction in which RNA is built.
2. Identify the mRNA made from 3′ TAC CGA ATT 5′.
3. Describe three changes made to a eukaryotic transcript.
4. Explain how one gene can give several polypeptides.
5. Describe the jobs of mRNA, tRNA and rRNA.
6. Explain why a shared code suggests common ancestry.
7. Predict the effect of a drug that blocks RNA polymerase.
8. Describe the flow of information in a retrovirus.

IN THE EXAM

Predicting the effect of a change? Three steps, in order. The molecule: what differs in the DNA, the mRNA or the machinery. The protein: a different polypeptide (or the same, as the code is redundant), less of it, or none. Then the phenotype.

GO FURTHER

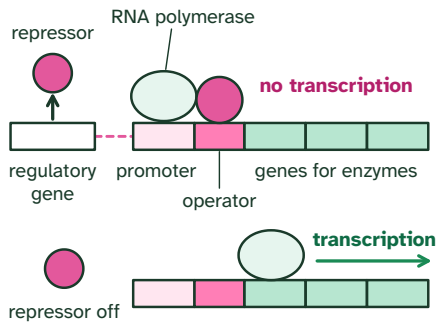
Animated figures, a dry lab and a marked Check are in the full guide online.

Genes, *on and off*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Cells hold the same genes but express different ones. Regulatory proteins bind regulatory sequences to set how much.



Off, then on. A repressor on the operator blocks RNA polymerase. With the repressor off, the genes are transcribed.

6.5.B START HERE

An operon: one switch for *several genes*

- An **operon** is a group of prokaryotic genes with one **promoter** and one **operator**. They are transcribed together into one mRNA, so they are regulated together.
- A regulatory gene elsewhere makes a **repressor**: a protein whose shape depends on a small molecule. On the operator it sits in the path of RNA polymerase and blocks transcription.
- **Location explains function.** A DNA site acts only where it sits. A regulatory protein travels through the cell, so its gene can lie anywhere.

THREE PARTS, AND WHAT LOSING EACH ONE DOES

P Promoter RNA polymerase binds here. Lost: never transcribed

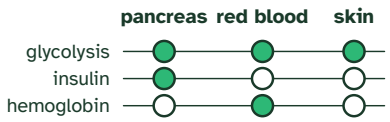
O Operator the repressor binds here. Lost: cannot be switched off

R Regulatory gene makes the repressor. Lost: cannot be switched off

6.5.A 6.6.B SAME DNA

One genome, many *cells*

- Nearly every cell of an organism holds the same genes. Cells differ because they **express different genes**.
- Gene regulation gives **differential gene expression**, so cells make different products and do different jobs.
- Phenotype is set by which genes are expressed and at what level: the **function and amount** of each product.



Green: transcribed. Every cell holds all three genes, and every cell needs the enzymes of glycolysis.

6.5.A SEQUENCES AND PROTEINS

On, off and *in between*

- A gene is "on" when it is being transcribed and "off" when it is not. Many sit in between.
- **Regulatory sequences** are stretches of DNA. **Regulatory proteins** bind them and raise or lower transcription.
- A regulatory sequence codes for nothing: it is a place on the DNA where one protein fits.
- Some regulatory proteins help RNA polymerase begin; others get in its way.

Constitutive genes always on
Expressed all the time, because the cell always needs the product.

Inducible genes on when needed
Expressed only when a signal or a substance is present.

6.5.B COORDINATE REGULATION

One signal, *many genes*

- Prokaryotes and eukaryotes both regulate genes in groups.
- One signal can switch on a whole set: every gene with a copy of the sequence responds.
- **Example:** estrogen enters a cell and binds a receptor protein. Together they act as a transcription factor.

Prokaryotes operons
The genes share one promoter and one operator.

Eukaryotes a shared sequence
Each gene has its own promoter. Genes with the same regulatory sequence answer to the **same transcription factor**, even on different chromosomes.

6.5.B REPRESSIBLE AND INDUCIBLE

Two operons, *opposite ways*

	REPRESSIBLE: THE TRP OPERON	INDUCIBLE: THE LAC OPERON
Usual state	**On**	**Off**
Its enzymes	Build the amino acid tryptophan.	Take up lactose and break it down.
The small molecule	Tryptophan, the **product**. It binds the repressor, which changes shape and **fits the operator**.	A molecule made from lactose, the **substance to use**. It binds the repressor, which changes shape and **lets go of the operator**.
Result	Plenty of tryptophan: transcription stops.	Lactose present: transcription starts.

In both, the repressor is a negative regulatory molecule: it binds DNA and blocks transcription.

trp and lac are examples

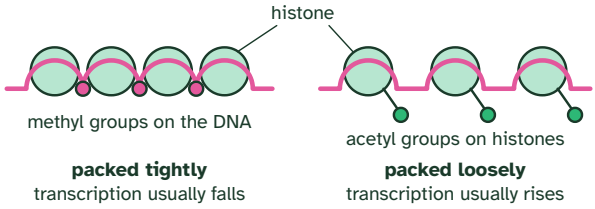
Eukaryotes: *tags*, transcription factors and small RNAs

AP BIOLOGY · UNIT 6

6.5.A EPIGENETIC CHANGES

Tags that open and close the *DNA*

- Eukaryotic DNA is wound on **histones**. Where it is packed tightly, a gene is hard to transcribe.
- **Epigenetic changes** are chemical tags on the DNA or the histones that change gene expression.
- The **base sequence is unchanged**, and the changes are **reversible**: enzymes add each tag and others remove it.



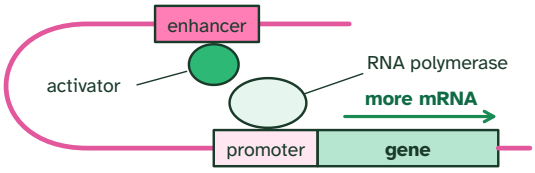
packed tightly
transcription usually falls

packed loosely
transcription usually rises

6.6.A STARTING TRANSCRIPTION

Transcription factors and *enhancers*

- RNA polymerase and **transcription factors** bind **promoter or enhancer** sequences to start transcription.
- These sequences can be **upstream or downstream** of the transcription start site. A distant enhancer still acts, because the DNA loops.
- **Negative regulatory molecules** inhibit expression by binding DNA and blocking transcription.



the DNA loops

6.6.B AFTER TRANSCRIPTION

Small RNAs *silence* a message

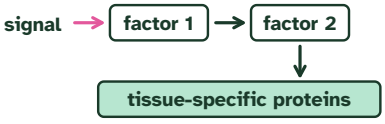
- Regulation does not end at transcription: an mRNA can be spliced in different ways, and can last a long or a short time.
- Certain **small RNA molecules** regulate expression. One pairs with a matching mRNA, which is then **broken down or not translated**.

mRNA differs between two cells	Look for regulation at transcription.
mRNA equal, protein not	The regulation is after transcription.

6.5.A DIFFERENTIATION AND DEVELOPMENT

Genes switched on *in order*

- **Differentiation** can be seen: cells express genes for **tissue-specific proteins**.
- In development, transcription factors are induced one after another. Each switches on genes that include the next factor: **sequential gene expression**.



the cell differentiates

6.6.B IN ORDER

Five places a eukaryotic cell can *regulate* a gene

1 PACKING	2 TRANSCRIPTION	3 SPLICING	4 THE MRNA	5 PROTEIN
Can it be reached? Tags open or close the DNA.	**Does it start?** Factors start it or block it.	**Which mRNA?** One gene, more than one mRNA.	**Does it last?** Kept, silenced or broken down.	**How much?** Function and amount set the phenotype.

WATCH OUT

Five mistakes that *cost points*

- ✕ **A gene that is not expressed is still there.** A skin cell keeps its insulin gene, switched off.
- ✕ **An enhancer makes nothing.** It is a site on the DNA; the activator that binds it is a protein with a gene of its own.
- ✕ **A repressor blocks transcription.** It does not destroy the gene or the mRNA, and it is not an enzyme.
- ✕ **An epigenetic change is not a mutation.** It changes whether a sequence is read, never what it says.
- ✕ **A small RNA does not switch the gene off.** The gene is still transcribed; less protein comes from each mRNA.

COVER THE SHEET

Can you *answer these?*

1. Explain how cells with the same genes can differ.
2. Describe how constitutive and inducible genes differ.
3. Explain how a repressor stops transcription.
4. Predict how the trp operon behaves with no repressor.
5. Describe one epigenetic change and its usual effect.
6. Explain how a distant enhancer can raise transcription.
7. Explain how one signal can switch on many genes.
8. Identify the stage regulated if mRNA is equal but protein is not.

IN THE EXAM

Ask first: is the part a site on the DNA, or the gene for a protein? A site acts only where it sits; a protein travels. Then say what binds where, and what transcription does.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 6 | TOPICS 6.7 AND 6.8

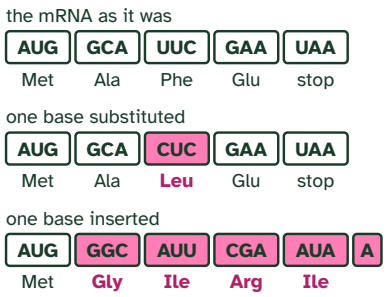
REVISION ON TWO PAGES

DNA that *changes*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

A mutation alters a DNA sequence, and can change a protein's type or amount. Random mutations are a source of variation.



Read in threes from AUG. A substitution changes one codon. An insertion changes every codon after it.

6.7.A START HERE

One nucleotide can change a *protein*

- A **mutation** is an alteration in a DNA sequence. It can change the **type** of protein made (a new amino acid sequence) or the **amount** (more, less or none), and so the phenotype.
- A **point mutation** substitutes one nucleotide for another. One codon changes, and the reading frame never moves.
- A **frameshift mutation** inserts or deletes nucleotides, so **every codon after it** is read differently. Three in or out adds or removes a whole codon and keeps the frame.

FOUR RESULTS FOR THE PROTEIN

S Silent — same amino acid: the code is redundant

C Changed — one amino acid is different

N Nonsense — a stop codon too early

F Frameshift — the frame moves

6.7.A 6.7.B THE VERDICT

Is it *beneficial*?

- A mutation is **beneficial, detrimental or neutral** by its effect on the protein and the phenotype. Most are neutral.
- It also depends on the **environment**: one allele can help in one place and harm in another.
- **Example:** a mutation gives a pocket mouse dark fur, and owls hunt by sight.

On dark rock beneficial
The mouse is hard to see, so it survives and reproduces.

On pale sand detrimental
The same mouse stands out.

6.7.B FOUR CAUSES, ONE RULE

Causes of *mutation*

- Mutations are **random**: they do not happen because an organism needs them.
- They are a **source of genetic variation**. Every new allele began as one.

COPYING
Replication
An error is not caught.

MENDING
Repair
Damage is fixed wrongly.

OUTSIDE
Radiation
Ultraviolet light, for one.

OUTSIDE
Chemicals
Reactive ones alter a base.

6.7.B NUMBER AND STRUCTURE

Whole *chromosomes*

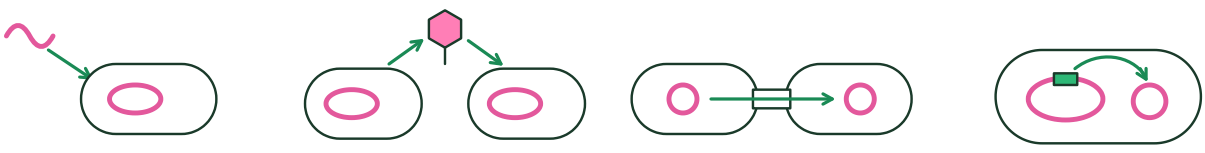
- Errors in **mitosis or meiosis** can change the phenotype without changing the sequence of any gene.
- In **nondisjunction** chromosomes fail to separate. Every gene on an extra chromosome is normal: there is one copy too many.

Number too many or too few
Often a new phenotype, and often a disorder that limits development.

Structure rearranged
A segment lost, repeated, turned around or moved can cause a genetic disorder.

6.7.C GENES THAT MOVE, AND SELECTION

Four ways a prokaryote *gains genes*



TRANSFORMATION
Loose DNA is taken up
from the surroundings.

TRANSDUCTION
A virus carries DNA
from one cell to the next.

CONJUGATION
Cell to cell
DNA passes between two joined cells.

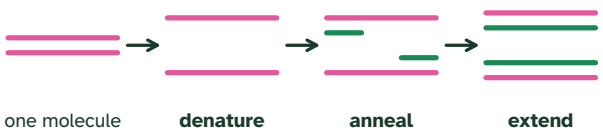
TRANSPOSITION
A segment moves
within or between DNA molecules.

- **Horizontal acquisition** of genetic information increases variation in prokaryotes. Related viruses that infect the same host cell can also **recombine** their genetic information.
- A change that raises survival and reproduction is **selected for by environmental conditions**. An antibiotic does not make resistance: it leaves resistant cells to reproduce.

Biotechnology: *copy*, sort, read and move DNA

6.8.A COPY

PCR *copies* one stretch of DNA

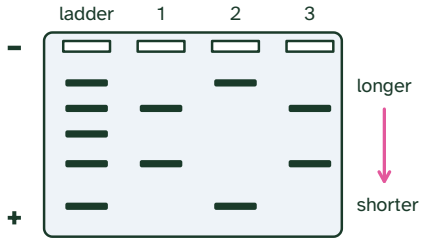


- The **polymerase chain reaction amplifies** a DNA fragment: many copies of one chosen stretch.
- **Denature:** heat separates the two strands. **Anneal:** short primers pair with the original strands, one each side of the target. **Extend:** DNA polymerase adds nucleotides to the 3′ end of each primer.
- Each cycle **doubles** the copies: 2^n after n cycles, about a billion after 30. The primers set which stretch is copied.
- **Used to** identify organisms and work out how they are related.

6.8.A SORT

A gel *sorts* fragments by length

- **Gel electrophoresis** separates DNA fragments by **size and charge**.
- DNA is negatively charged, so it moves toward the **positive electrode**. **Shorter fragments move farther** through the gel.
- A band is many copies of one length. A ladder of known lengths gives the sizes. **Used to** compare patterns from samples: forensic identification.



6.8.A READ

Sequencing *reads* the bases

- **DNA sequencing** determines the **order of nucleotides** in a DNA molecule.
- Line up the same stretch from different samples and count the differences: the fewer there are, the more closely related the samples.
- Lined up against the usual sequence, a sequence shows where a mutation is and what kind.

sample 1	A	T	G	C	C	T	A	G	G	A
sample 2	A	T	G	C	C	T	A	G	C	A
sample 3	A	T	A	C	C	T	T	G	C	A

PCR	A GEL	SEQUENCING
More of it?	**How long is it?**	**What does it say?**

6.8.A MOVE

Transformation *moves* a gene

- **Bacterial transformation** introduces foreign DNA into bacterial cells, usually a plasmid with the gene of interest and a gene for antibiotic resistance.
- Only a few cells take the plasmid up. On agar with the antibiotic only they grow, each into a colony.
- A transformed cell expresses the gene and copies the plasmid at every division: **gene cloning**. **Used to** make genetically modified organisms; transgenic animals carry another species' gene.



cells without the plasmid | cells with the plasmid

Both plates contain the antibiotic.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Mutation does not mean harmful.** Most are neutral, and the verdict depends on the environment.
- ✕ **A point mutation never shifts the reading frame.** A frameshift needs an insertion or a deletion.
- ✕ **Mutations are not made to order.** An antibiotic selects resistant cells; it does not create them.
- ✕ **A mutation does not denature a protein.** The protein is built with a different sequence from the start.
- ✕ **PCR copies only the stretch between the primers,** and a gel shows lengths, not base sequences.

COVER THE SHEET

Can you *answer these?*

1. Describe a silent mutation and a nonsense mutation.
2. Predict the effect of deleting one base early in a gene.
3. Explain how one mutation can help or harm.
4. Identify three causes of mutation.
5. Predict the zygote: a gamete with 5 meets one with 4.
6. Describe two ways a prokaryote gains a gene.
7. Calculate the copies after 10 cycles of PCR.
8. Explain why transformed cells are plated on an antibiotic.

IN THE EXAM

Follow a mutation step by step: nucleotide, codon, amino acid, protein, phenotype. **For a technique,** say what the result shows, then name the idea from the unit that explains it.

GO FURTHER

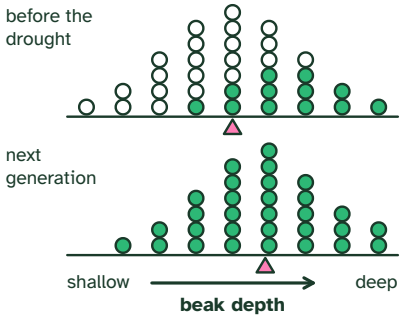
Animated figures, a dry lab and a marked Check are in the full guide online.

Who leaves the most *offspring*?

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Individuals vary, and some variation is heritable. Those whose traits suit the environment leave more offspring, so the population changes over generations.



A drought on one island. Green birds survived; white ones died. The pink mark is the mean.

7.1.A START HERE

More offspring than can *survive*

- Populations produce **more offspring than the environment can support**. Food, water, space and mates are limited, so individuals **compete**.
- Survival is not random: individuals with **more favorable phenotypes** are more likely to live and reproduce. This is **differential survival and reproduction**, and their offspring inherit the traits.
- Natural selection is **one major mechanism** of evolution (Darwin and Wallace, 1858 and 1859). Drift, gene flow and mutation come in the next guide.

WHAT SELECTION NEEDS — *Very Important Parents*

V Variation: individuals differ in a trait	**I** Inheritance: the differences are heritable	**P** Production: some leave more offspring, because of the trait

7.1.A NOT INDIVIDUALS

Populations *evolve*

- **Evolution** is a change in the **heritable traits of a population** over generations.
- **Individuals are selected; populations evolve.** A finch keeps its beak for life.
- A change gained in life (a lifter's muscle, a chipped beak) is in body cells, not in the DNA of the **gametes**, so it is **not inherited**.

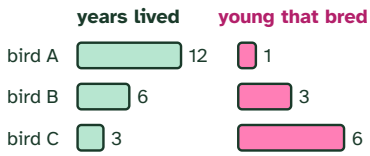
Lamarck rejected
A giraffe stretches and its calf is born with a longer neck.

Darwin supported
Necks already vary; longer necks reach more food and leave more calves.

7.1.B NOT STRENGTH

Fitness is *offspring*

- **Evolutionary fitness** is measured by **reproductive success**: offspring that survive and reproduce in their turn.
- Surviving counts only as a step toward offspring. A healthy, sterile mule has a fitness of zero.
- Fitness belongs to a phenotype **in a particular environment**. The alleles of the fittest become more common.



7.2.A WHERE VARIATION COMES FROM

Heritable variation

- Selection acts on **phenotypes**, but offspring receive **alleles**: variation caused by the environment alone is not passed on.
- Selection **never makes** a variation: it sorts what is there.

NEW ALLELES
Mutation
Random with respect to need.

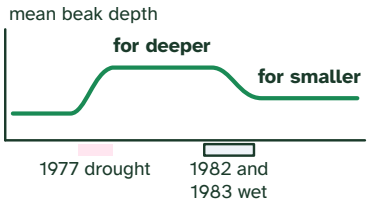
NEW MIXES
Meiosis
Crossing over, independent assortment.

NEW PAIRS
Fertilization
Gametes join at random.

7.2.A 7.1.B

When the environment changes, so does *selection*

- A **selective pressure** is any feature of the environment that makes some phenotypes do better: **abiotic** (rainfall, temperature, a chemical) or **biotic** (predators, parasites, competitors, food).
- Environments are **stable or fluctuating**, so the **direction and rate of evolution** can change, and different variations can be selected in different generations.
- **Daphne Major, Galápagos:** the 1977 drought killed over 4 in 5 medium ground finches and left only large, hard seeds, so deeper beaks survived and their offspring had deeper beaks. After the wet years of 1982 and 1983 left small, soft seeds, selection favored smaller birds.
- **Field mustard** grown from seed collected after a run of dry years in California **flowered earlier** than seed from before it (about 2 and 9 days at two sites).



A sketch of the pattern, not measured values.

One trait, two places, and selection by *people*

7.2.A DDT AND MOSQUITOES

Helpful here, *harmful* there

- A variation can **raise or lower the fitness** of an organism **in a particular environment**. No allele is good everywhere.
- **DDT** was sprayed against malaria mosquitoes from the 1940s. Resistance alleles arose by **chance mutation**; DDT killed the susceptible ones, so the resistant ones left the offspring.
- In *Anopheles funestus* one allele changes one amino acid in the enzyme GSTe2, which then breaks DDT down. With no DDT the allele often **costs** something, so it becomes rarer.
- The human case is the **sickle cell allele**, which helps where malaria is common (next guide).



Illustrative fitness values.

7.2.B MOLECULES VARY TOO

Variation *inside* the cell

- Individuals and populations vary in the **number and types of molecules** in their cells, not only in traits you can see.
- That variation gives a population a **greater ability to survive and reproduce** in different environments.

NUMBER
More gene copies
Some resistant mosquitoes carry many copies of an esterase gene: more enzyme to break the insecticide down.

TYPE
Membrane fatty acids
Kinked unsaturated tails keep a membrane fluid; cold-water fish have more.

VERSION
Hemoglobin
Mountain deer mice carry alleles for hemoglobin that binds oxygen more tightly.

7.3.A

Artificial selection: a *person* chooses

- In **artificial selection** humans choose which individuals reproduce, so **humans are the selective pressure**. The mechanism is the same: heritable variation, unequal reproduction, change over generations.
- **Wild cabbage** (*Brassica oleracea*) of European sea cliffs gave six vegetables, each selected for a different part. All six are still **one species**.
- **Maize** was bred from teosinte, a wild grass, from about 9,000 years ago in southern Mexico. In Illinois, maize has been selected for high and low oil every year since 1896.
- Breeders choose only among **variation that already exists**, and a breed or crop from a few chosen parents often has **lower genetic variation**: more inherited disorders, or a crop open to one disease.

PART SELECTED	VEGETABLE
Leaves	Kale
Terminal bud	Cabbage
Side buds	Brussels sprouts
Stem	Kohlrabi
Flower heads	Broccoli, cauliflower

Natural the environment selects
People add an antibiotic, but no one picks which bacteria live.

Artificial a person selects
The breeder picks who reproduces: the biggest cobs.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Organisms do not change because they need to.** Variation arises first, by chance; selection sorts it.
- ✕ **An individual never evolves.** Individuals are selected; the population changes over generations.
- ✕ **DDT did not cause the mutations.** The alleles were already there; DDT changed who survived to reproduce.
- ✕ **Fittest does not mean strongest.** Write "reproductive success" or "offspring" every time you write fitness.
- ✕ **Selection, natural or artificial, never makes new alleles.** Only mutation does.

COVER THE SHEET

Can you *answer these?*

1. Describe the steps of natural selection in a drought.
2. Explain why a trait gained in life is not inherited.
3. Identify how evolutionary fitness is measured.
4. Predict the next generation if beak depth were not heritable.
5. Explain how a fluctuating environment changes selection.
6. Predict the resistance allele's frequency once DDT stops.
7. Describe two ways molecules in cells vary.
8. Explain why a crop breed can lose genetic variation.

IN THE EXAM

Write the chain in full: heritable variation, a named selective pressure, differential survival and reproduction, a change in the population over generations. Never "the finches adapted because they needed to".

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

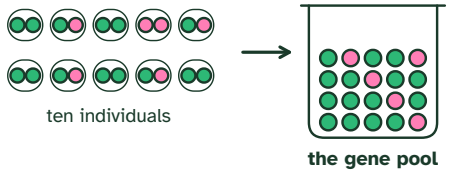
AP BIOLOGY | UNIT 7 | TOPICS 7.4, 7.5 AND 7.11 | REVISION ON TWO PAGES

Evolution, *counted*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Evolution is a change in allele frequencies. Mutation, drift and gene flow move them by chance; Hardy-Weinberg says what no change looks like.



14 of 20 copies: A = 0.7

6 of 20 copies: a = 0.3

add to 1

Count each heterozygote once for each allele. Ten individuals, twenty copies.

7.4.C START HERE

Count the *alleles*, not the animals

- A **gene pool** is every allele that the members of a population carry. A diploid population of N individuals holds **2N copies** of each gene.
- An **allele frequency** is one allele's share of those copies, from 0 to 1. For two alleles the frequencies add to 1. A **genotype frequency** is something else: the share of individuals with one genotype.
- **A change in allele frequencies** over generations is **evidence that a population is evolving**, whatever caused it.

200
copies in 100 diploid mice: 30 BB, 50 Bb, 20 bb

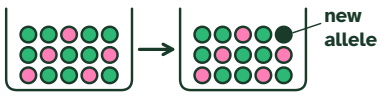
0.55
frequency of B: (2 × 30 + 50) ÷ 200

0.45
frequency of b: (2 × 20 + 50) ÷ 200

7.4.A 7.4.B NEW ALLELES

Mutation

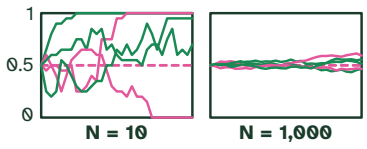
- Mutation is a **random process** that adds new genetic variation. It is the **only source of new alleles**.
- New alleles give **new phenotypes** for natural selection to act on.
- It is random with respect to need: bacteria that grow on an antibiotic plate carried resistance **before** they met the drug.
- For one gene it is rare, so alone it changes frequencies slowly.



7.4.A 7.4.B CHANCE

Genetic *drift*

- **Genetic drift** is a change in allele frequencies by chance, a **nonselective process**: which individuals breed, and which allele each passes on.
- Its effect **depends on population size**: largest in small populations. It can **lose an allele** or fix one, and let a small population **diverge**.



7.4.A TWO KINDS OF DRIFT

Bottlenecks and *founders*

- **Bottleneck effect**: cut to a few for at least one generation. **Founder effect**: a few start a new population.
- Numbers recover; **lost alleles do not**.

BOTTLENECK
Elephant seals
About 20 in the 1890s, over 200,000 now; variation still very low.

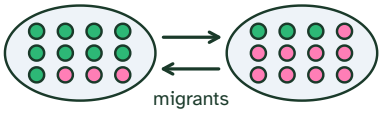
BOTTLENECK
Black robin
5 birds in 1980, one breeding female; all descend from her.

FOUNDER
Old Order Amish
A recessive syndrome far commoner, from one couple of the 1740s.

7.4.A 7.4.B ALLELES THAT MOVE

Gene flow keeps populations *alike*

- **Migration** can result in **gene flow**: alleles added to or removed from a population, but only when migrants **breed**.
- It changes frequencies when migrants' frequencies differ, and so it **prevents divergence** into separate species.
- **Examples:** prairie chickens brought into Illinois from 1992; a wildlife overpass.



7.4.A 7.4.C THE FOUR, TOGETHER

Four ways a gene pool *changes*

PROCESS	RANDOM?	WHAT IT DOES
Mutation	**Yes**	Makes new alleles, slowly, with no regard for need.
Genetic drift	**Yes**	Moves frequencies by chance; strongest in small populations.
Gene flow	**Yes**	Mixes gene pools; makes populations more alike.
Natural selection	**No**	Favors the phenotypes that leave more offspring in that environment.

The course calls mutation, drift and migration random processes.

Hardy-Weinberg, chi-square and why *diversity* matters

7.5.A THE MODEL

A population where *nothing happens*

- **Hardy-Weinberg equilibrium** models allele frequencies in a population that is **not evolving**.
- Its conditions are **never all met**, yet it is useful as a **null hypothesis**: what you would see if nothing were acting.
- Nonrandom mating alone changes **genotype** frequencies (more homozygotes), not allele frequencies.

CONDITION	RULES OUT
B **Large population**	Genetic drift
M **No migration**	Gene flow
M **No new mutations**	New alleles
R **Random mating**	Pairing by genotype
S **No natural selection**	Unequal survival

Big Mice Must Run Slowly

7.5.A ALLELES, THEN PEOPLE

Two *equations*, two ways in

- **$p + q = 1$** is about **alleles**. **$p^2 + 2pq + q^2 = 1$** is about **genotypes**: AA, Aa, aa.
- **Have all three counts?** Count the alleles: always valid. **See only the recessive phenotype?** It is q^2, so $q = \sqrt{q^2}$; this **assumes equilibrium**.
- **Carriers:** 1 in 2,500 affected gives $q^2 = 0.0004$, $q = 0.02$, $2pq = 0.0392$, about 1 in 25.

sperm \ eggs	A p = 0.6	a 0.4
A 0.6	**AA** $p^2 = 0.36$	**Aa** 0.24
a 0.4	**Aa 0.24**	**aa** 0.16

7.5.A 7.4.C CHI-SQUARE

Is this population *evolving*?

- **Null hypothesis:** the population is in equilibrium for this gene, so any difference between observed and expected counts is **due to chance**.
- Count alleles for p and q; expect p^2N, $2pqN$ and q^2N. $\chi^2 = \Sigma(o - e)^2 \div e$.
- The course's rule: 3 classes minus one, so **2 degrees of freedom**, critical value **5.99** at $p = 0.05$. Above it, **reject**; at or below, **fail to reject**, never "accept".

200 MICE	AA	Aa	aa
Observed	90	60	50
Expected	72	96	32
$(o - e)^2 \div e$	4.5	13.5	10.125

$p = 0.6$, $q = 0.4$. $\chi^2 = 28.125 > 5.99$: reject. Too few heterozygotes

7.11.A RESILIENCE

Less *diversity*, less to select from

- A population's ability to respond to a changed environment depends on its **genetic diversity**. Diverse populations are **more resilient**: some individuals can withstand a new pressure.
- Little diversity raises the risk of **decline or extinction**. **Irish potato famine** (1845 to 1852): one clonal variety, the Lumper, fell to the water mold *Phytophthora infestans*.
- An allele **adaptive in one environment** may be **deleterious in another**. One **sickle cell** allele protects against severe malaria; two cause disease.

22 IN 1982
Condor
All 27 in captivity by 1987; 561 in 2022.

18 CAUGHT
Ferret
Nearly all descend from 7 of them.

UNDER 50
Prairie chicken
Eggs failed; birds brought in from 1992.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Natural selection is not random.** Mutation, drift and migration are the random processes.
- ✕ **p is not the dominant phenotype.** p and q are allele frequencies; the dominant phenotype is $p^2 + 2pq$.
- ✕ **Recovered numbers are not recovered diversity.** Only mutation or gene flow adds alleles back.
- ✕ **Drift acts in every population,** not only tiny ones; it matters most where the population is small.
- ✕ **Gene flow needs breeding.** A migrant that leaves no offspring adds no alleles.

COVER THE SHEET

Can you *answer these?*

1. Calculate p and q for 98 GG, 84 Gg and 18 gg.
2. Explain why drift matters more in small populations.
3. Describe a bottleneck and a founder effect.
4. Predict the effect of gene flow on two populations.
5. Identify the five Hardy-Weinberg conditions.
6. Calculate 2pq when 16% show the recessive trait.
7. Justify rejecting a null hypothesis with $\chi^2 = 28.1$.
8. Explain why a clonal crop is at risk from disease.

IN THE EXAM

Write down what p and q stand for before any number, and say when you assume equilibrium. Allele frequencies changing over generations is the evidence of evolution; one count is not.

GO FURTHER

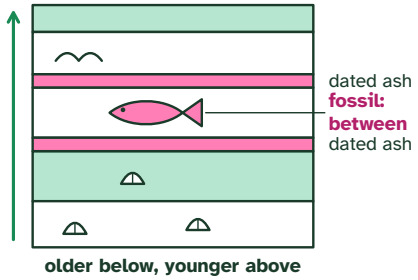
Animated figures, a dry lab and a marked Check are in the full guide online.

How we *know*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Rocks, bones and sequences, read apart, tell one story of common ancestry. A tree of it is a hypothesis, read at its nodes.



Date the ash, not the fossil. Sedimentary rock holds the fossils; volcanic layers hold the clock.

7.6.B START HERE

Reading the *rocks*

- A **fossil** is the preserved remains or traces of an organism from the past. In undisturbed sedimentary rock, **lower layers are older**: an order, not an age in years.
- For years, use a **radioactive isotope**, which decays at a fixed rate, its **half-life**. **Carbon-14** (about 5,730 years) dates once-living material up to about 50,000 years.
- Older rock needs slower isotopes. **Potassium-40** (half-life about 1.25 billion years; about a tenth decays to argon-40) is measured in **volcanic ash**, so a fossil between two dated ash layers gets an age between theirs.
- **Transitional forms** share features with extinct and extant groups: *Tiktaalik*, about 375 million years old, had gills and scales and limb-like fins.

½	¼	⅛
left after one half-life	after two: 11,460 years for carbon-14	after three

7.6.A EVIDENCE FROM MANY DISCIPLINES

Five kinds of data, one *story*

KIND	WHAT IT READS	ONE EXAMPLE
Geographical	Where species live, and where fossils are found.	Galápagos finches are most like birds of South America, the nearest mainland.
Geological	Rock layers and the fossils in them.	Fossils appear in a consistent order, layer on layer.
Physical	Radioactive decay at fixed rates.	Rocks and once-living material given ages in years.
Biochemical	DNA and protein sequences.	Close relatives have more similar sequences.
Mathematical	Counting.	Allele frequencies over generations; the changes a tree needs.

Methods that are independent and agree give strong support, not proof.

7.6.B ANATOMY

Same bones, *different jobs*

- **Homologous structures** share one plan from a **common ancestor**: the forelimbs of a human, bat, whale and horse.
- **Vestigial structures** are reduced remnants of structures fully formed in relatives: a whale's pelvis, a python's spurs. They are homologies too.
- Same job, different origin is **analogous**: a bird's wing and an insect's.
- **Vestigial is not useless:** a whale's pelvic bones anchor muscles used in mating. They are reduced from an ancestor's.



7.6.B MOLECULES

Sequences *remember* ancestors

- After two lineages split, mutations build up separately in each, so **fewer differences** means a **more recent common ancestor**.
- DNA changes faster than protein, so it separates close relatives. **Cytochrome c:** chimpanzee identical to human, rhesus 1 difference, yeast over 40.
- Nearly all life uses DNA and **the same genetic code**: evidence of one common ancestor of all of it.

human	A T G G C T A A G C T T	
chimpanzee	A T G G C T A A G C T T	0
mouse	A T G G C A A A G C T C	2
chicken	A T C G C A A G G C T A	4

Made-up sequence; pink bases differ from the human.

7.7.A CELLS AND GENOMES

What every *eukaryote* shares

- All eukaryotes share structural and functional features that point to **one common ancestor**.
- A complex feature built the same way in all of them was far more likely **inherited once** than evolved again and again.
- These are **typical of** eukaryotes, not found only in them.

MANY
Membrane-bound organelles
Nucleus, mitochondria, ER, Golgi.

LITTLE
Linear chromosomes
Strands with two ends.

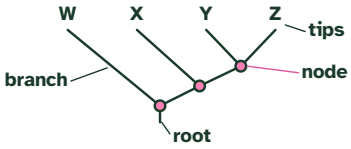
INTERRUPTIONS
Introns
Cut out of the RNA by a spliceosome.

Trees: read them, build them, *revise* them

7.9.A 7.9.B READING

Read a tree by its *nodes*

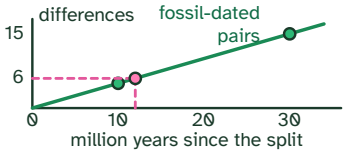
- Phylogenetic trees and cladograms show **hypothetical evolutionary relationships**, and can be tested.
- Each **node** is the **most recent common ancestor** of what branches from it: a speciation that has happened. The root is the ancestor of all.
- Follow two tips back to where they meet. Nodes **spin**, so tip order means nothing.



7.9.A CALIBRATING

Cladogram or tree, and *time*

- A **cladogram** shows **branching order only**; a **phylogenetic tree** also shows **change over time**.
- Time comes from **fossils** of known age and a **molecular clock**: differences build up at a roughly steady rate, so **time = differences ÷ rate**.
- It gives an estimate: generation time and selection change the rate.

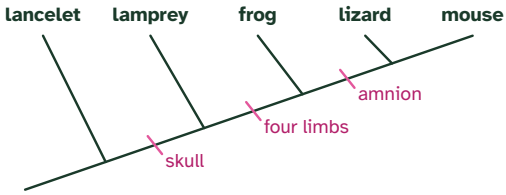


7.9.A BUILDING

From a table to a *cladogram*

	SKULL	LIMBS	AMNION
Lancelet			
Lamprey	✓		
Frog	✓	✓	
Lizard	✓	✓	✓
Mouse	✓	✓	✓

- The **out-group**, least related to the rest, shows the **ancestral** states.
- A **shared derived character** arose in a common ancestor and is in more than one descendant lineage. A trait everyone has groups no one.
- The trait most share is nearest the root. Where data clash, prefer the **fewest changes**.



7.9.B 7.8.A

Trees are *revised*, and evolution goes on

- Trees are built from **morphology** (living or fossil) and from **DNA and protein sequences**. **Molecular data** are typically **more accurate and reliable**: a character at every site, while similar body traits can evolve separately.
- Trees are **constantly revised**: in 2001 chloroplast DNA broke up the figwort family, grouped by its flowers.
- **All species continue to evolve.** Four kinds of evidence:

EVIDENCE	ONE CASE
Genomes	*E. coli* since 1988: 75,000 generations by 2022.
Fossils	Plankton shells change gradually, layer on layer.
Resistance	MRSA (1961), glyphosate (1996), tumor cells.
New diseases	2009 flu: pig, bird, human segments.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Carbon-14 does not date dinosaurs.** They are 66 million years old; carbon-14 reaches 50,000.
- ✕ **Humans did not evolve from chimpanzees.** Both are living tips with a shared ancestor.
- ✕ **Read nodes, not neighbors.** Tips side by side need not be close relatives.
- ✕ **A cladogram's line lengths mean nothing.** Read time only on a tree with an axis.
- ✕ **Single-celled does not mean prokaryote.** Amoebas and yeasts are eukaryotes.

COVER THE SHEET

Can you *answer these?*

1. Calculate the age of a bone with ⅛ of its carbon-14.
2. Describe how a fossil in sedimentary rock is dated.
3. Explain why homologous limbs support common ancestry.
4. Identify three features shared by all eukaryotes.
5. Explain why a cladogram shows no time.
6. Calculate a split: 12 differences, 1 per 2 million years.
7. Justify using DNA over body traits to build a tree.
8. Describe one piece of evidence that evolution continues.

IN THE EXAM

Name the data and what it shows: "the same bones in the same order, so inherited from a common ancestor". On a tree, quote the node where two tips meet.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

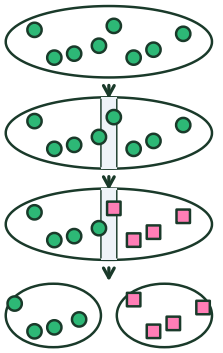
AP BIOLOGY | UNIT 7 | TOPICS 7.10 AND 7.12 | REVISION ON TWO PAGES

One species becomes *two*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

A new species forms when populations stop sharing alleles and diverge. Life began in a window the rocks mark out, perhaps with RNA first.



The river changes no animal. It stops gene flow; selection, mutation and drift do the changing.

7.10.A START HERE

Speciation starts when gene flow *stops*

- The **biological species concept**: a species is a group that can interbreed and exchange genes to produce **viable, fertile offspring**.
- **Speciation** occurs when two populations become **reproductively isolated**. While they interbreed, gene flow keeps their gene pools alike and prevents divergence.
- Once gene flow stops, **selection, mutation and drift** act on each side separately, and the differences build up until the split is permanent.
- **Example:** chimpanzees north of the Congo River and bonobos south of it; neither swims, and their ancestors were divided roughly 1 to 2 million years ago.

TWO TESTS OF THE OFFSPRING

V Viable — the offspring survive

F Fertile — they can breed in turn

7.10.A THE CONCEPT

What makes a *species*

- **Looks do not decide it; breeding does.** A Great Dane and a Chihuahua are one species; two meadowlarks that look alike, each answering only its own song, are two.
- A horse and a donkey make a healthy mule, but it is **sterile**, so no alleles pass on: **two species**.
- The concept is for sexual reproduction. It **cannot be applied** to asexual organisms or fossils, which are grouped by structure and DNA.

64 chromosomes in a horse

62 in a donkey

63 in a mule: they cannot all pair at meiosis

7.10.C TWO ROUTES

Apart, or in the *same place*

- **Allopatric speciation**: populations are **geographically isolated** by a sea, river, mountain range or distance.
- **Sympatric speciation**: populations have **geographic overlap**, and something else stops them interbreeding.
- Both end in reproductive isolation; they differ in **geography**.

Apple maggot fly sympatric, under way
Flies mate on the fruit they lay in. Since the 1860s some use apples, which ripen weeks before hawthorns, so the two groups mostly mate apart.

Still one species host races
Some flies still cross between the groups, so gene flow has fallen but not stopped.

7.10.C PREZYGOTIC AND POSTZYGOTIC

What keeps two species *apart*

BARRIER	WHEN	ITS NAME, AND ONE CASE
P Place	Prezygotic	**Habitat isolation:** one garter snake lives mostly in water, another on land.
T Time	Prezygotic	**Temporal isolation:** two skunks breed in late winter and in late summer.
B Behavior	Prezygotic	**Behavioral isolation:** every firefly species flashes its own courtship pattern.
F Fit	Prezygotic	**Mechanical isolation:** snails whose shells coil opposite ways cannot mate.
G Gametes	Prezygotic	**Gametic isolation:** sea urchin sperm proteins match only their own eggs.
Hybrid dies	Postzygotic	**Reduced hybrid viability:** most sheep and goat embryos die early.
Hybrid sterile	Postzygotic	**Reduced hybrid fertility:** the mule.
Its young fail	Postzygotic	**Hybrid breakdown:** some rice hybrids are fertile, but their offspring are weak or sterile.

Ask first: did a zygote ever form? If not, the barrier is prezygotic.

Both kinds prevent gene flow.

How fast, which way, and how life *began*

7.10.B DIVERGENT

One ancestor, *many forms*

- **Divergent evolution**: adaptation to new habitats gives **phenotypic diversification**.
- In **adaptive radiation**, speciation is especially fast as **new habitats become available**: new islands or lakes, or habitats emptied by extinction.
- **Hawaiian *Drosophila*:** flies reached the island chain once or a very few times, on older islands now worn below the sea, and became on the order of a thousand species.
- **Darwin's finches:** about 18 species from one ancestor, each beak suited to its food.

7.10.B CONVERGENT

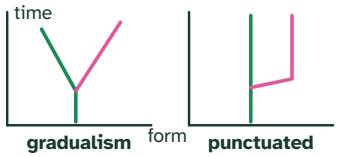
Different lineages, *one shape*

- **Convergent evolution**: **similar selective pressures** give similar adaptations in different populations or species.
- The traits arose separately: **analogous, not homologous**. Looking alike is weak evidence of relatedness.
- **Caribbean anoles:** each large island has twig, trunk and canopy forms, yet DNA shows each twig anole is closest to anoles on its own island.
- A shark and a dolphin; cacti and some euphorbias in two deserts.

7.10.B

Slow and steady, or long waits and *bursts*

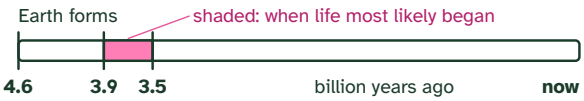
- **Gradualism**: evolution occurs **slowly**, over hundreds of thousands to millions of years.
- **Punctuated equilibrium**: **rapid change after a long period of stasis**. Rapid means thousands of years and many generations, never one.
- Both are in the fossil record. Stasis fits a steady environment; a burst fits new habitats. The evidence is long stasis, **not gaps**.



7.12.A WHEN

The window the *rocks* give

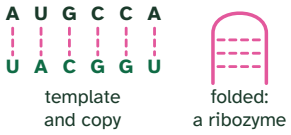
- Geological evidence supports models of the origin of life. Rocks are dated by **radioactive isotopes**.
- Earth formed about **4.6 bya**; it was **too hostile** for life (hot, struck from space) until about **3.9 bya**; the earliest fossils date to about **3.5 bya**.
- The oldest are **stromatolites**, mounds built by microbial mats, about 3.48 billion years old, in the Pilbara of Western Australia.
- The oldest fossils are the **latest** date by which life had begun, not its start. The window gives **when, not how**.



7.12.A HOW, PERHAPS

Why RNA may have come *first*

- The **RNA world hypothesis**: RNA could have been the **earliest genetic material**. It stores information in its bases, and some RNAs catalyze reactions: **ribozymes**.
- In every ribosome, RNA forms the peptide bond. No RNA that **fully copies itself** has been made yet.



1 **Copies**
RNA replication kept continuity.

2 **Pairs**
It needs base pairing.

3 **No proteins**
Proteins were not the catalysts.

WATCH OUT

Five mistakes that *cost points*

- ✕ **"They can mate" is not the test:** the offspring must be viable and fertile.
- ✕ **Both routes end in reproductive isolation;** they differ in geography.
- ✕ **No offspring is not always postzygotic:** did a zygote form?
- ✕ **Looking alike does not mean related:** convergence makes analogous traits.
- ✕ **The RNA world is a hypothesis,** not a proven account.

COVER THE SHEET

Can you *answer these?*

1. Describe the biological species concept.
2. Explain why horses and donkeys are two species.
3. Explain how a river can lead to two species.
4. Identify the barrier: two frogs breed in different months.
5. Describe the conditions for an adaptive radiation.
6. Explain how unrelated lizards come to look alike.
7. Describe gradualism and punctuated equilibrium.
8. Justify RNA, not DNA, as the first genetic material.

IN THE EXAM

Name what stops gene flow, then what makes the sides differ: "a barrier stops gene flow; different selection, mutation and drift make the gene pools diverge".

GO FURTHER

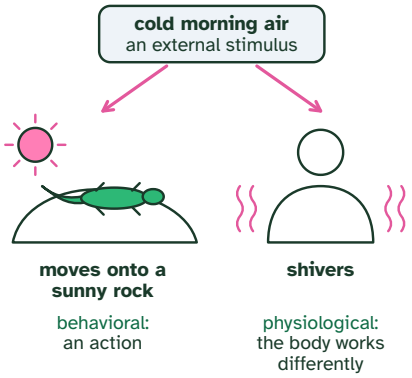
Animated figures, a dry lab and a marked Check are in the full guide online.

A change, then a *response*

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Organisms detect changes and respond to them. Responses that raise survival and reproductive success are favored by natural selection.



Sort by what happens, not by speed: an action is behavioral, a change in the body's workings is physiological.

8.1.A START HERE

Every response answers a *change*

- A **stimulus** is a change an organism can detect: **outside** it (light, cold, a predator) or **inside** it (falling blood sugar, rising body temperature). The **response** is what it does about it.
- A **behavioral response** is an action: the organism moves, calls, hides or feeds. A **physiological response** changes how its body works: it shivers, sweats or releases a hormone.
- Many responses are both: a hot dog pants and lies in the shade. Either way, responding keeps an organism alive and able to reproduce as conditions change.

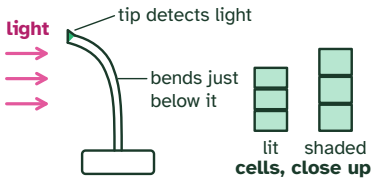
TWO KINDS OF RESPONSE — *Does, or Works*

B Behavioral — what the organism does	**P** Physiological — how its body works

8.1.A PLANTS GROW

Phototropism

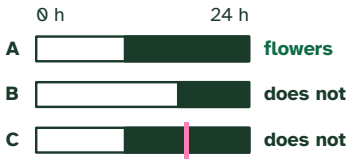
- A shoot lit from one side grows **toward the light**: cells on its **shaded side grow longer** than cells on its lit side.
- It is **growth, not movement**. The tip detects the light and the region below it bends, so a **signal** must pass between them (Darwin and his son, 1880).
- Turned to the light, the leaves catch more for photosynthesis.



8.1.A PLANTS TIME IT

Photoperiodism

- Many plants flower at one season, cued by day and night length. They flower together, when pollinators are about.
- The cue is the **longest unbroken night**. A minute of light in the middle of a long night stops plant C flowering.
- A **"short-day" plant** flowers when nights are longer than its **critical night length**: really a long-night plant.

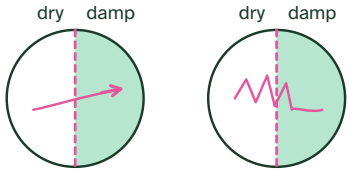


C: a minute of light at night

8.1.A ANIMALS MOVE

Taxis or *kinesis*

- **Taxis**: movement directly toward or away from a stimulus. Its track points.
- **Kinesis**: a change in **speed or turning** with no direction. Pill bugs walk fast and turn often in dry air and slow down where it is damp, so they gather there.
- Both gather animals; only the track tells them apart. Nocturnal and diurnal animals time activity to light and dark.



8.1.A SCIENCE PRACTICE 3.C

Testing a *response*

- **Choice chamber:** pill bugs are released between a damp and a dry dish and counted at the end.

CHANGE	MEASURE
Independent variable Damp or dry paper.	**Dependent variable** The count on each side.
HOLD **Controlled** Light, temperature, number released.	**COMPARE** **Control** Both sides damp.

Release at the join, use fresh animals each trial, then a chi-square test on the counts.

8.1.A INTERNAL CHANGES, EXTERNAL CUES

Changes inside, and *news* between organisms

- A stimulus can be **internal**: thirst sends an animal to drink. Organisms also **exchange information**: one bird calls at a hawk and the flock dives.

Fight or flight physiological, for a behavior
A threat is seen: **epinephrine** raises heart rate and blood sugar. Then the animal runs or hides.

A chewed plant chemicals on the air
Damaged leaves release airborne chemicals; a neighbor downwind **detects them** and raises its defenses.

Signals, learning and *cooperation*

8.1.B EACH SUITS A PLACE

Five kinds of *signal*

- **Communication**: a sender makes a signal, a receiver detects it, and **the receiver's behavior changes**. No change, no communication.

SIGNAL	SUITS	EXAMPLE
V Visual	Light and a clear line of sight	Fireflies flash in their own pattern.
A Audible	The dark, and around obstacles	A songbird sings at its territory edge.
T Tactile	Close up only	Bees in a dark hive follow a dancer.
E Electrical	Water too muddy to see in	Electric fish signal with pulses.
C Chemical	Lasts after the sender leaves	Ants lay a scent trail to food.

In order: *Very Active Toads Eat Crickets*

8.1.B FOUR USES

What signals are *for*

- A signal changes who survives and who leaves offspring: **differential reproductive success**.

1 **Dominance**
A contest settled without a fight.

2 **Food**
Others are led to it.

3 **Territory**
Held by song or scent at its edges.

4 **A mate**
Found and won by a display.

Vervet monkeys give different alarm calls for a leopard, an eagle and a snake, and each sends the troop a different way.

8.1.B TWO SOURCES

Innate or learned

- **Innate** behavior needs no experience: a spider's first web. **Learned** behavior changes with it.
- Most is both, and either is **favored by natural selection** when it raises survival and reproduction.
- **Test it:** raise young apart from adults. White-crowned sparrows raised so sing abnormally: they must hear their species at about 10 to 50 days old.

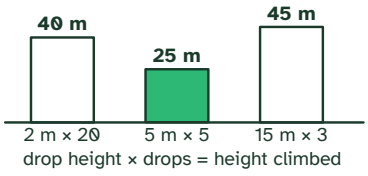
Innate works first time
Best where a mistake kills.

Learned fits a changing world
Best where conditions vary.

8.1.B FITNESS

Cost and *payoff*

- A behavior costs **energy, time and risk** and pays in food, mates or safety. Those it pays best leave more offspring, so its alleles spread.
- **Foraging:** crows drop whelks onto rocks. Height × drops is the cost, least near 5 m, where the crows drop from.
- **Courtship:** a long tail costs risk but wins mates. **Parents** feed the chicks that beg hardest.



8.1.B WHY HELP

Cooperation

- Hunting in a pack, moving as a herd, flock or school, living in a colony and warning others **raise the fitness of the individual** and the **survival of the population**.
- A wolf pack brings down prey no single wolf could; in a school, each fish is less likely to be taken.
- **Alarm calls** risk the caller. Female Belding's ground squirrels, living among relatives, call most: relatives share its alleles (**kin selection**).

102
predator encounters watched

4
summers, in the 1970s

WATCH OUT

Five mistakes that *cost points*

- ✕ **A response need not be quick, or by an animal.** A shoot bending and a plant flowering are responses too.
- ✕ **Kinesis is not random movement.** Its speed and turning depend on the stimulus, which is why the animals gather.
- ✕ **A plant "measuring day length" is measuring the night.** The names give no season.
- ✕ **Innate does not mean fixed, and learned does not mean free of genes.** The ability to learn is inherited.
- ✕ **Never "for the good of the species".** A behavior spreads when those doing it, or their relatives, leave more offspring.

COVER THE SHEET

Can you *answer these?*

1. Describe two kinds of response to cold.
2. Explain how a shoot grows toward light.
3. Explain what a "short-day" plant measures.
4. Describe how a track shows taxis rather than kinesis.
5. Identify the control in a choice chamber test.
6. Justify a sound signal for animals in a dark forest.
7. Describe how to test whether a song is learned.
8. Explain how a risky alarm call can be favored.

IN THE EXAM

Stimulus, response, payoff: name the change, say what the organism does, then how that raises survival or reproduction. In a design question, name the independent and dependent variables and justify the control.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

AP BIOLOGY | UNIT 8 | TOPIC 8.2

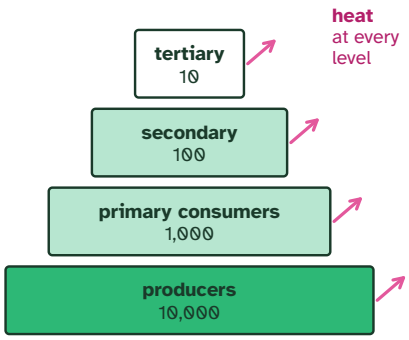
REVISION ON TWO PAGES

Energy *flows*, matter cycles

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Energy enters as light, passes up the trophic levels and leaves as heat: never recycled. Atoms are conserved and cycle between reservoirs.



kJ per m² per year, at one tenth a step

Draw it like this. Each bar as wide as the energy it holds; heat leaves every level.

8.2.B START HERE

Energy flows up, then *leaves as heat*

- Each feeding step is a **trophic level**: producers, then primary, secondary and tertiary consumers. An arrow points **from the eaten to the eater**, the way the energy goes.
- Most of a level's energy is **not passed on**. Only what is built into **new tissue** can be eaten: often about a tenth, though it **varies widely**.
- So each level holds less than the one below and food chains are short, **seldom over four or five levels**.
- Heat cannot become chemical energy again: **energy is never recycled**. Efficiency = energy at one level ÷ the level below × 100.

WHERE A LEVEL'S ENERGY GOES

Rabbit: 60 heat, 30 feces, 10 tissue

R Respired released as heat	**N** Not eaten roots, bark, bones	**F** Feces never absorbed	**G** Growth the only part passed on

8.2.B SMALL TO LARGE

Levels of *organization*

- Energy flows through an ecosystem; **matter cycles** within it. Living parts are **biotic**; temperature, water, minerals and light are **abiotic**.

P **Population** One species in one area.	C **Community** All the populations there.
E **Ecosystem** The community and its surroundings.	B **Biome** A kind of ecosystem set by climate.

Please Come Eat Breakfast

8.2.D TWO WAYS TO FEED

Make it or *take it*

- **Autotrophs** capture energy from their surroundings and make carbon compounds from carbon dioxide.
- **Heterotrophs** eat organic matter that came from autotrophs: herbivores, carnivores, omnivores, scavengers and decomposers.

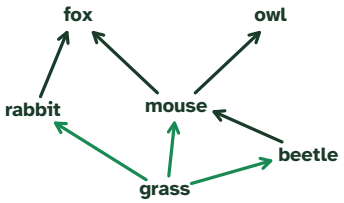
Photosynthetic from light
Plants, algae, cyanobacteria. What they store is the **primary productivity**.

Chemosynthetic from inorganic reactions
Bacteria at deep-sea vents oxidize **hydrogen sulfide**, in total darkness.

8.2.B 8.2.C WHO EATS WHOM

Food chains and *webs*

- A **food web** is chains that share members. Draw producers at the bottom, then **one arrow per eating pair**, food to eater.
- Name the level **along each chain**: a mouse eating seeds is a primary consumer; eating a beetle, a secondary one.
- Decomposers are fed by **every level**.



8.2.D 8.2.C THE ENERGY AT THE BASE

Primary *productivity*

- **Primary productivity**: the rate producers store energy in new organic matter, per area per year. **Light, water, temperature and nutrients** limit it: high in a rainforest, low in a desert or the tundra.
- Producers respire too, day and night. What consumers can use is **what producers fix minus their own respiration**.
- **Light and dark jars:** the dark jar's fall in oxygen is respiration; the light jar's rise is what was made beyond that. Together, all that was made.

+1.6 mg/L in the light: made minus used	**−1.4** mg/L in the dark: used	**3.0** mg/L made in all

8.2.C ENERGY AVAILABILITY

Change the *energy*, change everything

- Less light or fewer producers means **less energy at every level** above, so populations shrink all the way up.
- The **top level**, smallest to start with, may **disappear**: the web loses a level. More energy at the base can support larger populations and, in time, another level.
- **Off Peru:** in an El Niño year cold upwelling weakens, phytoplankton fall, and anchovies and seabirds crash.

−25% producers: 18,000 kJ in place of 24,000	**All** levels above fall by about a quarter

8.2.A ENDOTHERMS AND ECTOTHERMS

One animal's *energy budget*

- Energy in as food, out as heat, movement and upkeep. A **net gain** means storage, growth and more offspring; a **net loss**, mass lost, fewer offspring and in the end death.

	ENDOTHERM	ECTOTHERM
Heat	From its own metabolism	From its surroundings
Body	Held steady, as near 37 °C	Follows the air, unless behavior changes it
Cost	**High: much food**	**Low: little food**
Cold	Respires more food to stay warm	Cools and slows down

Endotherms: birds and mammals. Ectotherms: most other animals. Never say cold-blooded.

8.2.A REPRODUCTIVE STRATEGIES

Breed when the *food* is there

- Reproduction costs energy, so organisms **match its timing and kind to the energy available**.

1 **Seasonal**
Chicks hatch when caterpillars peak.

2 **Switch**
Water fleas clone while food lasts, then make males and tough fertilized eggs.

3 **Store first**
Biennial carrots store food, then flower the next year.

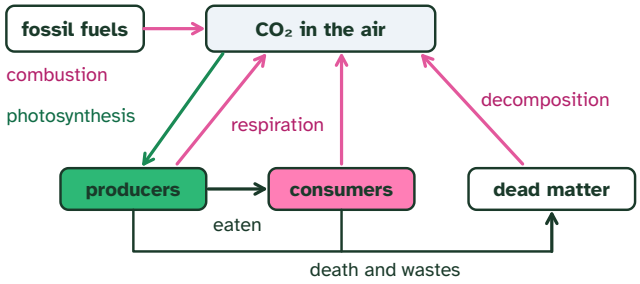
4 **Pause**
Monarchs that fly south breed only the next spring: diapause.

Asexual is fast; sexual gives varied offspring.

8.2.B FOUR PARTS

The *carbon* cycle

- A **biogeochemical cycle**: reservoirs, living and not, and the processes between them. **Matter is conserved**, only used again.
- Carbon enters life by **photosynthesis** and returns as carbon dioxide by **respiration, decomposition and combustion**.

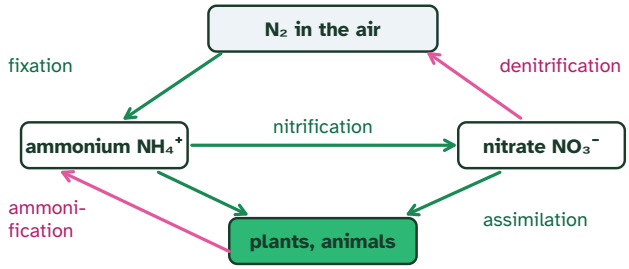


WATER
Oceans, surface water, air, life
Evaporation, transpiration, condensation, precipitation.

8.2.B FROM THE AIR

The *nitrogen* cycle

- The air is about **78% N_2**, which most organisms cannot use. **Fixation** by bacteria, free in soil or in legume root nodules, makes ammonium. Plants take up **nitrate and ammonium** through roots. *Farmers Need All Available Dirt.*



PHOSPHORUS
Rock; no gas at all
Weathering releases phosphate; decomposition and excretion return it. Slowest, so often limiting.

WATCH OUT

Five mistakes that *cost points*

- ✕ **Energy is never recycled.** It leaves as heat; decomposers release it as heat too. Only matter cycles.
- ✕ **Arrows point from eaten to eater.** Grass to rabbit to fox, the way the energy goes.
- ✕ **"About a tenth" is not a law.** Work from the numbers given.
- ✕ **Plants respire day and night.** They photosynthesize as well as respiring, not instead.
- ✕ **A tree's mass comes mostly from the air.** Carbon enters as carbon dioxide; the soil gives water and minerals.

COVER THE SHEET

Can you *answer these?*

1. Explain why food chains seldom have over five levels.
2. Calculate efficiency: 2,160 kJ from 24,000 kJ.
3. Identify the energy source of bacteria at a deep-sea vent.
4. Predict which level is lost first if the producers fall.
5. Explain why a mouse eats more than a lizard at 10 °C.
6. Explain why water fleas switch to sex as food runs short.
7. Describe how a carbon atom in the air can reach a fox.
8. Describe how nitrogen in the air reaches a protein.

IN THE EXAM
Energy and matter are different stories: energy flows one way and leaves as heat; atoms cycle. Name the process on every arrow, and for a calculation show (new − old) ÷ old × 100 with units.

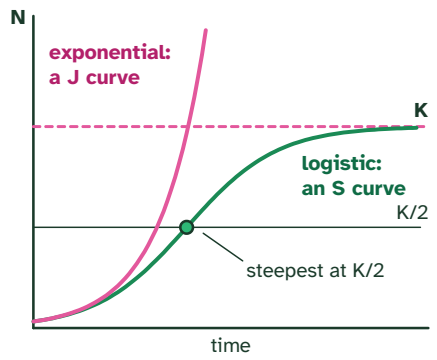
GO FURTHER
Animated figures, a dry lab and a marked Check are in the full guide online.

Populations *grow*, communities interact

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

Births minus deaths set how a population grows, until resources hold it near K. Interactions between species drive the sizes of their populations.



Draw it like this. K as a dashed line; the S curve levels off at it, the J curve never does.

8.3.A 8.4.A START HERE

Three equations, two *curves*

- **Growth: dN/dt = B − D**, births minus deaths per unit time. Positive, N grows; zero, it holds. Divide by N for a **per capita** rate.
- **Exponential: dN/dt = rmaxN**. With no constraints the per capita rate stays at its maximum, but the number added keeps rising: a **J curve**.
- **Logistic: dN/dt = rmaxN (K − N)/K**. The bracket is the share of K still free, so growth slows to zero at K: an **S curve**, steepest at K/2.
- All three are on the **formula sheet**: use them, do not learn them.

DENSITY-DEPENDENT FACTORS — *Crowded People Dislike Waiting*

C	**Competition**	less food and space each
P	**Predation**	prey easier to find
D	**Disease**	spreads faster up close
W	**Wastes**	build up in a crowd

8.3.A ONE SPECIES, ONE PLACE

A *population*

- The individuals of **one species in one area**, interacting with each other and their environment. Its size is **N**.
- Adaptations for getting and using **energy and matter** set how fast a species breeds and how long it lives.
- **Example:** 800 frogs, 240 born and 180 dead in a year.

60 dN/dt, frogs per year

0.075 per frog per year

8.3.A NOTHING IN THE WAY

Exponential growth

- It happens when a few individuals have **plentiful resources**: a new island, a fresh flask. It never lasts.
- With rmax = 0.5 per year, 1,200 add 600 a year and 2,400 add 1,200.
- Doubling each generation from 1 gives 1,024 after 10 generations and over a million after 20.
- On a **log scale** the J curve is a straight line: the easiest way to spot it.

29 reindeer, St. Matthew Island, 1944

6,000 about, by 1963

8.4.A WHAT STOPS IT

Carrying capacity

- **K**: the number of a species its environment's resources can sustain. It can change.
- A population that **overshoots K** can crash: St. Matthew's reindeer ate their lichen and only 42 were alive in 1966.

Density-dependent bites harder when crowded
A larger share is affected the denser the population.

Density-independent the same share
A frost kills 30% at any density. It is not harmless.

8.4.A FILL IN THE BRACKET FIRST

Logistic growth, *worked*

N	(K − N)/K	RMAXN	DN/DT PER YEAR	WHAT IT MEANS
100	0.9	40	**36**	Few breeders, plenty of room.
500	0.5	200	**100**	Half of K: the fastest growth.
900	0.1	360	**36**	Many breeders, little room.
1,000	0	400	**0**	At K births equal deaths; they have not stopped.
1,200	−0.2	480	**−96**	Above K, N falls back toward K.

K = 1,000 and rmax = 0.4 per year.

From data: 400 adding 96 with K = 2,000 gives rmax = 0.3

Communities: who gains, who loses, and *diversity*

8.5.B HELPED, HARMED OR UNAFFECTED

Five interactions, scored for *each side*

INTERACTION	SIGNS	EXAMPLE	WHAT IT DOES TO POPULATIONS
Competition	**– / –**	Two *Paramecium* on one food	Both get less; one may be lost.
Predation	**+ / –**	Lynx and hare; herbivory too	Each drives the other's numbers.
Parasitism	**+ / –**	A tick on a deer	Host deaths rise or births fall.
Mutualism	**+ / +**	Coral and the zooxanthellae in its cells	Lose the partner and K falls.
Commensalism	**+ / 0**	Barnacles riding on a whale	One gains; the other barely changes.

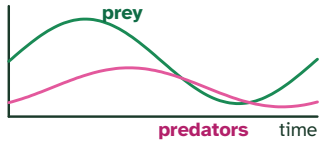
A **community**: interacting populations of different species in one place.

The three symbioses: *My Cat Purrs*

8.5.B EACH DRIVES THE OTHER

Predator and *prey*

- More prey, more predators; more predators, fewer prey; then the predators starve and the prey recover. **Predator peaks lag the prey's**.
- Isle Royale's moose: 840 in 2024, about 524 in 2026, a change of **–38%**.



8.5.B SHARING A RESOURCE

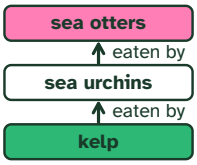
Competition and *niches*

- **Gause:** *P. aurelia* drove out *P. caudatum*, though nothing ate it; *P. bursaria*, eating yeast at the bottom, lived beside it.
- **Niche partitioning**: using different parts of a resource, as MacArthur's five warblers did in one spruce forest.
- **Connell:** with *Semibalanus* gone, *Chthamalus* lived lower: competition can **set where a species lives**.

8.5.B AND COOPERATION

Trophic cascades

- A **trophic cascade**: a change at one level passes down the chain, **each level moving the other way**.
- **Cooperation** changes what a population can reach: a wolf pack brings down a moose.



8.5.A ON THE FORMULA SHEET

Species *diversity* as a number

- **Composition:** which species. **Species diversity**: how many, how evenly shared.
- **Simpson's Diversity Index = 1 – Σ(n/N)²**: 0 for one species, toward 1 for many evenly shared.

0.75
counts 5, 5, 5, 5: squares sum to 0.25

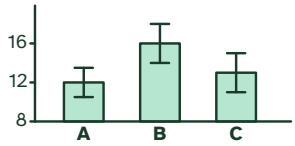
0.27
counts 17, 1, 1, 1: squares sum to 0.73

0.54
a stream net of 12, 6 and 2

8.5.A ERROR BARS

Do two means *differ*?

- Error bars of **± 2 standard errors** give about a 95% confidence interval.
- **No overlap:** the means probably differ. **Overlap:** no evidence of a difference, not proof of none.



WATCH OUT

Six mistakes that *cost points*

- ✕ **dN/dt is not per capita** until it is divided by N.
- ✕ **Exponential growth:** rmax is constant, not the number added.
- ✕ **Births do not stop at K.** They are matched by deaths.
- ✕ **Competition is – / –:** even the winner loses out.
- ✕ **Diversity is not the number of species.** Evenness counts too.
- ✕ **Symbiosis is not another word for mutualism.** A parasite and its host are a symbiosis too.

COVER THE SHEET

Can you *answer these?*

1. Calculate dN/dt for 400 animals, 60 born and 60 dead.
2. Calculate dN/dt with rmax 0.4, N 250 and K 1,000.
3. Identify a flood as density-dependent or not. Justify it.
4. Predict what the hares do if the lynx are trapped out.
5. Explain how sea otters decide whether kelp grows.
6. Explain how niche partitioning lets competitors coexist.
7. Calculate Simpson's index for counts of 10, 6 and 4.
8. Identify which pair of sites in the graph differs.

IN THE EXAM

Equation, numbers, units: "individuals per year". For an interaction, give each species its sign and say which rate it changes, births or deaths.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.

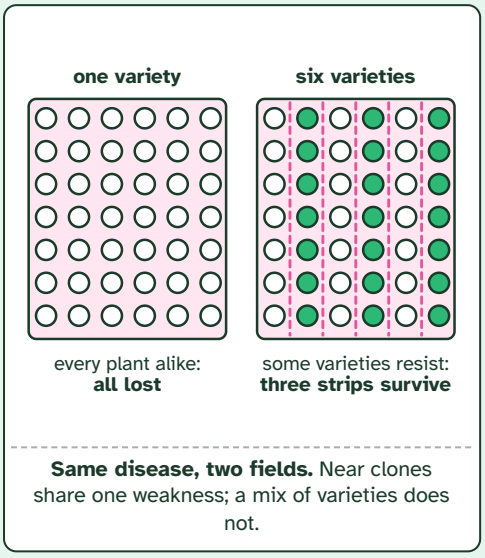
AP BIOLOGY | UNIT 8 | TOPICS 8.6 AND 8.7 | REVISION ON TWO PAGES

Diversity, and what *disrupts* it

What to know, what to draw and what to say. Nothing else.

THE ONE IDEA

An ecosystem with more parts, and more variety among them, keeps its structure through change. Mutation, invaders, people and the planet keep changing it.



Same disease, two fields. Near clones share one weakness; a mix of varieties does not.

8.6.A START HERE

Fewer parts, less *resilience*

- An ecosystem's **parts** are its species, the variety within each species, and its abiotic factors.
- **Resilience**: keeping its structure through a change in the environment, or returning to it afterward. It does not mean nothing changes.
- Ecosystems, natural or artificial, with **fewer parts and little diversity among them** are **often** less resilient: one change can hit every part the same way.
- **Example:** Irish potatoes in 1845 were mostly one variety, grown from tubers, so blight ruined the crop year after year; about a million people died.

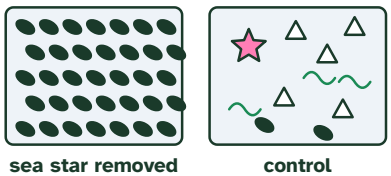
WHAT MAINTAINS DIVERSITY — *Plants And Bees Keep*

P Producers the food, often the habitat	**A** Abiotic water, light, nutrients	**B** Biotic pollinators, decomposers	**K** Keystone far beyond its numbers

8.6.A 8.6.B RARE BUT VITAL

Keystone species

- A **keystone species** has an effect on its ecosystem **far out of proportion to its abundance**. Remove it and the ecosystem often collapses.
- **Paine, from 1963:** he kept the sea star *Pisaster* off one strip of shore. Mussels, the strongest competitors for space, took over.
- **Sea otters** too: where they were hunted out, urchins grazed the kelp forests to bare rock.
- It can be a predator, a herbivore, a plant or a habitat builder.



8.6.B FOLLOW THE CHAIN

Add or remove a *part*

- Any part added or removed **changes the structure** of the ecosystem.
- **Short term:** what it ate and what ate it change first. **Long term:** species further along the web, and the habitat itself.
- **Predict as a chain:** the direct effect, then each knock-on effect, every link with a "because".

WHEN	BEAVERS RETURN
Months	Willows and aspens are cut for dams.
A year	The stream backs up into a pond.
Years	Still-water animals move in; ground becomes wetland.

8.7.A THEN SELECTION

The variety comes *first*

- **Mutations are random**: not directed by what the environment needs. The environment then **selects** among the variants already there.
- An **adaptation** is a genetic variation favored by selection, shown as a trait that helps **in a particular environment**.
- **Heterozygote advantage**: the heterozygote has a higher relative fitness than either homozygote, so both alleles stay.

0.90 two normal alleles	**1.00** one of each	**0.20** two sickle cell alleles

Relative fitness where malaria is common: each survival count ÷ the highest (invented numbers).

8.7.A HETEROZYGOTE ADVANTAGE

Sickle cell and *malaria*, an example to reason with

- One sickle cell allele and one normal allele protect against **severe malaria**. Two sickle cell alleles cause **sickle cell disease**.
- So where malaria is common the heterozygote leaves the most offspring.

With malaria the heterozygote is fittest
Selection keeps both alleles in the population.

Malaria gone no advantage left
The allele slowly falls: most copies sit in healthy heterozygotes, out of selection's reach.

61

Invaders, people and a *moving planet*

8.7.B TWO ROUTES

Invasive species

- An **invasive species**, introduced by people, spreads and changes its new ecosystem; most introduced species never do. Either way it goes, **diversity often falls**.

ROUTE 1
A niche free of enemies
Kudzu, a vine from East Asia, left its insects and fungi at home; it now covers trees in the Southeast.

ROUTE 2
Outcompetes the natives
Zebra mussels, carried from Europe in ballast water, filter out the plankton native mussels need.

8.7.B REJECT, OR FAIL TO REJECT

Testing a *claim*

- A decline after an arrival is not proof: compare plots **with and without** the invader.
- **Null hypothesis:** the vine makes no difference. 60 snails: 21 in vine plots, 39 in the others; 30 and 30 expected.
- $\chi^2 = 81 \div 30 + 81 \div 30 = \mathbf{5.4}$, above the critical value of 3.84 (1 degree of freedom, $p = 0.05$): **reject the null**. It is unlikely to be chance, but it does not prove the vine is the cause.

8.7.C EUTROPHICATION, THEN BIOMAGNIFICATION

People: *too much food*, and a poison that climbs

- Human impact **accelerates change**, locally and globally, and drives extinctions. Both processes start with something people add.

1 **Nutrients in** Nitrate, phosphate from fertilizer.

2 **Bloom** The algae multiply.

3 **Shade** Plants below die.

4 **Death** Algae die and sink.

5 **Decomposers** Respire the oxygen away.

6 **Fish die** Too little oxygen.

- A substance **not broken down or excreted**, stored in fat, becomes **more concentrated at each trophic level**: each eater keeps what was in all its prey.
- DDT thinned eagles' eggshells; the United States banned it for general use in 1972.



water 0.00005 ppm · plankton · small fish · larger fish · cormorant 26.4 ppm

8.7.D THEY CHANGE HABITATS AND WHERE ECOSYSTEMS ARE FOUND

A planet that *moves*: geological and meteorological events

EVENT	TIME SCALE	WHAT IT DOES TO HABITATS
Continental drift	Tens of millions of years	Carries whole ecosystems: the same land fossils lie on continents now apart.
Climate change	Decades	Ranges move toward the poles and uphill.
El Niño	Months	Trade winds weaken; upwelling off Peru fails; plankton, anchovies and seabirds fall.
Meteor impact	A day	Chicxulub, about 66 million years ago, left an iridium layer worldwide.

Biogeography, where species live and lived, is the evidence.

Slowest first: *Drifting Climates Even Meteors*

WATCH OUT

Six mistakes that *cost points*

- ✕ **Mutations are not made to order.** Selection acts on them.
- ✕ **Keystone is not "top predator".** It is an effect beyond its numbers.
- ✕ **The sickle cell allele is not harmless.** Two copies cause the disease.
- ✕ **Decomposers use up the oxygen.** Living algae make it.
- ✕ **Introduced is not invasive.** Most never spread.
- ✕ **Resilient is not unchanged.** It keeps, or gets back, its structure.

COVER THE SHEET

Can you *answer these?*

1. Describe what makes an ecosystem resilient.
2. Explain why a rare sea star can be a keystone species.
3. Predict the effects of removing a predator.
4. Calculate relative fitness for 450, 500 and 100 survivors.
5. Explain why fish die in a eutrophic lake.
6. Explain why a top predator holds the most DDT.
7. Identify the two routes by which an invader spreads.
8. Justify drift from fossils of one land animal.

IN THE EXAM

Name the cause, then the chain: nutrients, bloom, death, decomposers, low oxygen. With data, state the null, compare χ^2 with the critical value, then reject or fail to reject.

GO FURTHER

Animated figures, a dry lab and a marked Check are in the full guide online.