Cell Biology

Unit 1 · Foundations: Cell Theory and Cell Types

Every living thing is built from cells. This unit tells how the cell theory was put together, sorts all cells into prokaryotic and eukaryotic, compares plant and animal cells, lists what every cell is made of and shares, and maps the compartments inside a eukaryotic cell. After it you can draw and compare any cell type, work the size and composition problems examiners set, and know which organelle chapter of Unit 3 to open next.

Taught at 7 of 10 | Usually Sem 3 | 5 chapters

About this unit

This unit answers the first questions of cell biology: what is a cell, and what kinds of cell are there? Chapter 1.1 follows the cell theory from Hooke's cork in 1665 to Virchow's "every cell from a cell" in 1855. Chapter 1.2 splits all cells into two plans, prokaryotic and eukaryotic, and Chapter 1.3 compares the two best-known eukaryotic cells, plant and animal. Chapter 1.4 lists what every cell is made of and the features all cells share, and Chapter 1.5 draws the map of compartments inside a eukaryotic cell, which Unit 3 then explores one organelle at a time.

Chapters

1. Development of the cell theory
2. Prokaryotic and eukaryotic cell organization
3. Plant cells versus animal cells ADVANCED
4. Chemical composition and universal features of cells
5. Overview of cell organelles and compartments

How to use this book

- Read the lead paragraph and the figure of each chapter first; together they carry the one idea.
- Cover the solution of each worked example and do it yourself, with a calculator where there are numbers, before reading on.
- Answer every "Check yourself" question on paper before you open it, then compare with the model answer.

1.1 Development of the cell theory

The cell theory says three things: every living organism is made of one or more cells; the cell is the smallest unit that is alive; and every cell comes from an earlier cell by division. It took almost two hundred years to establish, from Robert Hooke's cork in 1665 to Rudolf Virchow's principle in 1855, because it had to wait for good microscopes. It is the base of biology and medicine: a disease is a disorder of cells, an antibiotic attacks bacterial cells, and biotechnology grows and engineers cells.

You need: only school biology.

Seeing cells: Hooke and Leeuwenhoek

In 1665 the English scientist Robert Hooke published *Micrographia*, a book of drawings made through his compound microscope. A thin slice of cork showed rows of tiny empty boxes, and he called them "cells", from the Latin *cella*, a small room. Hooke was looking at dead tissue: he saw the walls left behind by cork cells, with nothing living inside.

In the 1670s Antonie van Leeuwenhoek, a cloth merchant in Delft in the Netherlands, made single-lens microscopes that magnified a few hundred times. With them he saw and described living single cells: protists in pond water, bacteria scraped from his teeth, sperm cells and blood cells. He called the tiny moving ones "animalcules" and reported them in letters to the Royal Society of London; textbooks credit him with the first description of a living cell.

Lenses improved slowly after that. In 1831 the Scottish botanist Robert Brown noticed a round body in orchid cells and named it the nucleus.

Building the theory: Schleiden, Schwann and Virchow

In 1838 the German botanist Matthias Schleiden concluded that all plant tissues are made of cells. In 1839 the zoologist Theodor Schwann showed the same for animal tissues. Schwann noted that animal cells have a thin outer layer, today called the plasma membrane, and that plant cells have a cell wall outside it. He proposed that cells are the basic units of all living things: the Schleiden–Schwann cell theory.

Their theory had a gap. They could not say where new cells come from, and both believed new cells could form out of a structureless fluid, rather like crystals growing in a solution. In the early 1850s Robert Remak watched cells divide in developing embryos, and in 1855 the German doctor Rudolf Virchow stated the principle *omnis cellula e cellula*: every cell comes from a pre-existing cell. Virchow built cellular pathology on it, the idea that disease starts in cells. Around

1860 Louis Pasteur's swan-neck flask experiments showed that microbes do not arise from broth by themselves; they come only from other microbes.

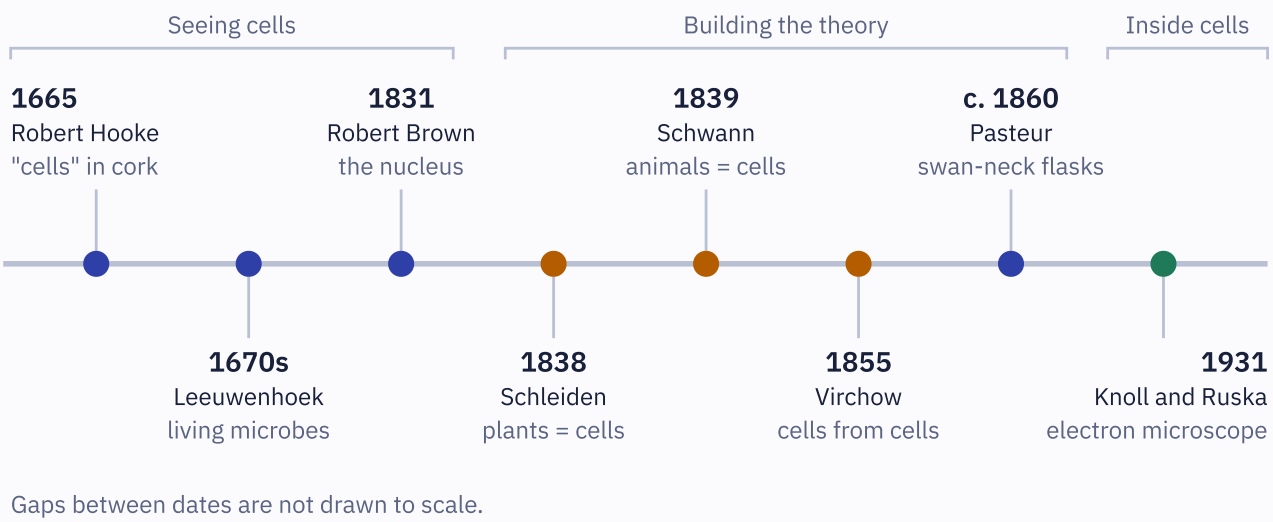


Figure 1.1.1 How the cell theory was built. Blue dots are advances in seeing cells; the three orange dots are the classical theory (Schleiden for plants, Schwann for animals, Virchow for the origin of cells); the green dot opened the inside of the cell. Notice the wait of more than 150 years between Leeuwenhoek and Schleiden: the idea needed better microscopes first.

The modern cell theory

The electron microscope, built by Max Knoll and Ernst Ruska in 1931, revealed the organelles inside cells, and molecular biology showed that the hereditary material is DNA. The theory as taught today keeps the three classical statements and adds three more:

1. All living organisms are made of one or more cells.
2. The cell is the basic unit of structure and function in living things.
3. All cells arise from pre-existing cells by division.
4. Cells carry hereditary information as DNA, which passes to daughter cells at division.
5. All cells have broadly the same chemical composition (Chapter 1.4).
6. The chemical reactions of life (metabolism) take place inside cells.

Exceptions and limits

Examiners often ask for "exceptions to the cell theory". Give each one with its reason:

- **Viruses** are not cells: they have no metabolism of their own and multiply only inside a host cell, so they sit outside the theory rather than disproving it.
- **Syncytia and coenocytes** have many nuclei in one continuous cytoplasm, not split into cells: a skeletal muscle fibre (made by many cells fusing), the hyphae of the bread mould *Rhizopus*, and the alga *Vaucheria*.

- **Cells without a nucleus**: mature mammalian red blood cells and the sieve tube elements of phloem lose their nucleus. They still live and work but cannot divide.
- **Mitochondria and chloroplasts** have their own DNA and ribosomes and divide by splitting, like cells inside cells (Chapter 1.2).
- **The first cell**: "every cell from a cell" cannot explain how the first cell arose, more than 3.5 billion years ago.

WORKED EXAMPLE

Question. The unaided eye can just separate two points about 0.1 mm (100 µm) apart at reading distance. (a) What is the smallest magnification at which a red blood cell 7.5 µm across can be seen as an object? (b) A bacterium 2 µm long? (c) If Leeuwenhoek's lens magnified 250 times, could he see bacteria? Could he see a ribosome about 25 nm across? (6 marks)

Idea. An object becomes visible when its magnified image is at least as large as the smallest detail the eye can resolve: magnification × object size ≥ 100 µm. So the minimum magnification is M = 100 µm ÷ object size.

1. Red blood cell: M = 100 µm ÷ 7.5 µm ≈ 13. About 13 times shows it as a dot; more is needed to see its shape.
2. Bacterium: M = 100 µm ÷ 2 µm = 50 times.
3. Leeuwenhoek and bacteria: image = 2 µm × 250 = 500 µm = 0.5 mm, five times the eye's limit. He could see bacteria as tiny moving specks, which is what he reported.
4. Ribosome: 25 nm = 0.025 µm, so image = 0.025 µm × 250 = 6.25 µm, far below 100 µm. More magnification would not help: a light microscope cannot separate details closer than about 0.2 µm, because of the wavelength of light (Unit 6). Ribosomes had to wait for the electron microscope.

Answer. (a) About 13 times. (b) 50 times. (c) Yes for bacteria (image 0.5 mm); no for ribosomes (image about 6 µm, and below the resolution limit of any light microscope).

EXAM TRAPS

- Hooke named cells but saw only dead cork walls; Leeuwenhoek is credited with first seeing and describing living cells. "Hooke discovered living cells" loses the mark.
- Two Roberts: Robert Hooke (1665, cells) and Robert Brown (1831, nucleus). Do not swap them.
- Schleiden worked on plants (1838) and Schwann on animals (1839). *Omnis cellula e cellula* is Virchow's (1855), and it corrected them: they thought cells could form from non-living fluid.
- For "exceptions", name viruses first and say why they fall outside the theory. A bare list without reasons earns half marks.

CHECK YOURSELF

– REMEMBER **State the three statements of the classical cell theory.** 3 marks

All organisms are made of one or more cells; the cell is the basic unit of structure and function; all cells arise from pre-existing cells.

– UNDERSTAND **Why was Virchow's statement needed to complete the theory of Schleiden and Schwann?** 2 marks

Schleiden and Schwann could not explain where new cells come from and believed in "free cell formation" from fluid. Virchow, building on Remak's observations, showed that cells arise only by division of existing cells, which explains growth, repair and inheritance.

– UNDERSTAND **A mature human red blood cell has no nucleus. Is it still a cell?** 2 marks

Yes. It is bounded by a plasma membrane, carries out metabolism (it breaks down glucose and carries oxygen) and arose by division of nucleated cells in the bone marrow. It only lacks the ability to divide.

– APPLY ***Mycoplasma* cells are about 0.3 µm across. What minimum magnification shows one to the eye, and can a light microscope show its shape?** 3 marks

M = 100 µm ÷ 0.3 µm ≈ 330 times. The cell is only just above the light microscope's limit of about 0.2 µm, so it appears as a dot; its shape needs an electron microscope.

– APPLY **Broth boiled in a swan-neck flask stays clear for months, but turns cloudy within days once the neck is broken. Explain using the cell theory.** 3 marks

Boiling kills the microbes already present. The curved neck traps dust that carries microbes, so no new cells arrive and none appear. Breaking the neck lets microbe-laden dust in, and the microbes multiply. New cells came only from existing cells, as the third statement says.

– ANALYZE **"A skeletal muscle fibre disproves the cell theory." Argue for and against.** 4 marks

For: one fibre has hundreds of nuclei in one cytoplasm with no cell boundaries, so it is not a single cell in the usual sense. **Against:** it forms when many myoblast cells fuse, each made by division, and it is built of cellular material and runs cellular metabolism. It is best called a syncytium, a modified cellular unit, so it refines the theory rather than disproving it.

BEYOND THE SYLLABUS

Not for the exam. The cell theory is now studied one cell at a time. Single-cell RNA sequencing reads the active genes of thousands of individual cells in one experiment, and the Human Cell Atlas project uses it to catalogue every human cell type. Organoids, tiny organ-like clusters grown from stem cells, show how cells build tissues. Other groups assemble "synthetic cells" from lipids and purified molecules to find the least a system needs to count as alive. Search: single-cell RNA-seq, Human Cell Atlas, organoids, bottom-up synthetic cell.

1.2 Prokaryotic and eukaryotic cell organization

All cells on Earth follow one of two plans. A prokaryotic cell (bacteria and archaea) has no nucleus: its DNA lies in the cytoplasm in a region called the nucleoid, and it has no membrane-bound organelles. A eukaryotic cell (protists, fungi, plants and animals) keeps its DNA inside a nucleus wrapped in a double membrane and divides its interior into membrane-bound compartments. The names are Greek: *karyon* is a kernel (the nucleus), *pro* means before and *eu* means true. The plan also decides which host a biotechnologist picks: *E. coli* for fast, cheap production, yeast or animal cells when a protein needs eukaryotic processing.

You need: Chapter 1.1.

The prokaryotic plan

A typical bacterium such as *Escherichia coli* is a rod about 2 µm long and 1 µm wide (1 µm is a thousandth of a millimetre). From the outside in (Figure 1.2.1A):

- **Capsule** (in many species): a sticky polysaccharide coat that helps the cell cling to surfaces and resist white blood cells.
- **Cell wall**: in bacteria a mesh of peptidoglycan that stops the cell bursting; thick in Gram-positive bacteria, thin and covered by an outer membrane in Gram-negative ones. Archaea have walls without peptidoglycan; *Mycoplasma* has no wall.
- **Plasma membrane**: the cell's working membrane, controlling what enters and leaves. Respiration, and light capture in photosynthetic bacteria, happen on it or on its infoldings.
- **Cytoplasm** with **70S ribosomes** (one 30S and one 50S subunit) and storage granules such as glycogen.
- **Nucleoid**: usually one circular chromosome, folded and supercoiled with proteins but with no membrane around it. Many cells also carry **plasmids**, small extra DNA circles that often carry antibiotic-resistance genes and serve as cloning vectors.
- **Flagella**, rotating propellers of the protein flagellin, and **pili**, thin hairs for attachment and for passing DNA in conjugation.

Because the DNA is not walled off, ribosomes start translating an mRNA while it is still being transcribed: transcription and translation are coupled. A prokaryote divides by binary fission, copying its chromosome and splitting in two, without mitosis.

Archaea look like bacteria and are prokaryotes, but in 1977 Carl Woese showed from ribosomal RNA (16S rRNA) sequences that they are a separate group. Their membrane lipids have ether bonds instead of ester bonds, and their machinery for reading DNA resembles that of eukaryotes. In 1990 Woese proposed three domains of life: Bacteria, Archaea and Eukarya.

The eukaryotic plan

A eukaryotic cell is usually 10 to 100 µm across (Figure 1.2.1B). It has:

- A **nucleus** bounded by a double membrane, the nuclear envelope, with pores. The DNA is split into several linear chromosomes wound on histone proteins (chromatin); the nucleolus makes ribosome subunits.
- An **endomembrane system** (endoplasmic reticulum, Golgi apparatus, lysosomes, endosomes, vesicles), plus **mitochondria**, **peroxisomes** and, in plants and algae, **chloroplasts** (Chapter 1.5).
- **80S ribosomes** (40S plus 60S) in the cytosol and on the rough ER.
- A **cytoskeleton** of microtubules, actin filaments and intermediate filaments, with motor proteins that move cargo (Unit 3).

- Division by **mitosis**, and by **meiosis** for sex cells (Unit 4). Transcription in the nucleus is separated from translation in the cytoplasm, so RNA is processed (capped, spliced, tailed) before it leaves.
- Cilia and flagella, where present, of microtubules in a 9 + 2 pattern, bent by the motor protein dynein: they beat like whips instead of rotating.

Mitochondria and chloroplasts are thought to descend from bacteria that an ancestral cell engulfed and kept: the endosymbiotic theory, championed by Lynn Margulis from 1967. Both have two membranes, their own circular DNA and bacteria-like ribosomes, and both divide by fission.

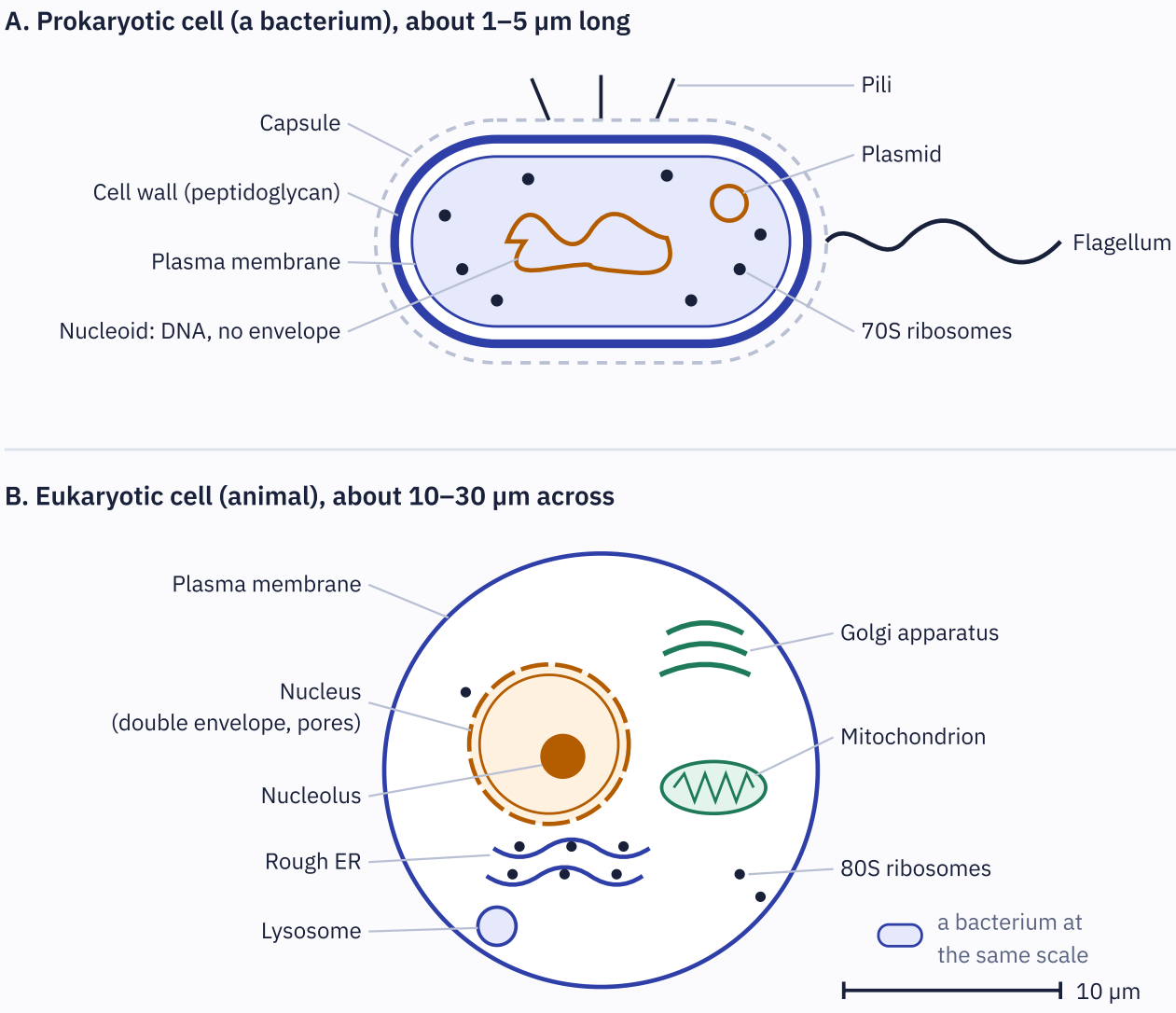


Figure 1.2.1 The two cell plans. (A) A bacterium, enlarged: its DNA (orange) lies in the cytoplasm as a nucleoid, with no membrane around it, beside a plasmid. (B) An animal cell: the DNA is closed inside a double-membraned nucleus and the interior is divided into organelles. The small rod at bottom right is a bacterium at the same scale as cell B; a eukaryotic cell is often a thousand times larger in volume.

Side by side

FEATURE	PROKARYOTIC CELL	EUKARYOTIC CELL
Typical size	1–5 µm	10–100 µm
Nucleus	none; DNA in a nucleoid	true nucleus with a double envelope
Chromosomes	usually one, circular; plasmids common	several, linear, wound on histones
Membrane-bound organelles	absent	present
Ribosomes	70S (30S + 50S)	80S (40S + 60S) in the cytosol; smaller, bacteria-like ones in mitochondria and chloroplasts
Cell wall	peptidoglycan in bacteria	cellulose (plants), chitin (fungi), none (animals)
Respiration	on the plasma membrane	in mitochondria
Division	binary fission	mitosis and meiosis
Gene expression	transcription and translation coupled; introns rare	separated by the nuclear envelope; introns common
Flagellum	rotates; made of flagellin	bends like a whip; 9 + 2 microtubules

WORKED EXAMPLE

Question. Treat a coccus (round bacterium) as a sphere 1 μm in diameter and an animal cell as a sphere 20 μm in diameter. (a) Find the surface area, volume and surface-area-to-volume ratio (SA/V) of each. (b) The time for a molecule to diffuse a distance x is roughly $t \approx x^2/(2D)$, where D is its diffusion coefficient. How many times longer does a molecule take to diffuse from the membrane to the centre of the animal cell? (c) What does this mean for how the cells are organized? (8 marks)

Formulas. For a sphere of radius r: $SA = 4\pi r^2$ and $V = (4/3)\pi r^3$, so $SA/V = 3/r$.

1. Bacterium, r = 0.5 μm: $SA = 4\pi(0.5)^2 = 3.14\ \mu m^2$; $V = (4/3)\pi(0.5)^3 = 0.524\ \mu m^3$; $SA/V = 3 \div 0.5 = 6.0\ \mu m^{-1}$.
2. Animal cell, r = 10 μm: $SA = 4\pi(10)^2 = 1257\ \mu m^2$; $V = (4/3)\pi(10)^3 = 4189\ \mu m^3$; $SA/V = 3 \div 10 = 0.30\ \mu m^{-1}$.
3. Compare: the animal cell has 8000 times the volume but only 400 times the surface, so each μm^3 of it has 20 times less membrane serving it.
4. Diffusion: D is the same for the same molecule, so t grows with x^2. Ratio = $(10\ \mu m \div 0.5\ \mu m)^2 = 20^2 = 400$.
5. Meaning: a large cell cannot rely on its outer membrane and on diffusion alone. Eukaryotes add internal membranes (ER, mitochondrial cristae) to multiply membrane area, compartments that keep each job in one place, and motor proteins that carry cargo along the cytoskeleton.

Answer. SA/V is $6.0\ \mu m^{-1}$ for the bacterium and $0.30\ \mu m^{-1}$ for the animal cell, 20 times less; diffusion to the centre takes about 400 times longer. Hence the compartments and active transport of eukaryotic cells.

EXAM TRAPS

- Prokaryotes do organize their DNA: the nucleoid is folded and packed with proteins. What they lack is a nuclear envelope.
- Svedberg units do not add up: 30S + 50S gives 70S, and 40S + 60S gives 80S. S measures how fast a particle sinks in a centrifuge, which depends on shape as well as mass.
- "Eukaryotes have 80S ribosomes" is true of the cytosol only; their mitochondria and chloroplasts have smaller, bacteria-like ribosomes.
- Older books draw mesosomes, membrane infoldings said to carry out respiration. Electron microscopists now regard them as artefacts of chemical fixation; say so if your book shows them.

CHECK YOURSELF

– REMEMBER **Name the subunits of a 70S and of an 80S ribosome.** 2 marks

70S = 30S + 50S (prokaryotes); 80S = 40S + 60S (eukaryotic cytosol).

– UNDERSTAND **Why can transcription and translation be coupled in *E. coli* but not in yeast?** 2 marks

In *E. coli* the DNA and ribosomes share one compartment, so ribosomes bind the mRNA while it is still being made. In yeast, transcription happens inside the nucleus and the mRNA is processed and exported before cytoplasmic ribosomes can reach it.

– UNDERSTAND **Give four pieces of evidence that mitochondria descend from bacteria.** 4 marks

Two membranes; their own circular DNA; bacteria-like ribosomes; division by fission (the cell never builds them from scratch).

– APPLY **A coccus is 2 μm across and a yeast cell 6 μm across. Treating both as spheres, find SA/V for each and the ratio.** 3 marks

Coccus: r = 1 μm, SA/V = 3 μm^{-1}. Yeast: r = 3 μm, SA/V = 1 μm^{-1}. The coccus has 3 times more surface per unit volume.

– APPLY **A eukaryotic cell is 15 times wider than a bacterium. How many times longer does diffusion across it take?** 2 marks

t grows with x^2, so $15^2 = 225$ times longer.

– ANALYZE **Human insulin is made commercially in *E. coli*, but erythropoietin (EPO), a glycoprotein, is made in Chinese hamster ovary (CHO) cells. Explain the choice.** 4 marks

EPO needs sugar chains added in the ER and Golgi to work as a drug; without them it is cleared from the blood too quickly. *E. coli* has no ER or Golgi and cannot add them, so a mammalian host is used. Insulin needs no sugar chains, so the cheaper, faster prokaryotic host is enough.

BEYOND THE SYLLABUS

Not for the exam. The two-plan picture is being refined. Asgard archaea, found by DNA sequencing of sea-floor sediments from 2015 onwards, carry genes once thought to exist only in eukaryotes and are the closest known prokaryotic relatives of eukaryotes. The bacterium *Thiomargarita magnifica*, described in 2022, is about a centimetre long and keeps its DNA in membrane sacs. Bacteria also have cytoskeletal proteins related to tubulin (FtsZ) and actin (MreB). Search: Asgard archaea, eukaryogenesis, *Thiomargarita magnifica*, bacterial cytoskeleton.

1.3 Plant cells versus animal cells

Plant and animal cells are both eukaryotic and share almost every organelle. Their differences follow from lifestyle. A plant stays in one place, makes its own food from light and holds itself up with water pressure, so its cells have a rigid wall, chloroplasts and a large water-filled vacuole. An animal moves, eats and changes shape, so its cells have no wall and keep centrioles and lysosomes. The others fold it into eukaryotic organization or take it as known from Class 11.

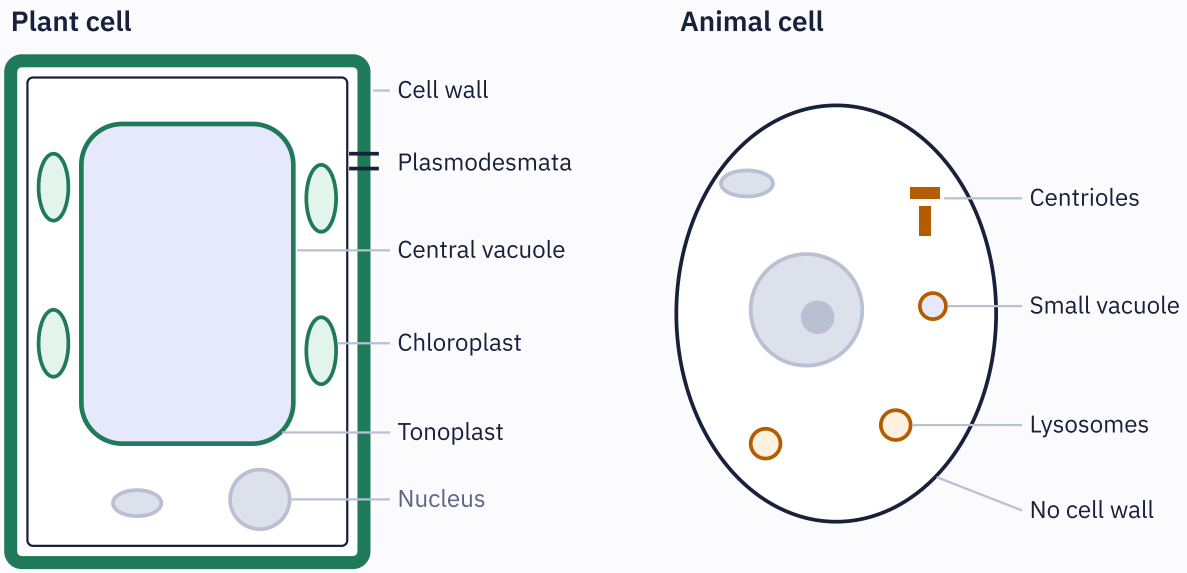
What both have

Nucleus, plasma membrane, mitochondria, endoplasmic reticulum, Golgi apparatus (in plants, many separate stacks called dictyosomes), ribosomes, peroxisomes and a cytoskeleton. A plant cell has mitochondria as well as chloroplasts: chloroplasts make sugar, mitochondria burn it, day and night.

The differences examiners ask for

FEATURE	PLANT CELL	ANIMAL CELL
Cell wall	present: cellulose, with pectin in the middle lamella between cells	absent; an extracellular matrix instead (Unit 5)
Plastids	chloroplasts (photosynthesis), chromoplasts (colour), leucoplasts (storage, such as starch in amyloplasts)	none
Vacuole	one large central vacuole bounded by the tonoplast, up to 90% of the cell volume	small and temporary, if any
Centrioles	absent in flowering plants and conifers	a pair in the centrosome
Lysosomes	few; the vacuole does most of the digesting	present
Stored carbohydrate	starch	glycogen
Cytokinesis	a cell plate grows outward from the middle	a furrow pinches in from outside (Unit 4)
Links between cells	plasmodesmata through the walls	gap junctions, tight junctions, desmosomes (Unit 5)
Shape	fixed, often box-like	variable, often rounded

Turgor ties the plant features together. The vacuole holds a concentrated solution, water enters it by osmosis (Unit 2), and the swelling vacuole presses the cytoplasm against the wall. The wall pushes back, so the cell becomes firm, or turgid, instead of bursting. An animal cell in pure water has nothing to push back, so it swells and can burst, as red blood cells do.



Green: only in plant cells. Orange: only in animal cells. Grey: in both.
Both also have mitochondria, ER, Golgi, ribosomes and peroxisomes.

Figure 1.3.1 A plant cell and an animal cell with their unique parts coloured. In the plant cell the central vacuole fills most of the space and pushes the cytoplasm, chloroplasts and nucleus into a thin layer against the wall; the animal cell has no wall, so its shape can change.

WORKED EXAMPLE

Question. A plant cell is a cube 50 µm on each side. Its central vacuole, also cube-shaped and centred, fills 90% of the cell volume. Ignoring the wall, how thick is the layer of cytoplasm around the vacuole? (3 marks)

1. Cell volume = $50^3 = 125\,000$ µm³.
2. Vacuole volume = $0.90 \times 125\,000 = 112\,500$ µm³, so the vacuole's side $s = \sqrt[3]{112\,500} = 48.3$ µm.
3. The cytoplasm lies in equal layers on both sides: thickness = $(50 - 48.3) \div 2 \approx 0.86$ µm.

Answer. Under 1 µm. The cytoplasm is a thin film against the wall, which suits light capture and exchange with neighbours, and the vacuole, mostly water, is a cheap way to build a big cell.

EXAM TRAPS

- Plant cells have mitochondria too. "Plants have chloroplasts instead of mitochondria" is wrong.
- Not every plant cell has chloroplasts: root and storage cells have leucoplasts instead.
- "No centrioles" holds for flowering plants and conifers; mosses, ferns and cycads make swimming sperm with basal bodies.
- A fungal cell also has a wall (of chitin, not cellulose) and stores glycogen, so "has a wall" alone does not make a cell a plant cell.

CHECK YOURSELF

– REMEMBER **Name the three kinds of plastid and the job of each.** 3 marks

Chloroplasts: photosynthesis. Chromoplasts: pigments that colour fruits and flowers. Leucoplasts: storage of starch, oils or proteins.

– UNDERSTAND **Why does a red blood cell burst in distilled water while a leaf cell only becomes firm?** 2 marks

Water enters both by osmosis. The leaf cell's wall resists the swelling and the cell becomes turgid; the red blood cell has no wall, so it swells until its membrane breaks.

– APPLY **Repeat the worked example for a 40 µm cube whose vacuole fills 80% of the volume.** 3 marks

Cell 64 000 µm³; vacuole 51 200 µm³; side $\sqrt[3]{51\,200} = 37.1$ µm; layer = $(40 - 37.1) \div 2 \approx 1.4$ µm.

– ANALYZE **Cell X has a wall, a large vacuole, starch grains and no chloroplasts. Cell Y has a chitin wall and glycogen granules. Identify each.** 3 marks

X is a non-green plant cell, such as a potato tuber or root cell (starch in amyloplasts). Y is a fungal cell: chitin walls and glycogen stores mark fungi.

– UNDERSTAND **Why does a plant cell divide with a cell plate instead of a furrow?** 2 marks

The rigid wall cannot pinch inward, so the new wall is built from the middle outward by vesicles from the Golgi that fuse into a cell plate.

BEYOND THE SYLLABUS

Not for the exam. Plant cells grown in steel bioreactors work as factories. Taliglucerase alfa, an enzyme for Gaucher disease made in carrot cells, became in 2012 the first drug from plant cell culture approved by the US FDA, and the anticancer drug paclitaxel is also produced by plant cell culture. Search: plant cell culture, molecular farming.

1.4 Chemical composition and universal features of cells

Grind up any cell and the list of ingredients is short: about 70% water by mass, then proteins, RNA, polysaccharides, lipids and DNA, with a little salt and some small molecules. Beneath the variety of life, every cell also runs the same core program: DNA stores the instructions, RNA carries working copies, ribosomes read them with the same genetic code to make proteins, a membrane encloses it all, and ATP pays for the work. These shared features are why a human insulin gene works inside *E. coli*, the trick on which the biotechnology industry was founded.

You need: Chapter 1.2. The chemistry of each kind of molecule is taught in detail in the Biochemistry course.

The elements of life

Four elements, oxygen, carbon, hydrogen and nitrogen, make up about 96% of the mass of the human body. With phosphorus and sulphur they form the six elements (CHNOPS) that build nearly all biological molecules. Ions of sodium, potassium, calcium, magnesium and chloride carry signals and stabilise structures, and trace elements such as iron, zinc, copper and iodine sit in enzymes and hormones. Carbon is central because each carbon atom forms four stable covalent bonds, so carbon builds the chains, branches and rings that are the backbones of organic molecules.

What a cell is made of

Water is about 70% of a cell's mass. It is polar and forms hydrogen bonds, so it dissolves ions, sugars and amino acids. Oily (hydrophobic) molecules avoid water and cluster together; this hydrophobic effect folds proteins and assembles membranes. Water's high heat capacity also protects the cell against sudden temperature changes.

Most of the remaining 30%, the dry mass, is large molecules built from small ones. Each is assembled by **condensation** (a water molecule is removed at every link) and broken down by **hydrolysis** (a water molecule is added back):

MACROMOLECULE	BUILT FROM	LINK	MAIN JOBS
Protein	20 kinds of amino acid	peptide bond	enzymes, structure, transport, signals
Nucleic acid (DNA, RNA)	nucleotides	phosphodiester bond	store and express genetic information
Polysaccharide	sugars (monosaccharides)	glycosidic bond	energy store (starch, glycogen); walls (cellulose, chitin, peptidoglycan)
Lipid	fatty acids and glycerol (fats, phospholipids); steroids are ring compounds	ester bond	membranes, energy store, hormones

Lipids are the odd one out: they are not polymers, but they gather into large assemblies such as membranes. Weak non-covalent forces hold these assemblies together: hydrogen bonds, ionic attractions, van der Waals forces and the hydrophobic effect. The same weak forces hold each protein in its folded shape and the two strands of DNA together, which is why heat or extreme pH unfolds them.

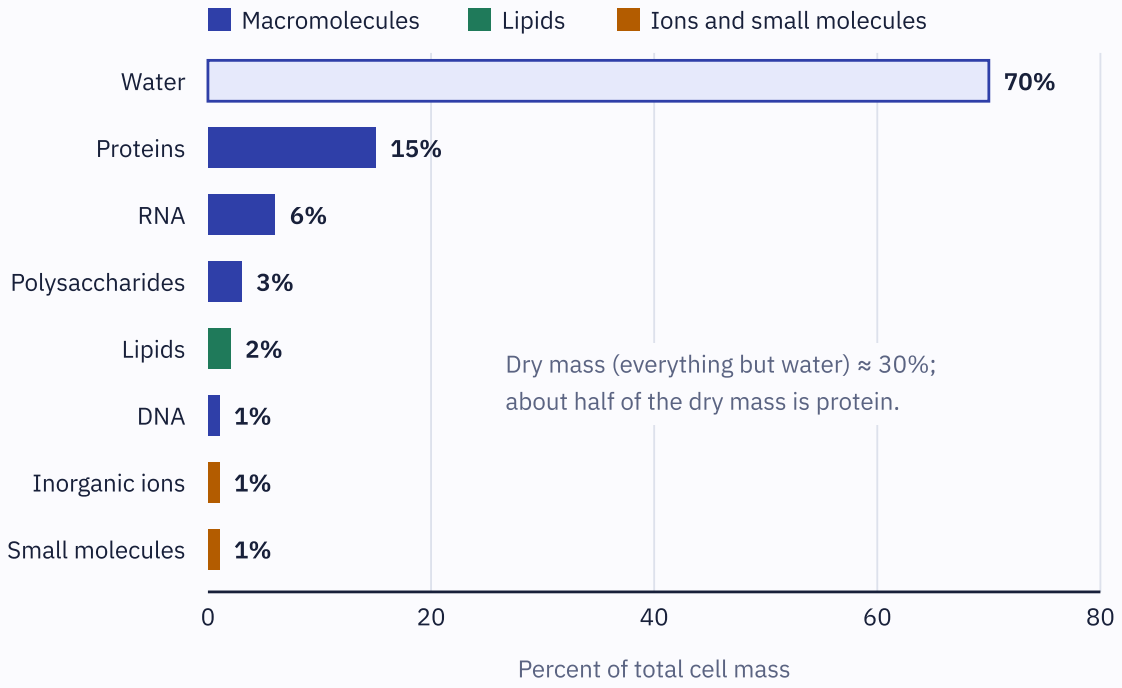


Figure 1.4.1 Approximate composition of a bacterial cell by mass, from a classic textbook table (University of Hamburg course page, see Sources). Water dominates; among the rest, protein is the largest share, and RNA outweighs DNA six to one because the cell's tens of thousands of ribosomes are built mostly of RNA. "Small molecules" adds amino acids, nucleotides and metabolic intermediates.

Features every cell shares

1. Hereditary information is stored as DNA, in the same four-letter code (A, T, G, C).
2. DNA is copied by templated polymerization: each strand guides the building of a new partner strand.
3. Parts of the DNA are transcribed into RNA, the working copy.
4. RNA is translated into protein on ribosomes, using a genetic code that is nearly the same in all organisms.
5. Proteins do most of the work, above all as enzymes (catalysts).
6. Life needs a steady input of free energy, and ATP is the common energy currency.
7. Every cell is enclosed by a plasma membrane, across which food and waste must pass.
8. All cells build from the same small molecules: sugars, fatty acids, amino acids and nucleotides.

These shared features point to one common ancestor of all life. Anabolism (biosynthesis) spends that energy to build monomers and then polymers. The Biochemistry course follows these pathways step by step.

WORKED EXAMPLE

Question. An *E. coli* cell has a dry mass of about 0.4 pg, of which about 0.2 pg is protein (1 pg = 10^{-12} g). Water is 70% of the total mass. Take the average protein as 300 amino acids of 110 Da each (1 Da = 1 g/mol). Estimate (a) the total mass of the cell, (b) the number of water molecules, (c) the number of protein molecules, (d) the number of water molecules per protein molecule. Avogadro's number $N_A = 6.02 \times 10^{23}$ mol^{-1}. (8 marks)

Formula. Number of molecules N = (mass ÷ molar mass) × N_A.

1. Dry mass is 30% of the total, so total mass = 0.4 pg ÷ 0.30 = 1.33 pg.
2. Water = 1.33 − 0.4 = 0.93 pg = 9.3×10^{-13} g. N(water) = (9.3×10^{-13} g ÷ 18 g/mol) × 6.02×10^{23} mol^{-1} = 3.1×10^{10}.
3. Average protein molar mass = 300 × 110 = 33 000 g/mol. N(protein) = (2×10^{-13} g ÷ 33 000 g/mol) × 6.02×10^{23} mol^{-1} = 3.6×10^{6}.
4. Water per protein = $3.1 \times 10^{10} \div 3.6 \times 10^{6} \approx 8\,500$.

Answer. About 1.3 pg in all; about 3×10^{10} water molecules and a few million protein molecules, so roughly 8 500 water molecules for every protein. Published estimates differ by a factor of two or three with cell size and growth rate, so examiners look for the method and the order of magnitude.

EXAM TRAPS

- "70% water" is by mass. Counted by number, about 99 of every 100 molecules in a cell are water.
- DNA is only about 1% of a bacterial cell's mass, far less than RNA (about 6%). Mass is not importance.
- Lipids are not polymers; "which class of biomolecule is not a polymer?" is a favourite one-mark question.
- The genetic code is nearly, not perfectly, universal: animal and yeast mitochondria and *Mycoplasma* read the stop codon UGA as tryptophan.
- Condensation joins monomers and releases water; hydrolysis splits polymers and uses water. Do not reverse them.

CHECK YOURSELF

– REMEMBER **Which four elements make up about 96% of the mass of the human body?** 1 mark

Oxygen, carbon, hydrogen and nitrogen.

– REMEMBER **Give the monomer and the linking bond of proteins, nucleic acids and polysaccharides.** 3 marks

Proteins: amino acids, peptide bonds. Nucleic acids: nucleotides, phosphodiester bonds. Polysaccharides: monosaccharides, glycosidic bonds.

– UNDERSTAND **Why do phospholipids form a membrane in water without any enzyme?** 2 marks

Each phospholipid has a water-loving head and two oily tails. In water the tails hide from water by facing each other, so a bilayer forms by itself, driven by the hydrophobic effect.

– UNDERSTAND **Which universal features let a human insulin gene be expressed in *E. coli*?** 3 marks

Both use DNA with the same four bases, transcribe it into mRNA, and translate mRNA on ribosomes with the same genetic code, so the bacterium builds the same amino-acid sequence. (The gene is supplied without introns and with a bacterial promoter.)

– APPLY **A HeLa (human) cell contains about 300 pg of protein. Taking an average protein of 50 kDa, how many protein molecules is that?** 3 marks

$N = (3 \times 10^{-10}\ \text{g} \div 50\,000\ \text{g/mol}) \times 6.02 \times 10^{23}\ \text{mol}^{-1} = 3.6 \times 10^{9}$, about 4 billion protein molecules.

– APPLY **How many water molecules are there in 1 pg of water?** 2 marks

$N = (10^{-12}\ \text{g} \div 18\ \text{g/mol}) \times 6.02 \times 10^{23}\ \text{mol}^{-1} = 3.3 \times 10^{10}$.

– ANALYZE **DNA is about 1% of a bacterial cell's mass, yet it is called the master molecule. Discuss mass versus information.** 3 marks

DNA's value is its sequence, not its mass: one copy holds the instructions for every protein and RNA. Proteins and RNA are made in many copies because they do the work, so they outweigh the DNA that encodes them. A small, stable store of information driving a large, renewable workforce is the logic of the cell.

BEYOND THE SYLLABUS

Not for the exam. How few genes can a cell live with? In 2016 the J. Craig Venter Institute built JCVI-syn3.0, a *Mycoplasma* cell running on a synthetic genome of 473 genes, and the job of about a third of them was unknown. Mass spectrometry now measures thousands of proteins at once, and "whole-cell" computer models try to simulate every molecule of a small bacterium. Search: minimal cell JCVI-syn3.0, quantitative proteomics, whole-cell model, BioNumbers.

1.5 Overview of cell organelles and compartments

A eukaryotic cell is divided by membranes into compartments, each with its own proteins, its own chemistry and its own job, much as a hospital has separate wards, laboratories and stores. Compartments keep incompatible reactions apart, gather the enzymes of a pathway in one place, and let membranes store energy as ion gradients. Membrane-bound compartments fill nearly half the volume of a typical cell, and in a liver cell the internal membranes have about 50 times the area of the plasma membrane. This chapter is the map; Unit 3 visits each organelle in turn.

You need: Chapters 1.2 and 1.4.

Why cells are compartmentalized

- **To keep reactions apart.** Lysosomes digest proteins, fats and nucleic acids with acid hydrolases that work best at pH 4.5 to 5, while the cytosol is near pH 7.2. A difference of about 2.5 pH units means the lysosome holds roughly 300 times more H^+ ($10^{2.5} \approx 316$). If a lysosome leaks, its enzymes are almost inactive at cytosolic pH: a built-in safety lock.
- **To concentrate a pathway.** Most enzymes of the citric acid cycle sit together in the mitochondrial matrix, so each product quickly meets the next enzyme.
- **To build gradients.** A membrane can hold a difference in ion concentration. The inner mitochondrial membrane and the chloroplast thylakoid pump H^+ to one side, and the H^+ flowing back drives ATP synthase.
- **To control information.** The nuclear envelope separates transcription from translation, so the cell can process RNA and choose which messages leave the nucleus.
- **To gain membrane area.** Many enzymes work only on a membrane, and folded internal membranes (ER, cristae, thylakoids) give far more area than the cell surface alone.

The main compartments

COMPARTMENT	MEMBRANE	MAIN JOB
Cytosol	none (the fluid around the organelles)	glycolysis; protein synthesis on free ribosomes
Nucleus	double (nuclear envelope with pores)	stores DNA; transcription and RNA processing; the nucleolus makes ribosome subunits
Endoplasmic reticulum	single	rough ER: membrane and secreted proteins; smooth ER: lipids, detoxification, Ca^{2+} store
Golgi apparatus	single (stacked cisternae)	modifies, sorts and packs proteins and lipids
Endosomes and lysosomes	single	sort material taken in from outside; digest it
Peroxisomes	single	oxidise fatty acids; destroy H_2O_2 with catalase
Mitochondria	double (inner one folded into cristae)	aerobic respiration; most of the ATP
Chloroplasts (plants, algae)	double, plus internal thylakoids	photosynthesis
Vacuole (plants, fungi)	single (tonoplast)	storage, turgor, digestion
Ribosomes, nucleolus, centrosome	no membrane	protein synthesis; ribosome assembly; organizing microtubules

The compartments form families that never mix their contents directly. The nucleus and cytosol are joined through nuclear pores. The ER, Golgi, endosomes, lysosomes and vesicles form one family, the **endomembrane system**, which passes material by vesicles. The inside (lumen) of each is topologically equivalent to the outside of the cell: what is inside a vesicle ends up outside when the vesicle fuses with the plasma membrane. Mitochondria, chloroplasts and peroxisomes stand apart and take most of their proteins straight from the cytosol.

How a protein finds its compartment

Almost every protein starts on ribosomes in the cytosol. A short stretch of amino acids, the **signal sequence**, works like a PIN code on an India Post parcel: it says where the protein should go. Proteins with no signal stay in the cytosol. The rest travel in one of three ways (Figure 1.5.1):

1. **Gated transport** through nuclear pores, which let folded proteins and RNA pass in and out of the nucleus.

2. **Transmembrane transport**: protein translocators thread the chain across a membrane, into the ER, mitochondria and chloroplasts as an unfolded chain, and into peroxisomes.
3. **Vesicular transport**: from the ER onwards, vesicles bud from one compartment and fuse with the next (ER to Golgi to lysosomes, the cell surface or secretion), and endocytosis brings material in from outside.

Unit 3 (Golgi apparatus and protein sorting) and Unit 2 (Endocytosis and exocytosis) follow these routes in detail.

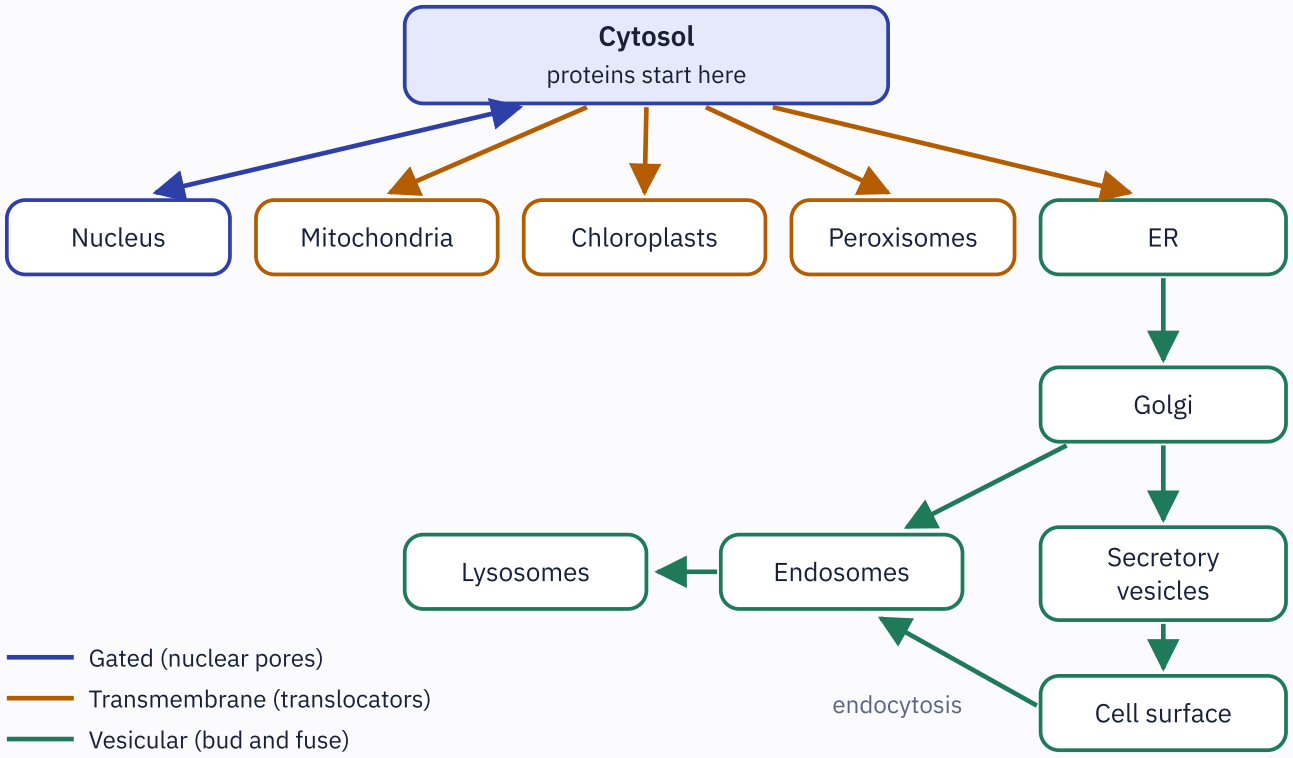


Figure 1.5.1 The protein traffic map of a eukaryotic cell. Blue: gated transport through nuclear pores (two-way). Orange: transmembrane transport by translocators from the cytosol into mitochondria, chloroplasts, peroxisomes and the ER. Green: vesicular transport inside the endomembrane system, from the ER through the Golgi to the cell surface or to lysosomes, plus endocytosis inward. Inside the endomembrane system, cargo moves between compartments in vesicles without crossing a membrane.

WORKED EXAMPLE

Question. A liver cell (hepatocyte) has about 100 000 μm² of internal membrane, about 50 times the area of its plasma membrane. Its ER membrane alone is about 25 times the plasma-membrane area. (a) Find the plasma-membrane area. (b) Find the ER membrane area and the share of internal membrane that is ER. (c) If the plasma membrane were a smooth sphere, what would the cell's diameter be? (d) What does (b) say about the liver cell's work? (6 marks)

1. Plasma membrane = 100 000 μm² ÷ 50 = 2 000 μm².
2. ER membrane = 25 × 2 000 μm² = 50 000 μm², which is 50 000 ÷ 100 000 = 50% of all internal membrane.
3. Sphere: $4\pi r^2$ = 2 000 μm², so r = √(2 000 ÷ 4π) = √159 = 12.6 μm and the diameter is about 25 μm, a sensible size for a hepatocyte.
4. Half of the internal membrane is ER: the liver cell makes large amounts of secreted protein (such as the blood protein albumin) on rough ER, and builds lipids and detoxifies drugs on smooth ER.

Answer. About 2 000 μm² of plasma membrane and 50 000 μm² of ER, half of all internal membrane, in a cell about 25 μm across: a cell organised around its ER.

EXAM TRAPS

- Count the membranes: nucleus, mitochondria and chloroplasts have two; ER, Golgi, lysosomes, peroxisomes and vacuoles have one; ribosomes, the nucleolus and centrioles have none.
- Cytoplasm is everything between the plasma membrane and the nucleus, organelles included; cytosol is only the fluid part.
- Lysosomes digest with acid hydrolases; peroxisomes oxidise with oxidases and destroy H_2O_2 with catalase. Do not swap them.
- Ribosomes are organelles without a membrane; rough ER is rough because ribosomes sit on its cytosolic face.

CHECK YOURSELF

– REMEMBER **Name three organelles bounded by a double membrane.** 1 mark

Nucleus (nuclear envelope), mitochondria and chloroplasts.

– REMEMBER **Distinguish cytoplasm from cytosol.** 2 marks

Cytoplasm: all the contents between the plasma membrane and the nucleus, organelles included. Cytosol: only the fluid part in which the organelles sit.

– UNDERSTAND **Why does a leaking lysosome not digest the whole cell?** 2 marks

Lysosomal hydrolases need an acidic pH of about 4.5 to 5. In the cytosol, at about pH 7.2, they are nearly inactive, and the small amount released is diluted.

– UNDERSTAND **Why is the lumen of the ER called topologically equivalent to the outside of the cell?** 2 marks

Material in the ER lumen moves in vesicles through the Golgi and is released outside when a vesicle fuses with the plasma membrane, without ever crossing a membrane into the cytosol. The lumen is "outside" folded into the cell.

– APPLY **A lysosome is at pH 4.8 and the cytosol at pH 7.2. How many times higher is the H^+ concentration in the lysosome?** 2 marks

Ratio = $10^{(7.2 - 4.8)} = 10^{2.4} \approx 250$ times.

– APPLY **In a pancreatic exocrine cell the ER membrane is about 12 times the plasma-membrane area. If the plasma membrane is 1 000 µm², estimate the ER membrane area.** 2 marks

12 × 1 000 µm² = 12 000 µm².

– ANALYZE **A pancreatic acinar cell is packed with rough ER, while an adrenal cortex cell, which makes steroid hormones, is packed with smooth ER. Explain.** 3 marks

The acinar cell secretes digestive enzymes, which are proteins made by ribosomes on rough ER. Steroid hormones are lipids made from cholesterol by enzymes in the smooth ER membrane. Each cell expands the compartment that does its main job.

BEYOND THE SYLLABUS

Not for the exam. Some compartments have no membrane at all. The nucleolus, stress granules and P-bodies are biomolecular condensates: droplets that form when certain proteins and RNAs separate from the cytosol like oil from water (liquid–liquid phase separation). Organelles also touch at membrane contact sites, such as ER–mitochondria contacts that pass lipids and calcium. Spatial proteomics maps which proteins live in which compartment, and the subcellular section of the Human Protein Atlas is free to browse. Search: biomolecular condensates, membrane contact sites, Human Protein Atlas subcellular.

Unit summary

KEY TERMS AND FORMULAS

TERM	MEANING OR FORMULA	CHAPTER
Cell theory	all organisms are made of cells; the cell is the basic unit of life; cells arise only from cells	1.1
Omnis cellula e cellula	"every cell from a cell": Virchow, 1855	1.1
Minimum magnification	M ≈ 100 µm (the eye's limit) ÷ object size; no light microscope resolves details closer than about 0.2 µm	1.1
Prokaryote, eukaryote	no nucleus, DNA in a nucleoid; DNA inside a nucleus with a double envelope	1.2
Ribosome types	70S = 30S + 50S (prokaryotes); 80S = 40S + 60S (eukaryotic cytosol)	1.2
Surface-to-volume ratio	for a sphere, SA/V = 3/r	1.2
Diffusion time	$t \approx x^2/(2D)$: twice the distance takes four times as long	1.2
Turgor	pressure of the swollen vacuole pressing the cytoplasm against the cell wall	1.3
Composition of a bacterial cell	water ≈ 70%, protein ≈ 15%, RNA ≈ 6%, DNA ≈ 1% of total mass	1.4
Number of molecules	$N = (m \div M) \times N_A$, with $N_A = 6.02 \times 10^{23}\ mol^{-1}$	1.4
Condensation, hydrolysis	water removed to join monomers; water added to split polymers	1.4
pH and H^+	ratio of H^+ concentrations = $10^{\Delta pH}$	1.5
Protein transport modes	gated (nuclear pores), transmembrane (translocators), vesicular (bud and fuse)	1.5

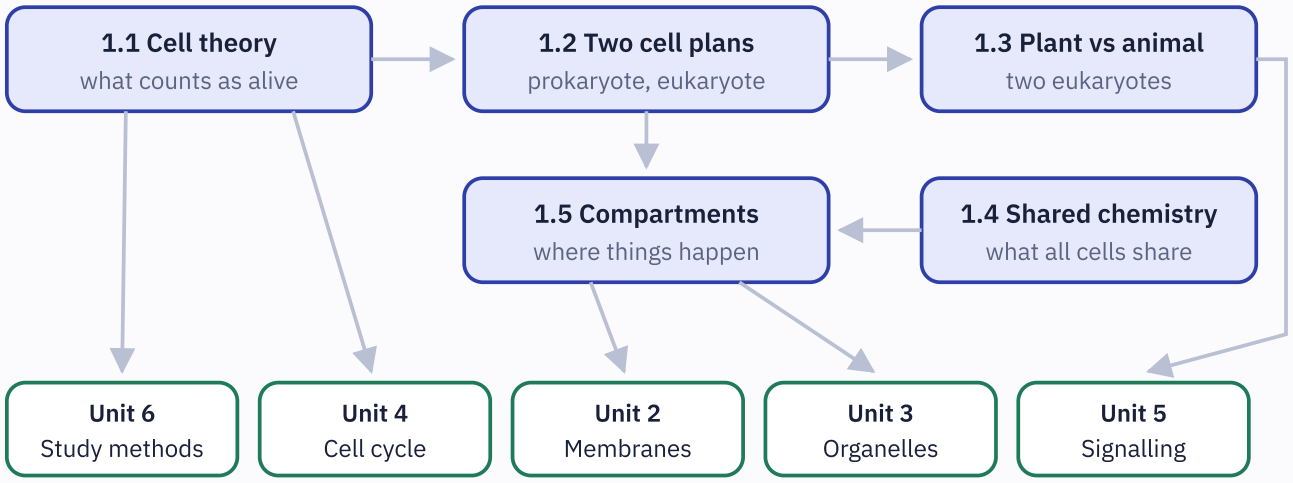


Figure U1.1 How the chapters connect and where they lead. The cell theory (1.1) sets up the two cell plans (1.2), which split into plant and animal cells (1.3) and lead to the compartment map (1.5), fed by the chemistry all cells share (1.4). Arrows point on to the units that open each idea: cells from cells to the cell cycle (Unit 4), seeing cells to the study methods (Unit 6), compartments to membranes and organelles (Units 2 and 3), and the plant wall to the extracellular matrix and cell wall in Unit 5.

Takeaways

1. Hooke named cells (1665), Leeuwenhoek saw living ones (1670s), Schleiden and Schwann made cells the unit of all life (1838–39), and Virchow added "every cell from a cell" (1855).
2. Viruses, syncytia, cells without nuclei and the first cell are the standard exceptions to the cell theory; always give the reason with each.
3. Prokaryotes have no nucleus or membrane-bound organelles, 70S ribosomes and binary fission; eukaryotes have a nucleus, organelles, 80S cytosolic ribosomes and mitosis.
4. Small cells can live on diffusion: SA/V = 3/r, and diffusion time grows with the square of distance. Large eukaryotic cells need internal membranes, compartments and motor-driven transport.
5. Plant cells add a cellulose wall, plastids and a large central vacuole; animal cells have no wall and keep centrioles and lysosomes.
6. A cell is about 70% water by mass, and about half of its dry mass is protein.
7. All cells share DNA, RNA, ribosomes, a near-universal genetic code, ATP and a plasma membrane: evidence of a common ancestor, and the reason genetic engineering works.
8. Compartments keep reactions apart, concentrate pathways, build gradients and multiply membrane area; proteins reach them by gated, transmembrane or vesicular transport.

Exam question bank

Long-answer questions in the style of university papers. Each answer outline lists the points an examiner looks for; write them out in full sentences, with a diagram wherever one fits.

Remember and understand

- REMEMBER **Trace the development of the cell theory from Hooke to Virchow, and state the modern cell theory.** 12 marks

  Hooke 1665, *Micrographia*, cork "cells" (dead walls). Leeuwenhoek 1670s, single lenses, first living cells (protists, bacteria, sperm, blood cells). Brown 1831, nucleus. Schleiden 1838 (plants) and Schwann 1839 (animals): cells are the units of all organisms. Their error: new cells from structureless fluid. Remak (early 1850s) and Virchow 1855: *omnis cellula e cellula*; cellular pathology. Pasteur, about 1860: no spontaneous generation. Electron microscope 1931. Modern theory: the three classical statements plus DNA passed at division, similar chemistry in all cells, metabolism inside cells. A labelled timeline earns marks.

- UNDERSTAND **With a labelled diagram, describe the organization of a bacterial cell.** 8 marks

  Diagram with capsule, cell wall, plasma membrane, cytoplasm, 70S ribosomes, nucleoid, plasmid, inclusions, flagellum, pili. One line on each: capsule (adhesion, protection), peptidoglycan wall (shape, prevents bursting; Gram-positive thick, Gram-negative thin plus outer membrane), membrane (transport, respiration), nucleoid (single circular chromosome, no envelope), plasmids (extra genes, cloning vectors), flagellum (rotary motion), pili (attachment, conjugation). Add binary fission and coupled transcription and translation.

- UNDERSTAND **Differentiate prokaryotic and eukaryotic cells under at least ten headings.** 10 marks

  Size; nucleus; chromosomes (number, shape, histones); membrane-bound organelles; ribosomes (70S versus 80S, with the organelle exception); cell wall chemistry; site of respiration; mode of division; gene expression (coupled versus separated, introns); flagellum structure; examples. A two-column table is the expected format; one mark per correct contrast.

– UNDERSTAND **Describe the chemical composition of a cell and list the universal features shared by all cells.** 12 marks

Elements: O, C, H, N about 96% of body mass; CHNOPS; ions and trace elements. Water about 70%, its properties and the hydrophobic effect. The four classes of macromolecule with monomers, bonds and jobs; condensation and hydrolysis; lipids not polymers; weak non-covalent forces. Composition figures for a bacterial cell. Universal features: DNA store, templated copying, transcription, translation with a near-universal code, protein enzymes, ATP, plasma membrane, shared building blocks; conclusion: common ancestry.

– REMEMBER **List the organelles of an animal cell, giving the number of membranes around each and its main function.** 10 marks

Nucleus (two; DNA, transcription, nucleolus makes ribosome subunits). Rough and smooth ER (one; proteins; lipids, detoxification, Ca^{2+}). Golgi (one; modify, sort, package). Lysosomes (one; acid hydrolases). Endosomes (one; sorting of taken-in material). Peroxisomes (one; oxidation, catalase). Mitochondria (two; respiration, ATP). Ribosomes, nucleolus and centrosome (none). A labelled diagram adds marks.

Apply

– APPLY **A coccus is 1.5 µm across and a liver cell 25 µm across. Treating both as spheres, calculate SA/V for each and the ratio of diffusion times from surface to centre. Explain why the liver cell needs compartments.** 8 marks

Coccus: r = 0.75 µm, SA/V = 3 ÷ 0.75 = 4.0 μm^{-1}. Liver cell: r = 12.5 µm, SA/V = 0.24 μm^{-1}; the coccus has about 17 times more surface per volume. Diffusion time ratio = $(12.5 \div 0.75)^2 \approx 280$. Explanation: too little surface per volume and slow diffusion over long distances, so the liver cell uses internal membranes (ER, cristae), compartments that concentrate pathways, and motor-driven transport.

– APPLY **A cell has a total mass of 2 pg; 70% is water and half of the dry mass is protein. Taking an average protein of 40 kDa, estimate the number of water molecules, the number of protein molecules, and the ratio between them.** 8 marks

Water 1.4 pg: $N = (1.4 \times 10^{-12}\ g \div 18\ g/mol) \times 6.02 \times 10^{23} = 4.7 \times 10^{10}$. Dry mass 0.6 pg, protein 0.3 pg: $N = (3 \times 10^{-13}\ g \div 40\,000\ g/mol) \times 6.02 \times 10^{23} = 4.5 \times 10^{6}$. Ratio ≈ 10 000 water molecules per protein. State the formula $N = (m \div M) \times N_A$ and keep units at every step.

– APPLY **Draw a plant cell and an animal cell side by side and list eight differences. A plant cell is a cube 60 µm on a side with a central vacuole filling 85% of its volume; find the thickness of the cytoplasm layer.** 10 marks

Diagrams with the wall, plastids, central vacuole and tonoplast, plasmodesmata (plant) and centrioles, lysosomes, small vacuoles (animal). Differences: wall, plastids, vacuole, centrioles, lysosomes, stored carbohydrate, cytokinesis, cell links, shape. Calculation: cell 216 000 µm³; vacuole 0.85 × 216 000 = 183 600 µm³; side $\sqrt[3]{183\,600} = 56.8$ µm; layer = (60 – 56.8) ÷ 2 ≈ 1.6 µm.

– APPLY **A lysosome is at pH 4.6 and the cytosol at pH 7.2. A hepatocyte's internal membranes total about 100 000 µm², 50 times its plasma membrane. Use these numbers to explain two benefits of compartmentalization.** 8 marks

H^+ ratio = $10^{(7.2 - 4.6)} = 10^{2.6} \approx 400$: the lysosome keeps digestion acidic and apart, and its leaked enzymes are almost inactive in the cytosol. Plasma membrane = 100 000 ÷ 50 = 2 000 µm²: internal membranes multiply the area for membrane-bound enzymes, protein synthesis on rough ER and ATP synthesis on cristae. Mention concentration of pathways and control of gene expression for full marks.

Analyze and evaluate

– EVALUATE **"Viruses, skeletal muscle fibres and red blood cells are exceptions to the cell theory." Evaluate this statement.** 10 marks

Viruses: acellular, no metabolism, multiply only in host cells, so outside the theory rather than against it. Muscle fibre: a syncytium formed by fusion of cells that arose by division; refines "unit" rather than breaking the theory. Mammalian red blood cells: no nucleus, cannot divide, but are living cells that arose from nucleated cells. Add coenocytes (*Rhizopus*, *Vaucheria*), organelles with DNA, and the first cell. Conclude: the theory stands; the cases show its limits and its modern wording.

– ANALYZE **Discuss the endosymbiotic theory of the origin of mitochondria and chloroplasts. What does it tell us about the boundary between prokaryotes and eukaryotes?** 10 marks

Theory: an ancestral cell engulfed an aerobic bacterium (mitochondria) and, in the plant line, a cyanobacterium (chloroplasts); Margulis, 1967. Evidence: double membranes, own circular DNA, bacteria-like ribosomes, division by fission, size similar to bacteria. Spans Chapters 1.2 and 1.5. Conclusion: every eukaryotic cell contains prokaryote-derived parts, so the eukaryotic plan grew out of the prokaryotic one; Asgard archaea point to the host's ancestry.

– ANALYZE **A company must produce (a) human insulin and (b) human erythropoietin. Recommend a host cell for each and justify your choice from cell organization and the universal features of cells.** 12 marks

Universal features (DNA, transcription, translation, genetic code) let any host read a human gene supplied as cDNA with a suitable promoter. Insulin: no sugar chains needed, so *E. coli*: fast growth, cheap media, high yield. EPO: a glycoprotein whose sugar chains are added in the ER and Golgi and are needed for it to act as a drug, so a eukaryotic host with an endomembrane system, such as CHO cells. Weigh cost, speed and yield against correct processing. Spans Chapters 1.2, 1.4 and 1.5.

– EVALUATE **"Compartmentalization is what made large cells possible." Discuss, using surface-to-volume ratio, diffusion and the functions of organelles.** 12 marks

SA/V = 3/r falls as cells grow; diffusion time grows with distance squared (worked numbers). Internal membranes multiply area (hepatocyte internal membranes about 50 times the plasma membrane). Compartments keep incompatible reactions apart (lysosome pH), concentrate pathways (matrix), build gradients (ATP synthesis) and separate transcription from translation. Counterpoint: the cytoskeleton and motor transport also matter, and some bacteria grow large in other ways. Spans Chapters 1.2 and 1.5.

– ANALYZE **Archaea look like bacteria but share some machinery with eukaryotes. Using the universal features and the differences between the cell plans, discuss how many basic kinds of cell there are.** 10 marks

Shared by all: the universal features of Chapter 1.4. By structure, two plans (no nucleus versus nucleus). By molecular evidence (16S rRNA, Woese 1977), three domains: archaea differ from bacteria in ether-linked lipids and walls without peptidoglycan, and resemble eukaryotes in their DNA-reading machinery. Conclusion: two organizational plans but three lineages; answer depends on whether structure or ancestry is the criterion. Spans Chapters 1.2 and 1.4.

Glossary

Archaea	Prokaryotes that form a domain of their own, separate from bacteria, with ether-linked membrane lipids and no peptidoglycan.
Binary fission	Division of a prokaryotic cell into two after copying its chromosome, without mitosis.
Capsule	Sticky polysaccharide coat outside the wall of many bacteria.
Cell theory	All organisms are made of cells, the cell is the basic unit of life, and cells arise only from cells.
Centriole	Small cylinder of microtubules; a pair forms the centrosome of animal cells.
Coenocyte, syncytium	A mass of cytoplasm with many nuclei and no dividing walls; a syncytium forms by cells fusing.
Compartment	A membrane-enclosed space in a cell with its own set of proteins and conditions.
Condensation	Reaction that joins two molecules and releases water; builds polymers.
Cytoplasm	Everything between the plasma membrane and the nucleus, organelles included.
Cytosol	The fluid part of the cytoplasm, outside all organelles.
Endomembrane system	ER, Golgi, endosomes, lysosomes and vesicles, which exchange material by vesicles.
Endosymbiotic theory	Mitochondria and chloroplasts descend from bacteria engulfed by an ancestral cell.
Eukaryote	Organism whose cells keep their DNA in a nucleus and have membrane-bound organelles.
Hydrolysis	Reaction that splits a bond by adding water; breaks polymers into monomers.
Lumen	The inside space of a membrane-bound organelle such as the ER or a lysosome.
Macromolecule	Large molecule built from many small units: protein, nucleic acid or polysaccharide.
Nucleoid	Region of a prokaryotic cell holding its DNA, with no membrane around it.
Nucleolus	Dense region inside the nucleus where ribosome subunits are made.
Organelle	A structure in a cell with a specific job, such as a mitochondrion or a ribosome.

Peptidoglycan	Mesh of sugar chains cross-linked by short peptides that forms the bacterial cell wall.
Plasmid	Small circular DNA molecule that copies itself apart from the chromosome.
Plasmodesmata	Channels through plant cell walls that join the cytoplasm of neighbouring cells.
Plastid	Double-membrane plant organelle: chloroplast, chromoplast or leucoplast.
Prokaryote	Organism (bacterium or archaeon) whose cells have no nucleus and no membrane-bound organelles.
Resolution	The smallest distance at which two points can still be seen as separate.
Signal sequence	Short stretch of amino acids that directs a protein to its compartment.
Svedberg unit (S)	Measure of how fast a particle sinks in a centrifuge; used to name ribosomes and their subunits.
Tonoplast	Membrane around the central vacuole of a plant cell.
Turgor pressure	Pressure of the water-filled vacuole pushing the cytoplasm against the cell wall.

Sources and further reading

Textbooks

- Alberts B. et al. *Molecular Biology of the Cell*, 7th edition, W. W. Norton (2022): the chapters on cells and genomes, cell chemistry, and intracellular compartments and protein sorting (from memory; check).
- Lodish H. et al. *Molecular Cell Biology*, W. H. Freeman: the opening chapters on cells and their molecules (from memory; check).
- Cooper G. M. *The Cell: A Molecular Approach*, Oxford University Press: the chapters on the origin and composition of cells (from memory; check).
- Karp G. *Cell and Molecular Biology: Concepts and Experiments*, Wiley: the introductory chapter on cells (from memory; check).
- NCERT *Biology*, Class XI, chapter "Cell: The Unit of Life", for a school-level recap of cell theory and cell types (from memory; check).

Open web resources used for numbers in this book

- BioNumbers 105911, internal membrane area of a hepatocyte, about 100 000 μm², 50 times the plasma membrane (source given there: Alberts et al.):

bionumbers.hms.harvard.edu/bionumber.aspx?id=105911

- BioNumbers 110374, relative amounts of membrane types; the ER membrane is about 25 times (liver) and 12 times (pancreatic exocrine cell) the plasma-membrane area: bionumbers.hms.harvard.edu/bionumber.aspx?id=110374
- BioNumbers 110373, membrane-enclosed compartments occupy nearly half the volume of a cell: bionumbers.hms.harvard.edu/bionumber.aspx?id=110373
- University of Hamburg course page, "Molecular composition of a bacterial cell" (data for Figure 1.4.1): www-archiv.fdm.uni-hamburg.de/b-online/library/biology107/bi107vc/fa99/terry/table2.html
- Thermo Fisher Scientific, "Macromolecular components of *E. coli* and HeLa cells" (masses used in the Chapter 1.4 worked example and questions): thermofisher.cn, Ambion technical reference

Syllabus: the University free n easy universal syllabus, built from top universities' syllabi.

Built for the University free n easy YouTube channel from the universal syllabus of Cell Biology (Oct 2026). Written with top universities' syllabi and standard textbooks; check a formula against your prescribed book before an exam, and report mistakes on the channel.