

Cells (Unity and diversity) revision notes

Cells are the basic structural unit of all living organisms. This group covers the structure of prokaryote and eukaryote cells and the microscopy used to study them, how the first cells may have arisen on the early Earth (HL), and the structure, life cycles and evolution of viruses (HL).

For IB Diploma Biology, Standard Level and Higher Level (first assessment 2025). **HL only** is additional higher level content, for HL students only.

1 Origins of cells Spec A2.1 HL only

Early Earth and the first carbon compounds Spec A2.1.1, A2.1.4

Earth formed about 4.5 billion years ago. Conditions on the early Earth were very different from today, and these differences explain how the first **carbon compounds** could have formed before any life existed (pre-biotic formation).

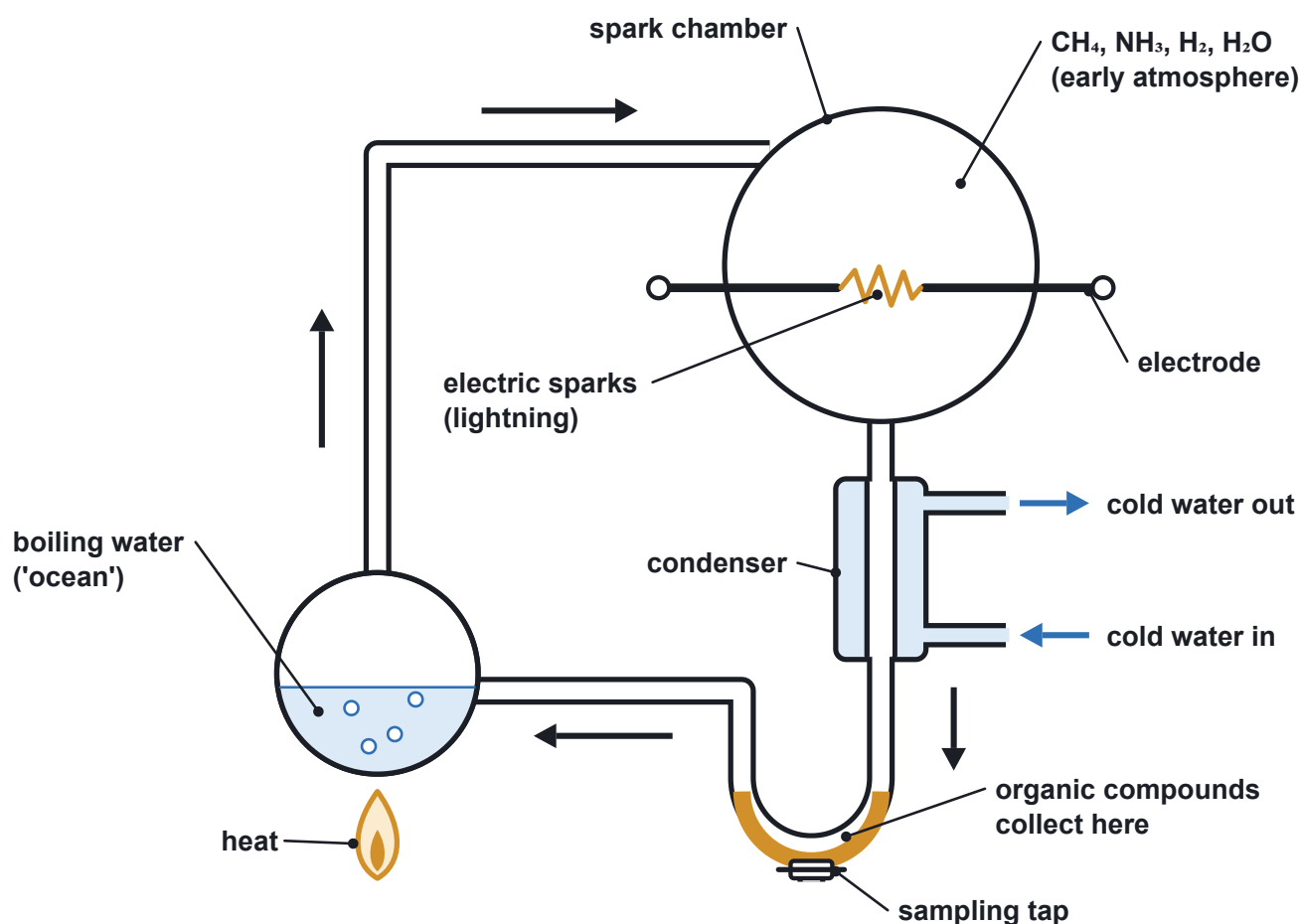
Conditions on early Earth		
Feature	Early Earth	Consequence
Free oxygen (O₂)	Little or none in the atmosphere	Newly formed carbon compounds were not broken down by oxidation
Ozone layer	Absent, because ozone (O ₃) forms from oxygen	Ultraviolet light penetrated to the surface and supplied energy for reactions
Carbon dioxide and methane	Much higher concentrations than today	Strong greenhouse effect, so higher temperatures
Other energy sources	Frequent lightning, volcanic activity and meteorite impacts	Energy to break and form chemical bonds

Under these conditions a variety of carbon compounds, such as amino acids, sugars and nucleotide bases, may have formed **spontaneously by chemical processes that do not now occur**. Today such compounds would not build up, because oxygen in the atmosphere oxidises them and living organisms quickly consume them.

Evidence: the Miller-Urey experiment

In 1952–53, Miller and Urey tested whether carbon compounds could form from inorganic molecules under conditions thought to resemble the early Earth.

1. Water was boiled in a flask to produce water vapour, representing the ocean and evaporation.
2. The vapour mixed with methane (CH₄), ammonia (NH₃) and hydrogen (H₂), representing an early atmosphere with no oxygen.
3. Electrodes produced continuous sparks in the gas mixture, simulating lightning as an energy source.
4. A condenser cooled the gases, so water and any dissolved products fell like rain into a trap and returned to the flask.
5. After about a week the liquid had turned brown. Analysis showed several amino acids, including glycine and alanine, and other carbon compounds.



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The Miller-Urey apparatus: sparks act as **lightning** in an early-atmosphere gas mixture, and the condensed products collect in the trap.

Evaluating the experiment

Evaluating the Miller-Urey experiment	
Aspect	Evaluation
Main finding	Strength: it showed that amino acids and other carbon compounds can form from inorganic molecules with no living organisms present.
Control and repeatability	Strength: the sealed, sterilised apparatus meant products could not come from contaminating organisms, and the experiment has been repeated many times. Reanalysis of stored samples in 2008 detected more than 20 amino acids.
Gas mixture	Limitation: the early atmosphere is now thought to have been less reducing, with more CO ₂ and N ₂ . Repeats using such mixtures give much smaller yields of amino acids.
Scope	Limitation: it produced monomers only. It did not show how polymers, self-replicating molecules or cells formed.
Realism	Limitation: the exact conditions on early Earth are unknown and cannot be replicated, so the model may not match them.

Amino acids have also been found in some meteorites, which supports the idea that carbon compounds can form by non-biological chemistry.

Exam tip: 'Evaluate' needs strengths and limitations and a judgement: the experiment supports the idea that carbon compounds could form spontaneously, but says nothing about how cells arose.

Living and non-living, and the challenge of the first cells Spec A2.1.2, A2.1.3

Cells are the smallest units of self-sustaining life. A single cell can take in energy and materials, carry out metabolism, keep its internal conditions stable and reproduce. Nothing smaller than a cell, such as an organelle or a molecule, can do all of these on its own.

Living things carry out all the functions of life: metabolism, nutrition, growth, response to stimuli, homeostasis, excretion, movement and reproduction. Non-living things may show one or two of these (a crystal grows, a flame uses oxygen) but not all of them together, and they have no genetic material that is inherited and evolves.

Why viruses are considered non-living

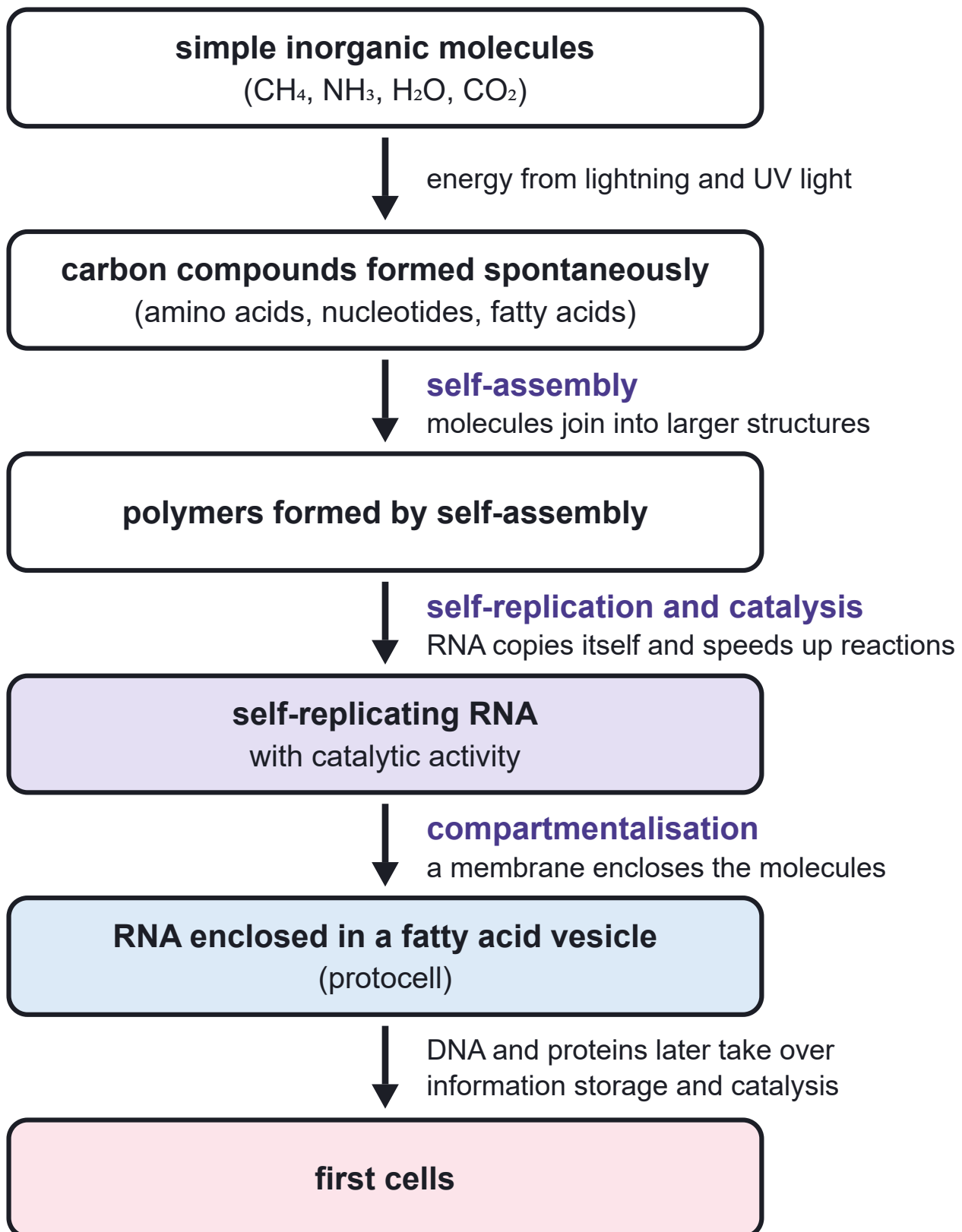
- They are not cells: they have no cytoplasm and no plasma membrane of their own.
- They have no metabolism of their own: they produce no ATP and have few or no enzymes.
- They cannot reproduce independently: they use the host cell's ribosomes, enzymes, ATP, nucleotides and amino acids to make copies of themselves.
- They do not grow, excrete or maintain homeostasis, and outside a host cell they are inert particles.

Viruses do have genetic material and evolve by natural selection, which is why their status is sometimes debated.

The challenge of explaining the origin of cells

Cells are highly complex structures that can **currently only be produced by division of pre-existing cells**. For the first cells to arise from non-living matter, several requirements had to be met.

Requirements for the evolution of the first cells	
Requirement	Why it was needed
Catalysis	Reactions had to be speeded up so molecules could be made fast enough; early catalysts may have been mineral surfaces or RNA
Self-replication of molecules	A molecule had to be copied so that information could be passed on and inherited
Self-assembly	Molecules had to join spontaneously into larger structures, such as polymers and membranes
Compartmentalisation	A membrane boundary had to enclose the molecules so internal chemistry could differ from the surroundings



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From chemicals to the first cells: each step meets one of the requirements for life.

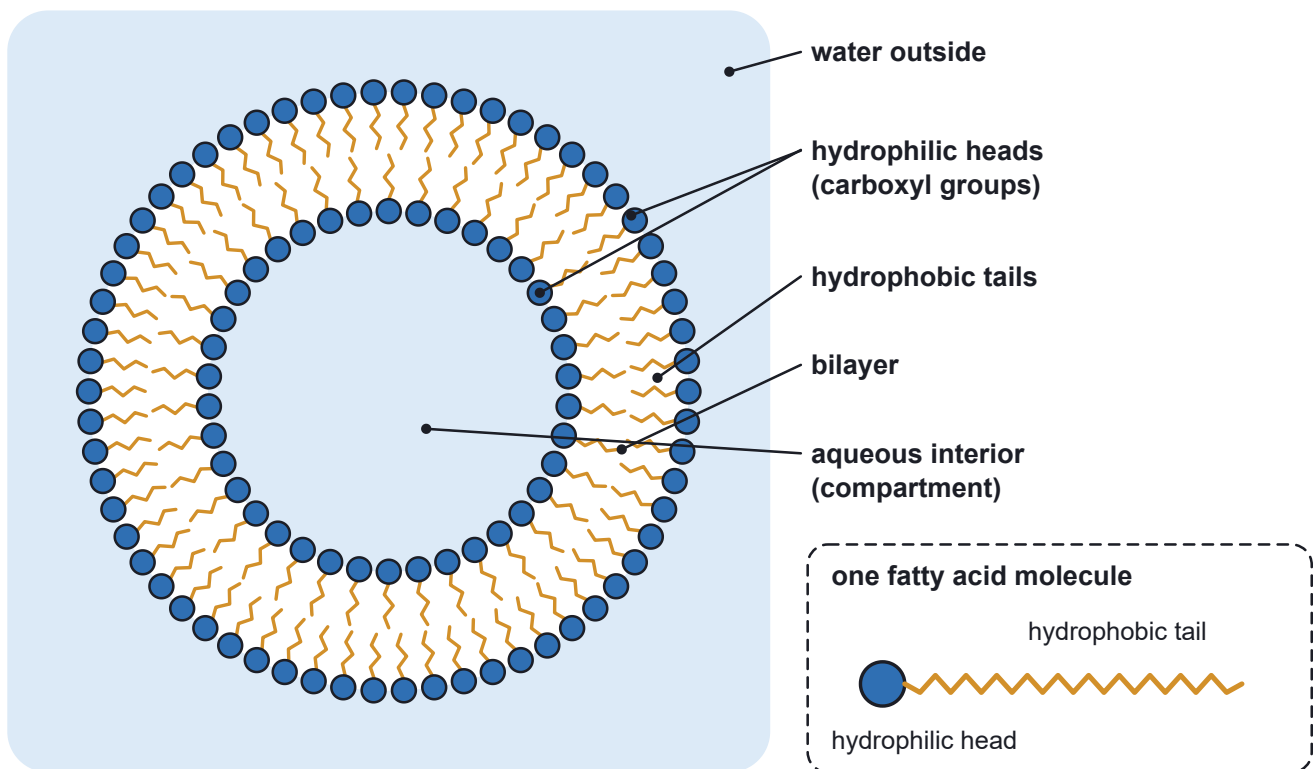
Exam tip: Nature of science: hypotheses must be testable. The exact conditions on pre-biotic Earth cannot be replicated and the first protocells did not fossilise, so hypotheses about the origin of cells are difficult to test.

Vesicles and RNA as the first genetic material Spec A2.1.5, A2.1.6

Fatty acids are **amphipathic**: each has a hydrophilic carboxyl head and a long hydrophobic hydrocarbon tail. In water they **coalesce spontaneously into spherical bilayers**, with the heads facing the water inside and outside and the tails hidden in the middle. These hollow spheres are vesicles.

No enzymes or energy input are needed: the bilayer forms because the hydrophobic tails are excluded from water, and closing into a sphere leaves no exposed edges.

- Formation of a **membrane-bound compartment** allows internal chemistry to become different from that outside the compartment.
- Molecules such as RNA can be concentrated inside, so they meet and react more often.
- Fatty acid vesicles can grow by taking in more fatty acids and can divide, a simple model of how protocells might have reproduced.



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Fatty acids coalesce into a **bilayer vesicle**, enclosing an aqueous compartment.

RNA as a presumed first genetic material

Modern cells store information in DNA and use proteins as enzymes, but each depends on the other: DNA is needed to make proteins, and proteins are needed to copy DNA. RNA can do both jobs, so it is **presumed to have been the first genetic material**, an idea called the RNA world hypothesis.

Why RNA could have been the first genetic material

Property of RNA	Why it matters
Stores information in its base sequence	It can act as genes
Can be replicated by complementary base pairing	Information can be copied and inherited
Has some catalytic activity (ribozymes)	It can act as an enzyme, possibly even helping to catalyse its own replication

Evidence: **ribozymes in the ribosome** are still used to catalyse **peptide bond formation** during protein synthesis. The catalytic site of the ribosome is made of rRNA, not protein. Later, DNA (more stable) probably took over information storage, and proteins (more varied and better catalysts) took over most catalysis.

Exam tip: Linking question: for what reasons is heredity an essential feature of living things? Self-replicating RNA gave the first heritable variation for natural selection to act on.

The last universal common ancestor Spec A2.1.7, A2.1.8, A2.1.9

The **last universal common ancestor (LUCA)** is the most recent population of organisms from which all organisms now living on Earth are descended. It was not the first cell: it already had DNA, ribosomes and a membrane.

Evidence for LUCA

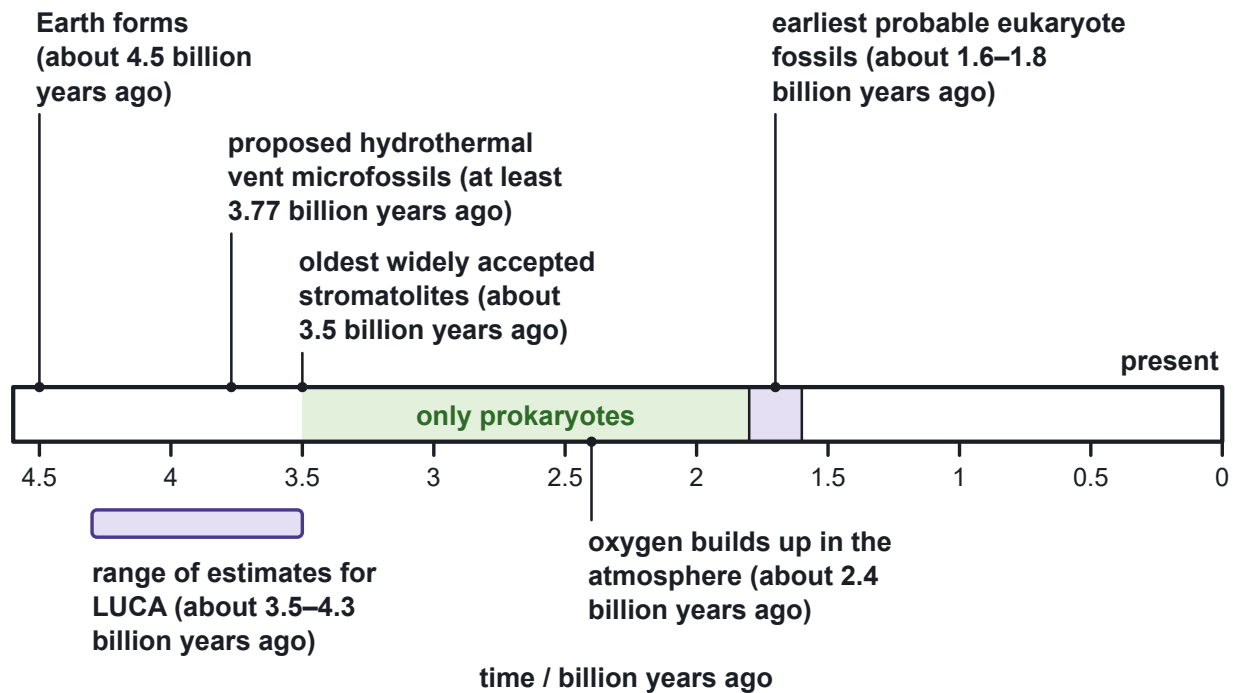
- The **universal genetic code**: almost all organisms use the same codons for the same amino acids. Such an arbitrary code is very unlikely to have evolved identically more than once.
- **Shared genes** across all organisms: genomic studies have identified several hundred genes found in both bacteria and archaea, including genes for ribosomal proteins and for DNA replication, transcription and translation.
- Shared biochemistry: all cells use DNA, ribosomes, ATP and the same 20 amino acids.

Other forms of life probably also evolved, but became extinct, most likely due to **competition from LUCA and its descendants**. This explains why all life today shares one genetic code.

Estimating the dates of the first cells and LUCA

Approaches used to estimate dates	
Approach	How it works
Fossils	Microfossils and stromatolites (layered rocks built by mats of microbes) show that cells were present; the oldest widely accepted stromatolites, from Western Australia, are about 3.4–3.5 billion years old
Radiometric dating	Radioactive isotopes in rocks decay at a known rate (fixed half-life), so the age of the rock containing a fossil is calculated from the ratio of parent isotope to decay product
Carbon isotope ratios	Organisms take up carbon-12 in preference to carbon-13, so carbon enriched in carbon-12 in ancient rocks suggests biological activity
Molecular clock	Differences in the base sequences of conserved genes build up at a roughly constant rate; calibrated with dated fossils, the number of differences estimates when lineages split, back towards LUCA

Earth is about 4.5 billion years old. Evidence for the first cells ranges from widely accepted fossils about 3.5 billion years old to disputed traces that are older: possible vent microfossils at least 3.77 billion years old and carbon enriched in carbon-12 in a 4.1-billion-year-old mineral grain. Molecular clock estimates for LUCA vary widely between studies; a 2024 study put it at about 4.2 billion years ago. Life has therefore been evolving for an **immense length of time**, roughly 4 billion years.



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Life has existed for about 4 billion years, and for roughly 2 billion years only prokaryotes were present.

Evidence that LUCA evolved near hydrothermal vents

Hydrothermal vents on the sea floor release hot, mineral-rich water. They provide energy from chemical gradients, such as dissolved hydrogen, and iron and sulfur minerals that can act as catalysts.

- Fossil evidence: tiny tubes and filaments resembling microbes have been found in ancient sea-floor hydrothermal vent precipitates in rocks from Quebec, Canada, that are at least 3.77 billion years old.
- Genomic evidence: conserved sequences traced back to LUCA include genes for living without oxygen and at high temperatures, for using hydrogen and carbon dioxide, and for many iron-sulfur proteins. These match the conditions at hydrothermal vents.

Common mistake: LUCA was not the first living cell. It was a later, already complex organism; earlier lineages existed but left no surviving descendants.

Quick check

1. Why did ultraviolet light reach the surface of early Earth?
2. Name the four requirements for the evolution of the first cells.
3. Which molecule in the ribosome catalyses peptide bond formation?
4. Give two pieces of evidence for a last universal common ancestor.

2 Cell structure Spec A2.2

Cell theory and structures common to all cells Spec A2.2.1, A2.2.4

Cell theory is one of the most important theories in biology. It states that:

- All living organisms are composed of one or more cells.
- Cells are the **basic structural unit of all living organisms**, and the smallest unit of life.
- Cells only arise from pre-existing cells.

Cell theory was built up from a very large number of observations made with microscopes. It can then be used to make predictions: a newly discovered organism can be predicted to consist of one or more cells.

Exam tip: Nature of science: deductive reasoning generates predictions from a theory. If an observation does not fit, such as cells with many nuclei or none, the theory may need refining.

Structures common to cells in all living organisms

What all typical cells have, and why	
Structure	Reason it is needed
DNA as genetic material	Stores the instructions for making proteins, including enzymes, and can be replicated so that copies pass to daughter cells
Cytoplasm composed mainly of water	Water is the solvent in which most metabolic reactions happen; enzymes and substrates dissolve and move in it
Plasma membrane composed of lipids	A hydrophobic barrier that encloses the cytoplasm, keeps its contents in and controls what enters and leaves

All cells also contain **ribosomes** for protein synthesis, although ribosomes in prokaryotes are smaller than those in the cytoplasm of eukaryotes.

Microscopy skills Spec A2.2.2

Making a temporary mount

1. Place a thin layer of tissue, such as onion epidermis or cells scraped from the inside of the cheek, on a clean slide in a drop of water or stain.
2. Stain to increase contrast: iodine solution for plant cells (stains starch and makes nuclei visible) or methylene blue for animal cells (stains the nucleus).
3. Lower a coverslip at an angle with a mounted needle to avoid trapping air bubbles.
4. Blot away excess liquid with filter paper.

Focusing

1. Start with the low-power objective lens.
2. Use the **coarse adjustment** to bring the specimen roughly into focus.
3. Centre the area you want, then rotate to a higher-power objective.
4. Use only the **fine adjustment** at high power, so the lens does not hit and crack the slide.

Measuring with an eyepiece graticule

An **eyepiece graticule** is a scale in the eyepiece marked in arbitrary units. It is calibrated against a stage micrometer, a slide with a ruled scale (often 1 mm divided into 100 divisions of 10 μm). Calibration is repeated for each objective lens, because the length of specimen covered by one eyepiece unit changes with magnification.

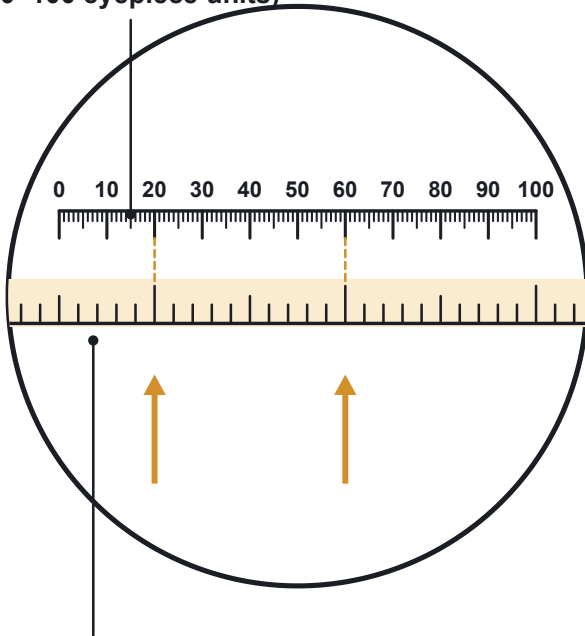
Calibrating a graticule

At $\times 400$, 40 eyepiece units line up with 10 divisions of a stage micrometer. Each division is $10\text{ }\mu\text{m}$. A cheek cell is 24 eyepiece units across. Calculate its actual diameter.

1. 10 stage divisions = $10 \times 10\text{ }\mu\text{m} = 100\text{ }\mu\text{m}$
2. 40 eyepiece units = $100\text{ }\mu\text{m}$, so 1 eyepiece unit = $100 \div 40 = 2.5\text{ }\mu\text{m}$
3. Cell diameter = $24 \times 2.5\text{ }\mu\text{m} = 60\text{ }\mu\text{m}$

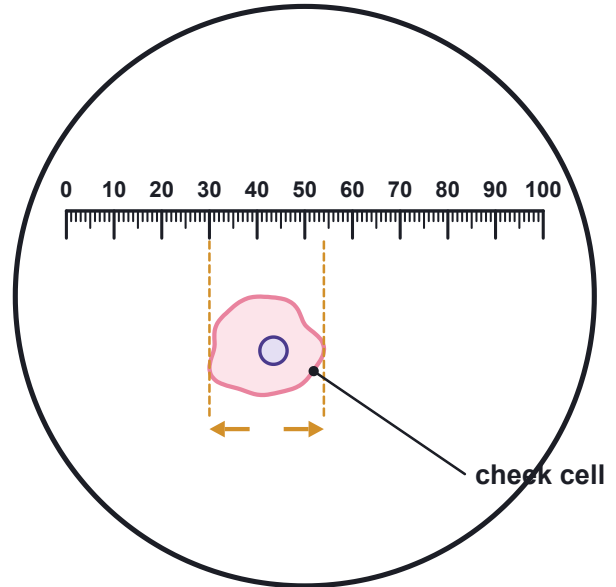
Answer: $60\text{ }\mu\text{m}$

eyepiece graticule
(0–100 eyepiece units)



stage micrometer
(1 division = $10\text{ }\mu\text{m}$)

40 eyepiece units = 10 divisions = $100\text{ }\mu\text{m}$
so 1 eyepiece unit = $100 \div 40 = 2.5\text{ }\mu\text{m}$



cheek cell

cell = 24 eyepiece units across
diameter = $24 \times 2.5\text{ }\mu\text{m} = 60\text{ }\mu\text{m}$

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Calibrating the graticule: $40\text{ eyepiece units} = 100\text{ }\mu\text{m}$, so a cell 24 units across is $60\text{ }\mu\text{m}$ in diameter.

Magnification, actual size and scale bars

magnification = size of image $\div$ actual size of specimen

Rearranged: actual size = size of image $\div$ magnification. Convert to the same units first: $1\text{ mm} = 1000\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m} = 1000\text{ nm}$.

Actual size from a micrograph

A *Staphylococcus* cell is $30\text{ }\mu\text{m}$ across on an electron micrograph with a magnification of $\times 30\text{ }000$. Calculate its actual diameter in μm .

1. Convert the image size to μm : $30\text{ mm} \times 1000 = 30\text{ }000\text{ }\mu\text{m}$
2. actual size = image size $\div$ magnification = $30\text{ }000\text{ }\mu\text{m} \div 30\text{ }000$
3. = $1\text{ }\mu\text{m}$

Answer: $1\text{ }\mu\text{m}$

Producing a scale bar

On the same micrograph ($\times 30\,000$), how long should a scale bar representing $0.5\text{ }\mu\text{m}$ be?

1. image size = actual size $\times$ magnification
2. = $0.5\text{ }\mu\text{m} \times 30\,000 = 15\,000\text{ }\mu\text{m}$
3. $15\,000\text{ }\mu\text{m} \div 1000 = 15\text{ mm}$

Answer: A line 15 mm long, labelled $0.5\text{ }\mu\text{m}$

Maths skill: To find magnification from a scale bar, measure the bar with a ruler, convert it to the unit written on the bar, then divide the measured length by the value on the bar.

Practical skill: Photographs can be taken through the eyepiece with a camera or phone; add a scale bar so sizes can be measured later. Measurement with an instrument is quantitative observation, so record each reading with its uncertainty.

Developments in microscopy Spec A2.2.3

Resolution is the ability to distinguish two points that are close together as separate. Increasing magnification without increasing resolution only gives a bigger, blurred image.

Light and electron microscopes compared		
Feature	Light microscope	Electron microscope
Radiation used	Light	A beam of electrons
Resolution	About $0.2\text{ }\mu\text{m}$ (200 nm)	About 1–2 nm for biological specimens
Useful magnification	Up to about $\times 1500$	Over $\times 100\,000$
Specimens	Living or dead; natural colour can be seen	Dead only, because the specimen is in a vacuum; images are black and white
What it shows	Cells, nuclei, chloroplasts	Ultrastructure: ribosomes, membranes and the inside of organelles

The **advantage of electron microscopy** is its much higher resolution, because electrons have a far shorter wavelength than light. Transmission electron microscopes pass electrons through thin sections to show internal structure. Scanning electron microscopes scan the surface to give 3D images.

Freeze fracture

A sample is frozen rapidly and then cracked with a blade. The fracture often runs along the middle of membranes, between the two layers of lipid. A thin metal replica of the fractured surface is examined with an electron microscope. Freeze fracture revealed **proteins spanning the membrane**, which supported the fluid mosaic model.

Cryogenic electron microscopy (cryo-EM)

Samples are frozen so fast that water forms glass-like ice rather than crystals, which preserves molecules in their natural shape. Thousands of images of individual molecules are combined by computer to build a **3D model of a protein**, often at near-atomic resolution, without the need to crystallise it. Cryo-EM is used to find the structures of membrane proteins and virus capsids.

Fluorescence in light microscopy

- **Fluorescent stains** bind to specific structures, such as DNA, and emit visible light when illuminated with light of a particular wavelength (often ultraviolet). The stained structures glow against a dark

background.

- **Immunofluorescence** uses antibodies carrying a fluorescent marker. Each antibody binds one specific protein (its antigen), so the glow shows exactly where that protein is in the cell. Several proteins can be labelled in different colours at once.

Exam tip: Give a specific advantage: 'higher resolution, so ribosomes and membranes can be seen' scores; 'a clearer picture' does not.

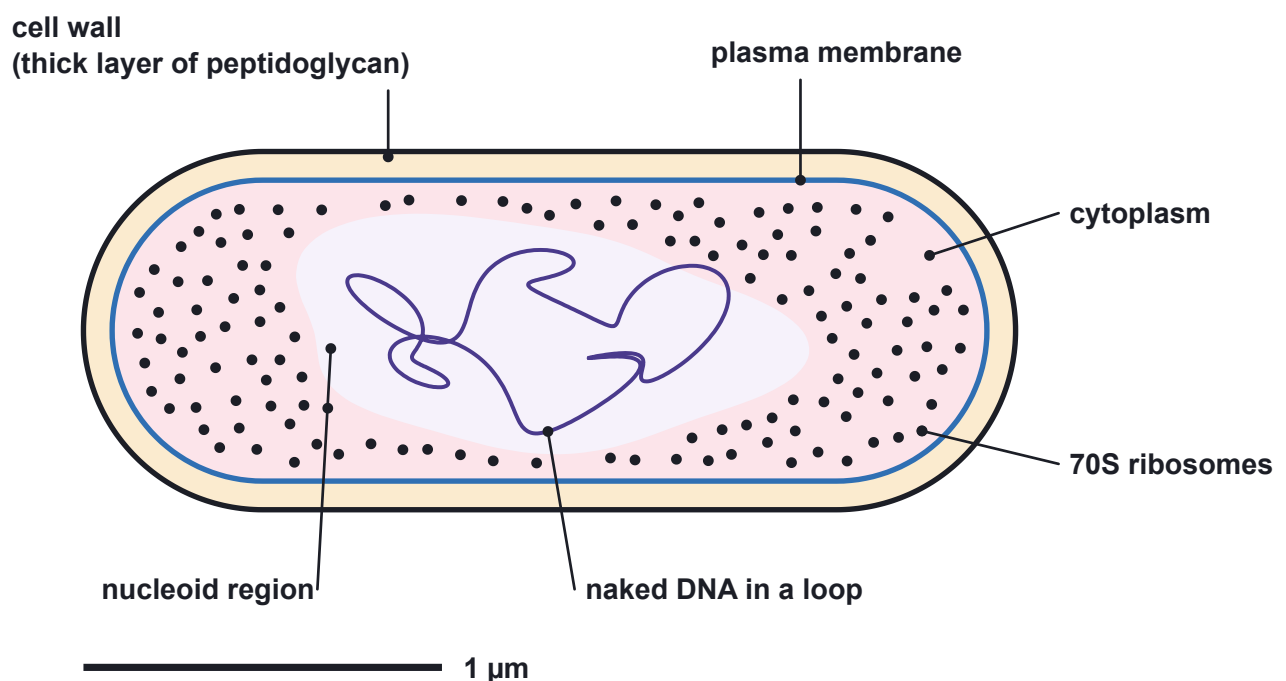
Prokaryote and eukaryote cell structure Spec A2.2.5, A2.2.6

Prokaryote cell structure

Prokaryotes have no nucleus. The structure you need is that of **Gram-positive eubacteria** such as *Bacillus* and *Staphylococcus*.

Components of a Gram-positive bacterium	
Component	Description and function
Cell wall	A thick layer of peptidoglycan outside the plasma membrane, with no outer membrane beyond it; protects the cell and stops it bursting when water enters by osmosis
Plasma membrane	Phospholipid bilayer with proteins; controls the entry and exit of substances
Cytoplasm	Mainly water; the site of metabolic reactions; not divided into compartments
Naked DNA in a loop	A single circular chromosome, not associated with histones, in a region called the nucleoid
70S ribosomes	Smaller ribosomes, free in the cytoplasm, that carry out protein synthesis

Prokaryote cell structure varies. Many prokaryotes also have plasmids, flagella, pili or a capsule, but the details of these variations are not required.



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A Gram-positive bacterium such as *Bacillus*: **naked DNA in a loop** in the nucleoid region, and **70S ribosomes**.

Eukaryote cell structure

- A plasma membrane enclosing a compartmentalised cytoplasm with 80S ribosomes.
- A nucleus with chromosomes made of DNA bound to histones, contained in a double membrane with pores (the nuclear envelope).
- Membrane-bound cytoplasmic organelles: mitochondria, rough and smooth endoplasmic reticulum, the Golgi apparatus and a variety of vesicles or vacuoles, including lysosomes.
- A cytoskeleton of microtubules and microfilaments, which supports the cell, moves organelles and allows some cells to move.

Compartments let enzymes and substrates be concentrated where they are needed, keep potentially harmful enzymes (such as those in lysosomes) away from the rest of the cell, and allow different conditions, such as pH, in different organelles.

Prokaryotes and eukaryotes compared		
Feature	Prokaryote	Eukaryote
Nucleus	Absent; DNA in a nucleoid region	Present, with a double membrane and pores
DNA	Naked and circular	Linear chromosomes bound to histones
Ribosomes	70S	80S in the cytoplasm
Membrane-bound organelles	Absent	Present: mitochondria, ER, Golgi apparatus, lysosomes
Cytoplasm	Not compartmentalised	Compartmentalised
Typical size	About 0.5–5 µm	About 10–100 µm

Common mistake: Do not write that prokaryotes have 'no DNA' or 'no chromosome'. They have DNA, as a single naked loop; what they lack is a nucleus.

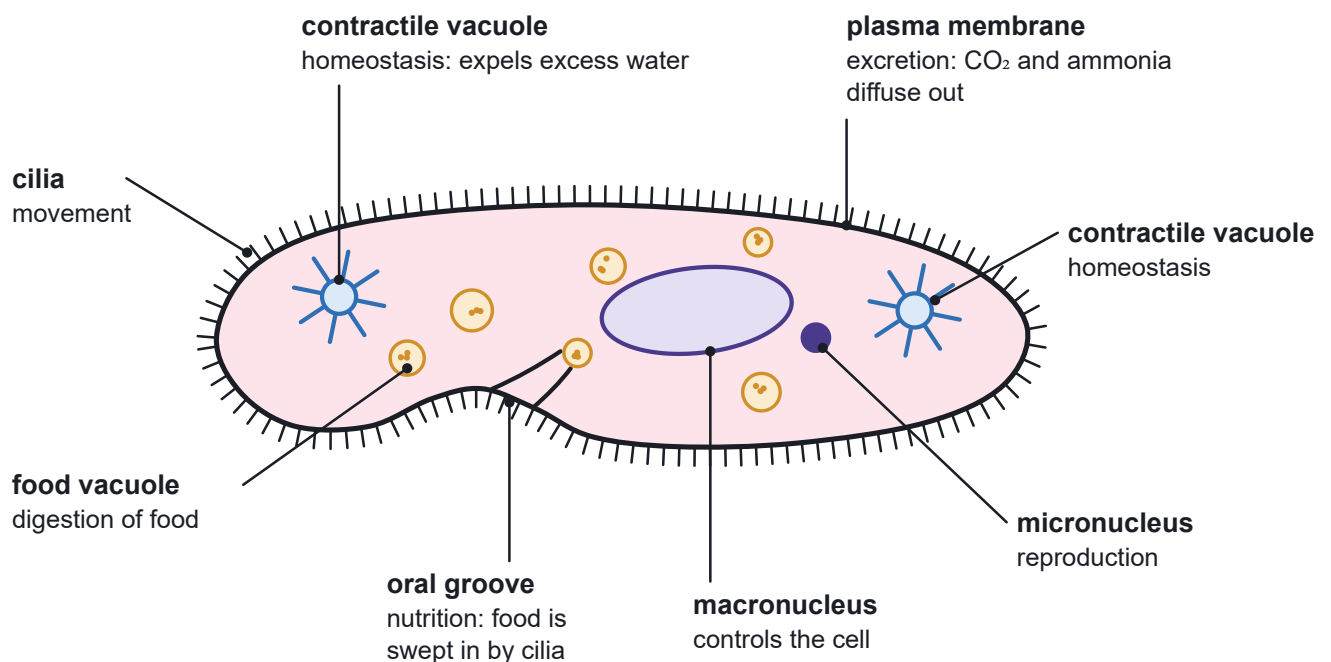
Processes of life in unicellular organisms Spec A2.2.7

A unicellular organism consists of one cell, so that one cell must carry out all the functions of life.

Homeostasis	Keeping internal conditions within narrow limits
Metabolism	All the enzyme-catalysed reactions in the cell
Excretion	Removal of the waste products of metabolism

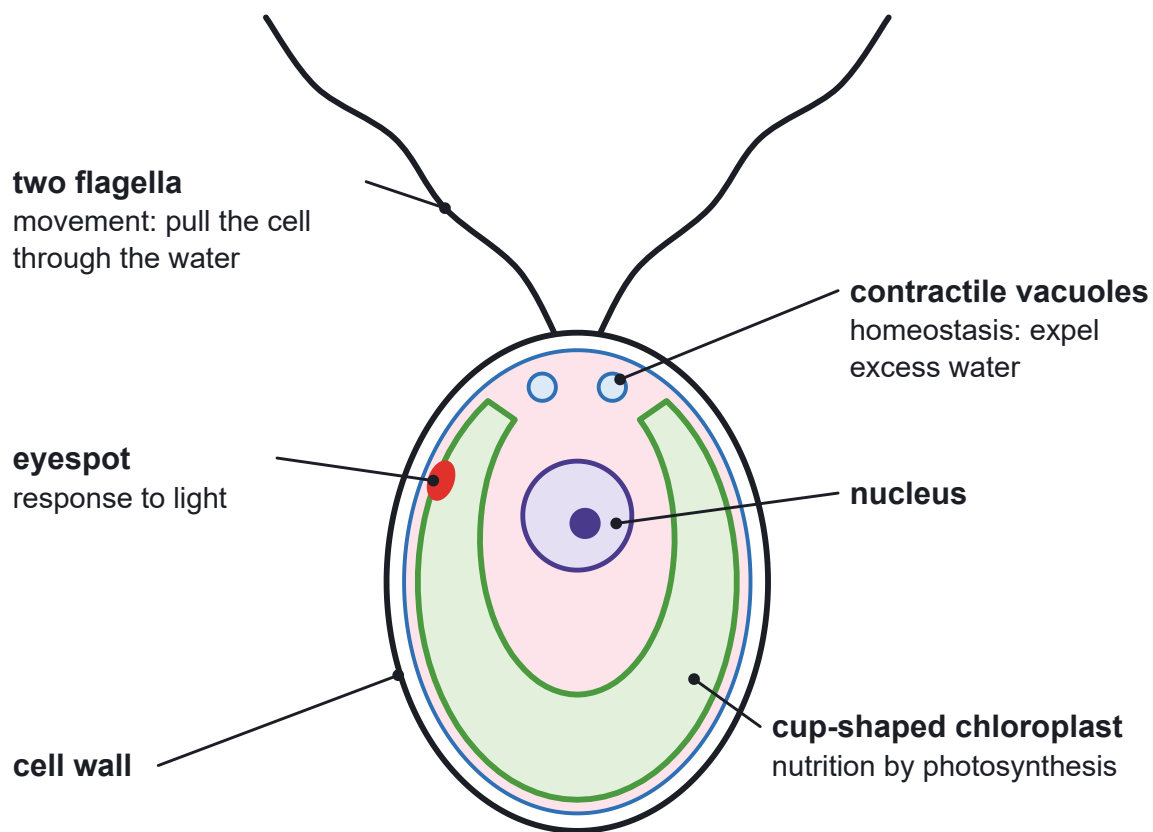
Functions of life in two unicellular organisms

Function	Paramecium (heterotroph)	Chlamydomonas (autotroph)
Homeostasis	Contractile vacuoles collect and expel excess water that enters by osmosis	Contractile vacuoles expel excess water
Metabolism	Enzyme-catalysed reactions in the cytoplasm and mitochondria, including respiration	Reactions in the cytoplasm, mitochondria and chloroplast, including photosynthesis and respiration
Nutrition	Ingests bacteria and other food into food vacuoles, where it is digested	Makes its own food by photosynthesis in a large cup-shaped chloroplast
Movement	Beating cilia over the cell surface	Two flagella pull the cell through the water
Excretion	Wastes such as carbon dioxide and ammonia diffuse out across the plasma membrane	Oxygen from photosynthesis and other wastes diffuse out
Growth	Increases in size and dry mass by making new molecules	Increases in size and dry mass by making new molecules
Response to stimuli	Reverses direction when it meets an obstacle or harmful chemical	An eyespot detects light, so it swims towards light
Reproduction	Asexually, by dividing in two (binary fission)	Asexually by mitosis, or sexually when gametes fuse



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Paramecium, a heterotroph, carries out all the functions of life in **one cell**



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Chlamydomonas, an autotroph, makes its food by **photosynthesis** in a cup-shaped chloroplast.

Exam tip: Learn the eight functions as a list: homeostasis, metabolism, nutrition, movement, excretion, growth, response to stimuli and reproduction. Questions often ask how a named organism carries out each one.

Animal, fungal and plant cells, and atypical cells Spec A2.2.8, A2.2.9

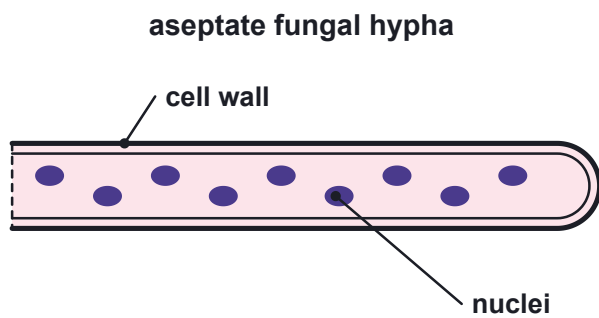
Differences in eukaryotic cell structure			
Feature	Animal cells	Fungal cells	Plant cells
Cell wall	Absent	Present, made of chitin	Present, made of cellulose
Vacuoles	Small and temporary, such as food vacuoles and vesicles	Present; can be large in older hyphae	A large permanent central vacuole of cell sap; maintains turgor and stores substances
Chloroplasts and other plastids	Absent	Absent	Chloroplasts in green tissues; other plastids, such as amyloplasts, store starch
Centrioles	Present	Absent in most fungi	Absent in flowering plants
Cilia and flagella	Present in some cells, such as ciliated epithelium and the sperm flagellum	Absent in most fungi; only some produce spores with flagella	Absent in flowering plants; mosses and ferns have sperm with flagella

Common mistake: Not every plant cell has chloroplasts: root cells have none. Write 'plant cells may have chloroplasts' when comparing cell types.

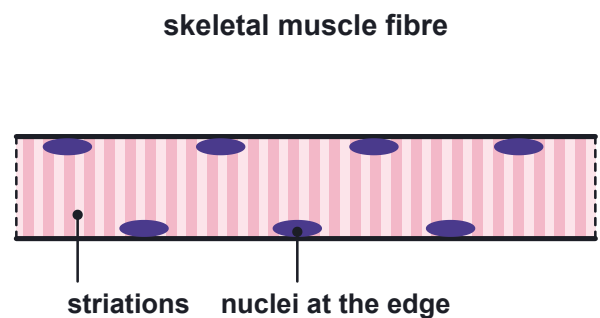
Atypical cell structure in eukaryotes

Cell theory pictures a cell as one unit with one nucleus. The **numbers of nuclei** show that some eukaryotic cells are atypical.

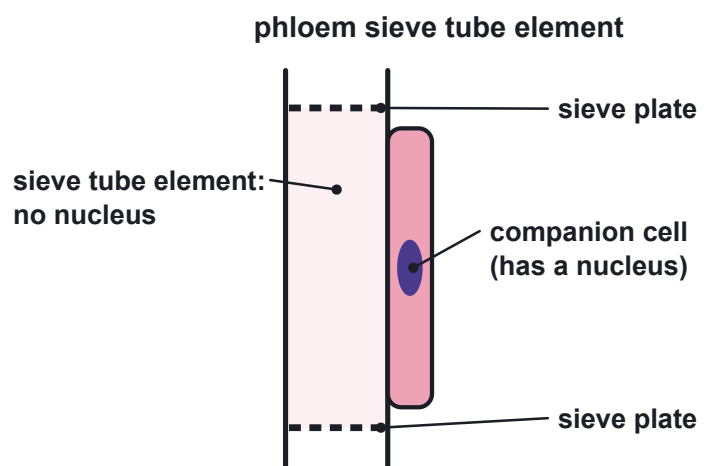
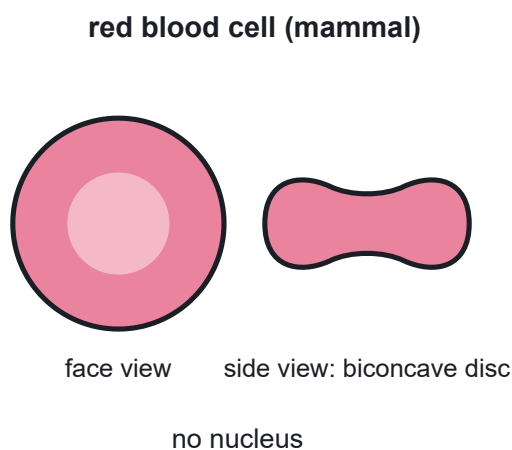
Atypical cells		
Cell	Number of nuclei	Explanation
Aseptate fungal hyphae	Many	The long hyphae have no cross walls (septa), so many nuclei share one continuous cytoplasm
Skeletal muscle fibres	Many	Each fibre forms when many embryonic muscle cells fuse, and it can be several centimetres long
Red blood cells (mammals)	None	The nucleus is lost as the cell matures, leaving more space for haemoglobin; the cell cannot divide and lives about 120 days
Phloem sieve tube elements	None	The nucleus and most organelles break down so sap can flow freely; a companion cell with a nucleus keeps each element alive



no septa (cross walls): multinucleate



multinucleate: formed by fusion of cells



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Atypical cells: two with **many nuclei** and two with **none**

Micrographs, drawing and annotation Spec A2.2.10, A2.2.11

Identifying the cell type

Clues to cell type in micrographs	
Cell type	Look for
Prokaryote	Small (about 0.5–5 µm); nucleoid region with no nuclear membrane; cell wall; no membrane-bound organelles
Plant	Cell wall; large sap vacuole; chloroplasts in green tissue; often a regular, angular shape
Animal	No cell wall; no large vacuole; may have microvilli; often an irregular shape

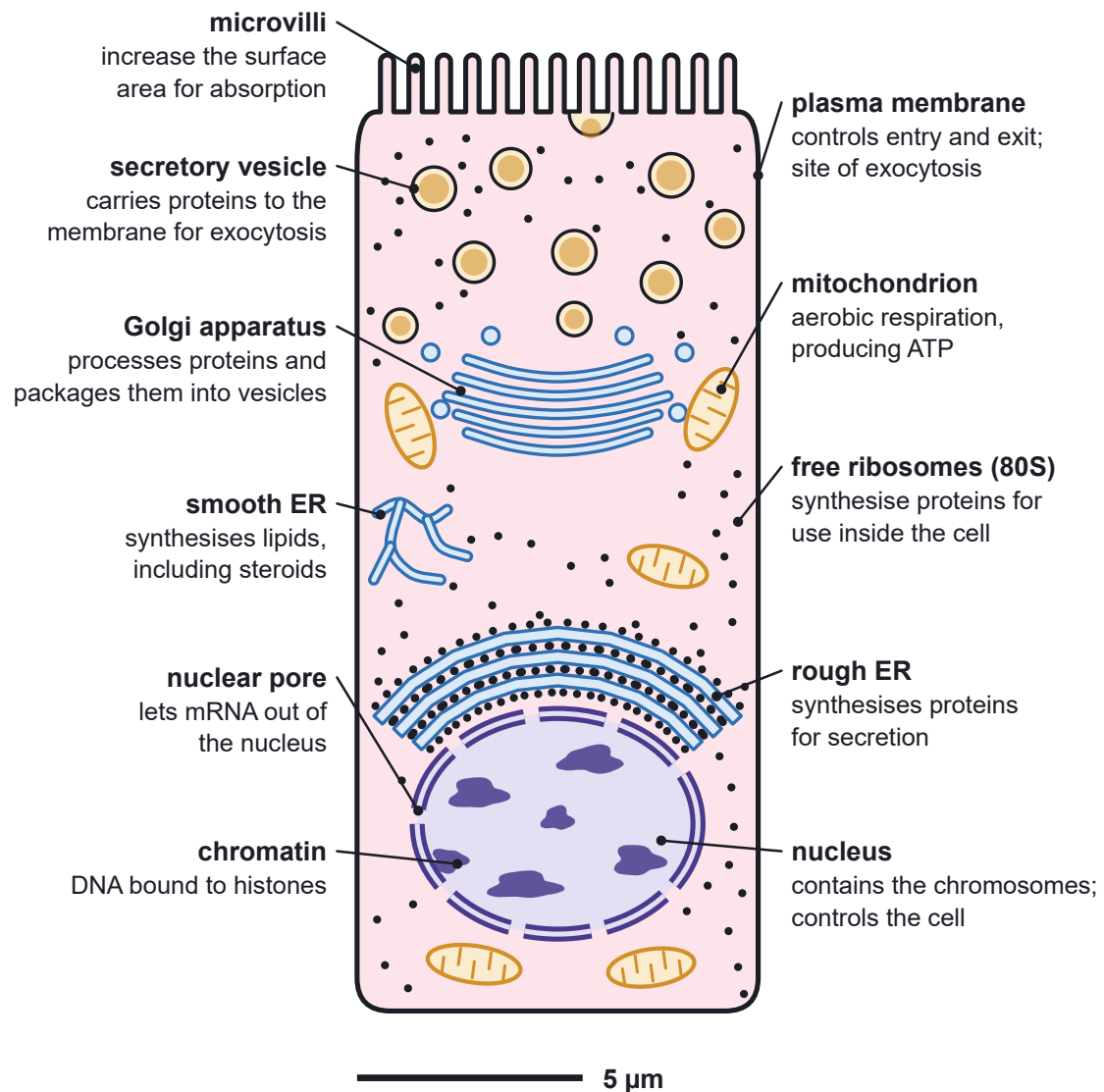
Structures in electron micrographs

Appearance and function of structures in electron micrographs		
Structure	Appearance	Function (for annotations)
Nucleoid region	Paler area of fine fibres in a prokaryote, with no membrane around it	Contains the loop of DNA
Prokaryotic cell wall	Dense layer just outside the plasma membrane	Protects the cell and prevents bursting
Nucleus	Large and round; double membrane with pores; dark patches of chromatin	Contains the chromosomes; controls the cell through gene expression
Chromosomes	Dark, condensed bodies, visible in dividing cells	Carry the genes; condensed so they can be separated in division
Mitochondrion	Oval; double membrane, with the inner membrane folded into cristae	Site of aerobic respiration, producing ATP
Chloroplast	Double membrane; stacks of thylakoids (grana); may contain starch grains	Site of photosynthesis
Sap vacuole	Large, pale area bounded by a single membrane	Stores cell sap; maintains turgor
Golgi apparatus	Stack of curved, flattened membrane sacs with vesicles at the edges	Processes proteins and packages them into vesicles
Rough endoplasmic reticulum	Flattened membrane sacs studded with ribosomes	Synthesises proteins for secretion or for membranes
Smooth endoplasmic reticulum	Branching tubular membranes without ribosomes	Synthesises lipids, including steroids
Ribosomes	Tiny dark granules, free in the cytoplasm or on rough ER	Protein synthesis
Cell wall (plant)	Thick layer outside the plasma membrane	Supports the cell and resists turgor pressure
Plasma membrane	Thin dark line at the edge of the cytoplasm	Controls the entry and exit of substances
Secretory vesicles	Small membrane-bound spheres near the Golgi apparatus or plasma membrane	Carry proteins to the plasma membrane for secretion by exocytosis
Microvilli	Finger-like projections of the plasma membrane	Increase the surface area for absorption

Drawing and annotating from an electron micrograph

- Use a sharp pencil and clear, continuous lines, with no shading or colouring.
- Draw only what is visible, with structures in the correct proportions and positions.
- Label with straight, ruled lines that do not cross and that end exactly on the structure.
- Annotate each labelled structure with its **function**; this is required, not optional.
- Add a title and a scale bar or magnification.

Exam tip: An annotation is more than a label. 'Mitochondrion: site of aerobic respiration, producing ATP' is an annotation; 'mitochondrion' alone is only a label.



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A secretory cell: proteins are made on **rough ER**, processed in the **Golgi apparatus** and secreted by exocytosis.

Origin of eukaryotic cells by endosymbiosis Spec A2.2.12 HL only

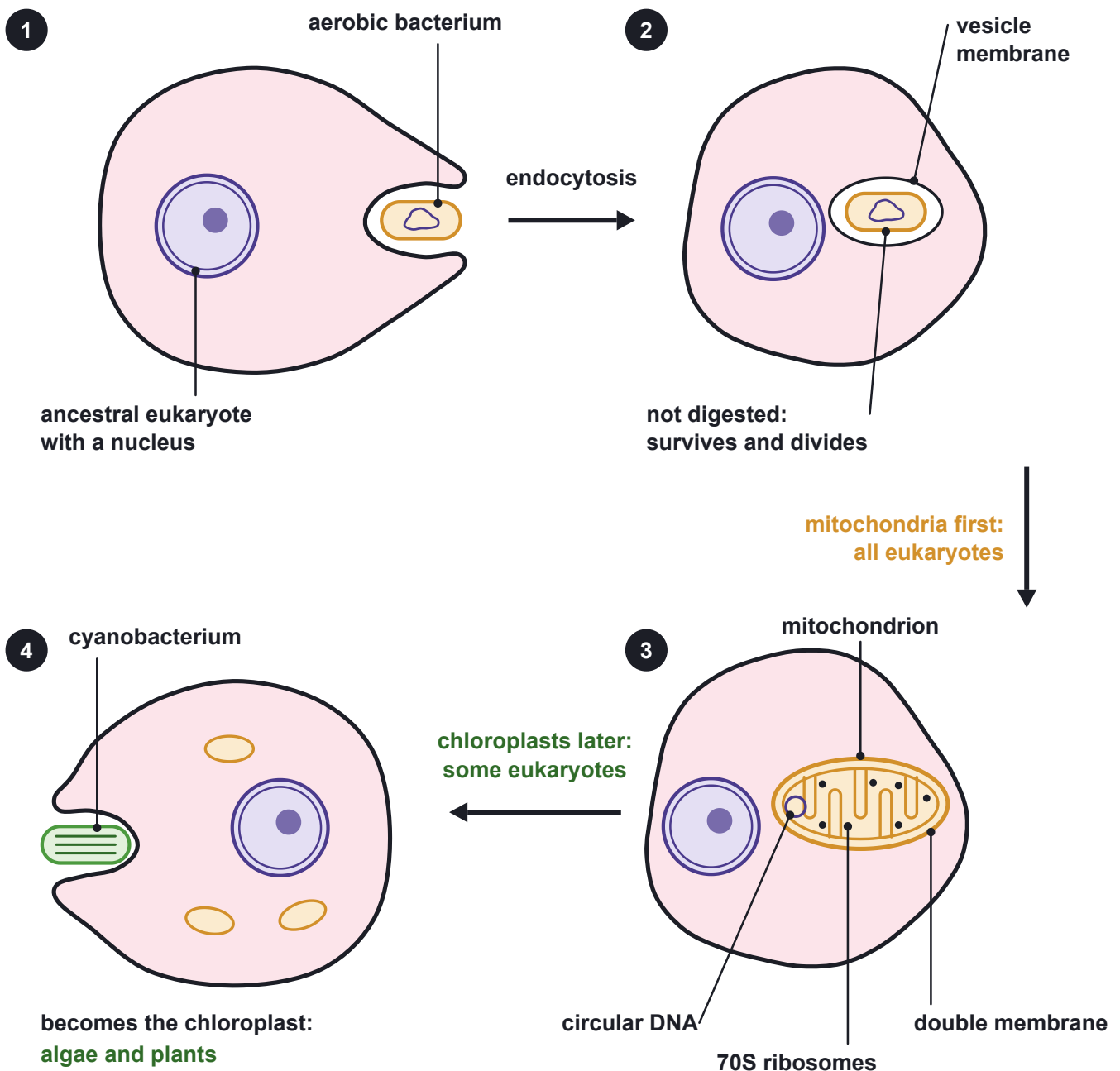
Evidence suggests that **all eukaryotes evolved from a common unicellular ancestor** that had a nucleus and reproduced sexually. Mitochondria and chloroplasts then arose by **endosymbiosis**.

1. An ancestral eukaryotic cell took in an aerobic prokaryote by endocytosis, but did not digest it.
2. The prokaryote survived and divided inside the host. The host gained ATP from the prokaryote's aerobic respiration, and the prokaryote gained protection and a supply of carbon compounds.

3. Over many generations the two became dependent on each other, and the prokaryote evolved into the mitochondrion. All eukaryotes are descended from this cell.
4. Later, in some eukaryotes only, a photosynthetic prokaryote (a cyanobacterium) was taken in the same way and became the chloroplast, giving rise to algae and plants.

Evidence that mitochondria and chloroplasts were once prokaryotes

Evidence	What it shows
70S ribosomes	The same size as prokaryote ribosomes, not the 80S ribosomes of the eukaryotic cytoplasm
Naked circular DNA	Like a prokaryote chromosome, not linear chromosomes bound to histones
Ability to replicate	They divide by a process like binary fission; a cell cannot make them from scratch
Double membrane	Consistent with a prokaryote being taken in by a host cell; the inner membrane resembles a prokaryote plasma membrane
Gene base sequences	Most similar to those of aerobic bacteria (mitochondria) and cyanobacteria (chloroplasts)



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Endosymbiosis: **mitochondria first**, in the ancestor of all eukaryotes, then **chloroplasts later** in some lineages.

Exam tip: Nature of science: a theory is strong when it explains many observations. Endosymbiosis accounts for the ribosomes, DNA, membranes, division and gene sequences of both organelles.

Cell differentiation and the evolution of multicellularity

Spec A2.2.13, A2.2.14

HL only

In a multicellular organism nearly all cells contain the same genome. **Cell differentiation** is the process by which cells develop into specialised types, forming tissues.

The basis of differentiation is **different patterns of gene expression**. In each cell type some genes are switched on (transcribed) and others are switched off. Changes in gene expression are often triggered by changes in the cell's environment, such as signal molecules from neighbouring cells or the cell's position in the embryo.

For example, only developing red blood cells express the genes for haemoglobin, and only certain cells in the pancreas express the insulin gene, although almost every body cell carries both genes.

Common mistake: Differentiation does not remove genes. A specialised cell keeps the full genome; it expresses only some of its genes.

Evolution of multicellularity

Multicellularity has evolved repeatedly, separately in different lineages. Many fungi and eukaryotic algae, and all plants and animals, are multicellular.

- Larger body size: an organism is not limited to the size of one cell, which is restricted by its surface area to volume ratio.
- Cell specialisation: different cells carry out different functions (division of labour), so each function can be carried out more efficiently.

Quick check

1. State the three parts of cell theory.
2. Why must an eyepiece graticule be calibrated for each objective lens?
3. What size of ribosome do prokaryotes have?
4. Which substance makes up fungal cell walls?
5. **HL only** Give two pieces of evidence for the endosymbiotic origin of mitochondria.

3 Viruses Spec A2.3 HL only

Structure and diversity of viruses Spec A2.3.1, A2.3.2

Viruses are not cells. **Relatively few features are shared by all viruses:**

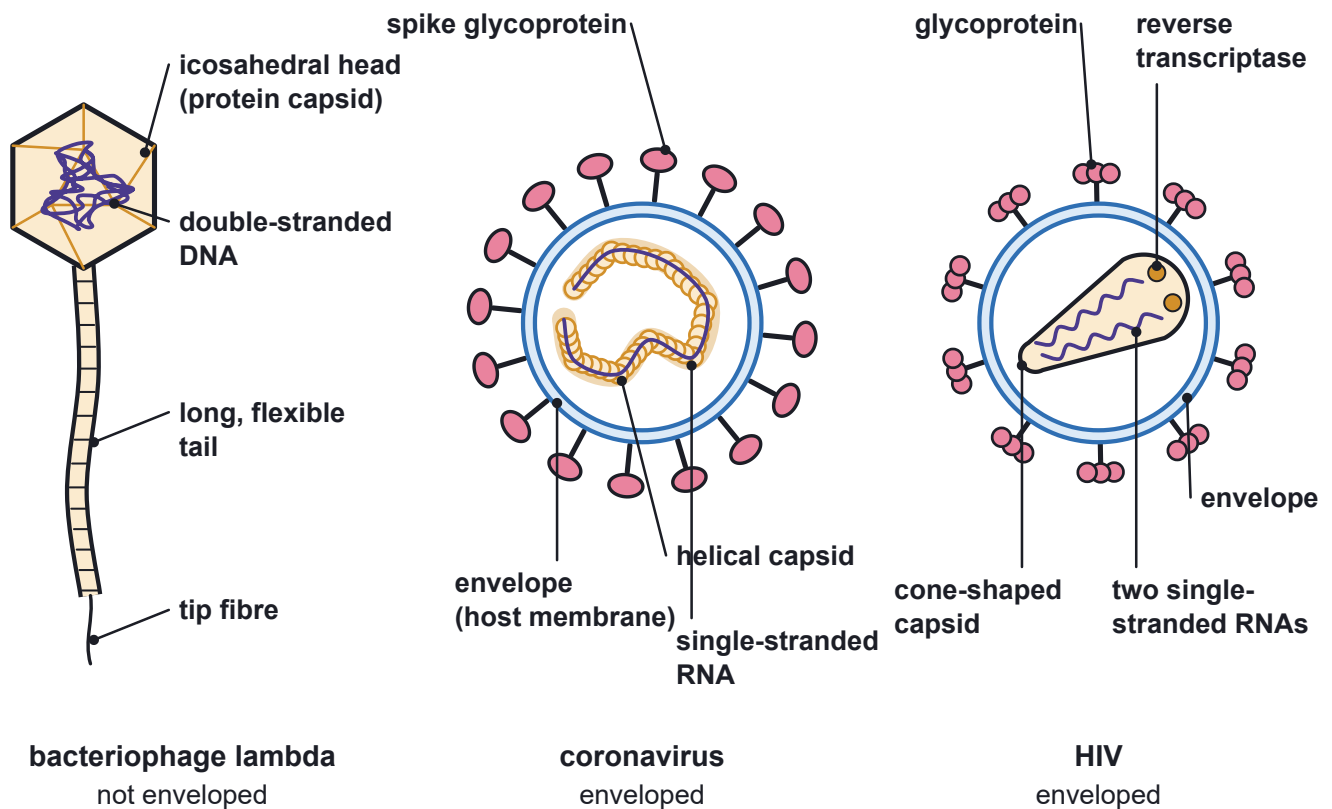
- A small, fixed size: most are about 20–300 nm across, far smaller than bacteria, and they do not grow.
- Nucleic acid as genetic material: either DNA or RNA.
- A **capsid** made of protein subunits, which protects the nucleic acid.
- No cytoplasm.
- Few or no enzymes, so they depend on a host cell for metabolism.

Diversity of structure

Viruses are **highly diverse** in shape and structure. Their genetic material may be RNA or DNA, and either can be single- or double-stranded. Some viruses are **enveloped** in membrane taken from the host cell; others are not enveloped.

Three example viruses			
Feature	Bacteriophage lambda	Coronaviruses (e.g. SARS-CoV-2)	HIV
Host	The bacterium <i>Escherichia coli</i>	Mammals and birds; SARS-CoV-2 infects cells lining the human airways	Humans, mainly helper T cells
Genetic material	Double-stranded DNA	Single-stranded RNA	Single-stranded RNA (two copies)
Capsid	Icosahedral head on a long, flexible tail; the tail tip binds the host	Helical capsid wrapped around the RNA	Cone-shaped capsid
Envelope	Not enveloped	Enveloped, with spike glycoproteins that bind host cell receptors	Enveloped, with glycoproteins that bind receptors on helper T cells
Enzymes carried	None	None	Reverse transcriptase, integrase and protease

An envelope is a piece of host plasma membrane picked up as the virus buds out of the host cell, with viral glycoproteins inserted into it.



not drawn to scale

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Viruses are diverse: **DNA or RNA**, and **enveloped or not**

Exam tip: Guiding question: how can viruses exist with so few genes? They need no genes for ribosomes, ATP production or most metabolism, because the host cell supplies all of these.

Lytic and lysogenic cycles Spec A2.3.3, A2.3.4

Viruses **rely on a host cell** for energy supply, nutrition, protein synthesis and other life functions. Bacteriophage lambda infects *E. coli* and can follow either of two cycles.

Lytic cycle

1. **Attachment:** the tip of the phage tail binds to a specific receptor protein on the outer surface of *E. coli*.
2. **Injection:** the phage injects its DNA into the cell; the empty capsid stays outside.
3. **Replication and synthesis:** the linear viral DNA forms a circle. Viral genes are transcribed by the host's RNA polymerase and translated by host ribosomes, using the host's ATP, nucleotides and amino acids. The viral DNA is replicated many times.
4. **Assembly:** capsid proteins assemble into heads and tails, and copies of the viral DNA are packed into the heads.
5. **Lysis and release:** viral proteins make holes in the plasma membrane and a viral enzyme (endolysin) breaks down the cell wall, so the cell bursts, and around 100 new phages are released to infect other cells.

Lysogenic cycle

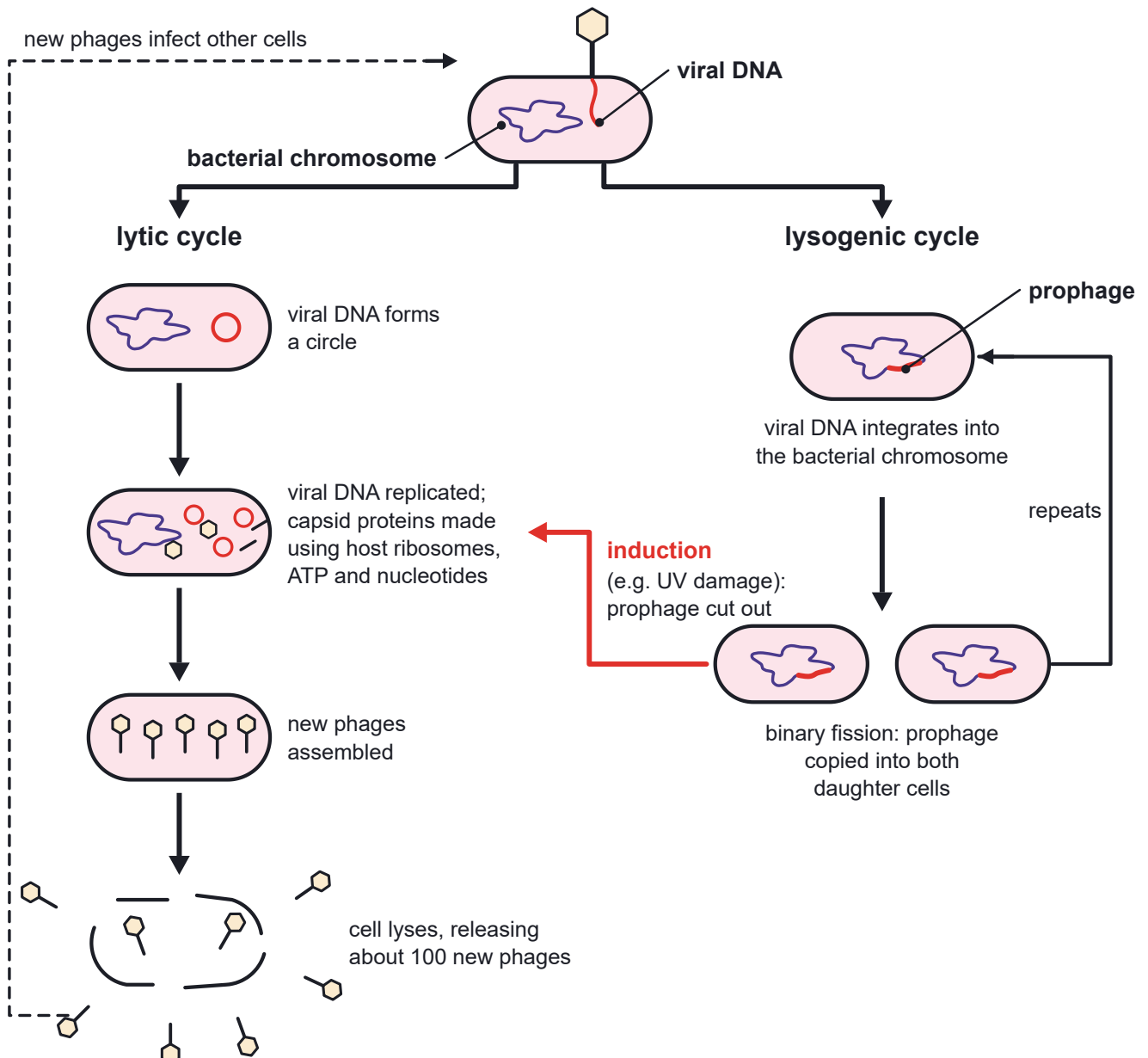
1. Attachment and injection happen as in the lytic cycle.

2. The lambda DNA integrates into the host chromosome at a specific site, catalysed by a viral enzyme, integrase. The integrated viral DNA is called a prophage.
3. A viral repressor protein switches off the genes needed for the lytic cycle, so no new viruses are made and the host survives.
4. Each time the bacterium divides by binary fission, the prophage is replicated with the host chromosome and passed to both daughter cells.
5. If the host is stressed, for example when its DNA is damaged by ultraviolet light, the prophage is cut out of the chromosome and the lytic cycle begins. This is called induction.

Lytic and lysogenic cycles compared

Feature	Lytic cycle	Lysogenic cycle
Viral DNA	Stays separate from the host chromosome	Integrated into the host chromosome as a prophage
New virus particles	Made quickly	Not made while the prophage is dormant
Effect on the host	Killed by lysis	Survives and divides normally
How the virus spreads	Released phages infect new cells	Copied to daughter cells when the host divides

phage attaches to *E. coli* and injects its DNA



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Lambda phage can kill its host at once (**lytic**) or lie dormant as a **prophage** (lysogenic) until induction.

Exam tip: In a lytic cycle answer, name the host resources used: **ATP, nucleotides, amino acids, ribosomes and enzymes**. These earn the marks for 'viruses rely on a host cell'.

Origins and rapid evolution of viruses Spec A2.3.5, A2.3.6

Evidence for several origins

The great **diversity of viruses** suggests several possible origins from other organisms, rather than one common ancestor of all viruses.

- Viruses share an **extreme form of obligate parasitism**: none can reproduce outside a host cell. The features they have in common, such as a small size and a protein capsid, could be **convergent evolution**: similar features evolving separately in different lineages because of the same way of life.
- The **genetic code is shared** between viruses and living organisms, which suggests that viruses arose from cellular life rather than independently of it.

Possible ways viruses arose from other organisms

Hypothesis	Idea
Escape	Pieces of genetic material, such as plasmids, escaped from cells and gained a protein coat
Reduction	Parasitic cells lost genes until little more than those for replication and capsids remained; very large viruses with many genes fit this idea

Different groups of viruses may have arisen in different ways, which would fit their diversity.

Exam tip: Linking question: what mechanisms contribute to convergent evolution? The same selection pressures, here entering host cells and protecting a genome between hosts, can produce similar features in unrelated lineages.

Rapid evolution in viruses

- **High mutation rate**: RNA viruses copy their genome with RNA polymerases, and HIV uses reverse transcriptase. These enzymes do not proofread, so copying errors are frequent.
- Short generation time: a new generation of virus particles can be produced within hours.
- Huge numbers: each infected cell releases many virus particles, so there is a lot of variation for natural selection to act on.
- Mixing of genes: when two strains infect the same cell, their genetic material can combine.

Influenza

Influenza A viruses have an RNA genome in eight segments and two surface glycoproteins, haemagglutinin (H) and neuraminidase (N), which antibodies recognise. Frequent mutations gradually change these antigens (**antigenic drift**), so antibodies from earlier infections or vaccines bind less well. If two strains infect the same host, for example a pig, their segments can mix (antigenic shift), producing a new subtype to which few people are immune. The vaccine is therefore reformulated every year to match the strains expected to circulate.

HIV

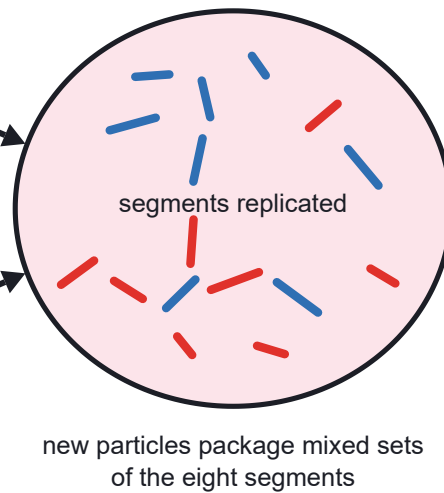
HIV's reverse transcriptase makes many errors and huge numbers of new virus particles are produced every day, so many variants exist within each infected person. When one antiviral drug is used, variants carrying resistance mutations are selected and multiply. Patients therefore take **combination antiretroviral therapy**: several drugs acting on different targets, so a variant would need several resistance mutations at once. The variability of HIV's surface glycoproteins has also made a vaccine very difficult to develop.

Exam tip: Consequences for treatment: vaccines need regular updating, antiviral drugs lose effectiveness as resistance evolves, and immunity from earlier infections gives less protection.

bird influenza virus



pig cell infected by both viruses



new subtype



little existing immunity

human influenza virus



▷ H (haemagglutinin) ◻ N (neuraminidase) — blue — bird — red — human

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Antigenic shift: mixing of RNA segments in one host produces a **new subtype**

Quick check

1. What is the protein coat of a virus called?
2. What is a prophage?
3. Which host does bacteriophage lambda infect?
4. Give two reasons why HIV evolves rapidly.

Quick check answers

Origins of cells

1. There was no free oxygen and therefore no ozone layer to absorb it.
2. Catalysis, self-replication of molecules, self-assembly and compartmentalisation.
3. rRNA, acting as a ribozyme.
4. The universal genetic code and genes shared by all organisms.

Cell structure

1. All organisms consist of one or more cells; cells are the basic structural unit of life; cells only arise from pre-existing cells.
2. The length of specimen covered by one eyepiece unit changes with magnification.
3. 70S.
4. Chitin.
5. They have 70S ribosomes and naked circular DNA (and can replicate by division).

Viruses

1. The capsid.
2. Viral DNA integrated into the host bacterium's chromosome.
3. The bacterium E. coli.
4. Reverse transcriptase does not proofread, so the mutation rate is high; and huge numbers of virus particles are produced with a short generation time.