Cell Biology

Unit 1 · Lesson 2 · Cell chemistry and compartments

The notes for Lesson 2 of Unit 1: chapters 1.4 to 1.5 of the unit book, with their figures, worked examples, exam traps and quizzes, in one file. The full unit book, with every chapter, the exam question bank and the glossary, is linked at the end.

Lesson 2 of 2 | 2 chapters | Chapters 1.4 to 1.5

About these notes

These are the notes for **Lesson 2 · Cell chemistry and compartments** of the University free n easy video lessons on Cell Biology Unit 1, Foundations: Cell Theory and Cell Types. They are chapters 1.4 to 1.5 of the unit book, unchanged, so a page here is the same page in the full book.

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.

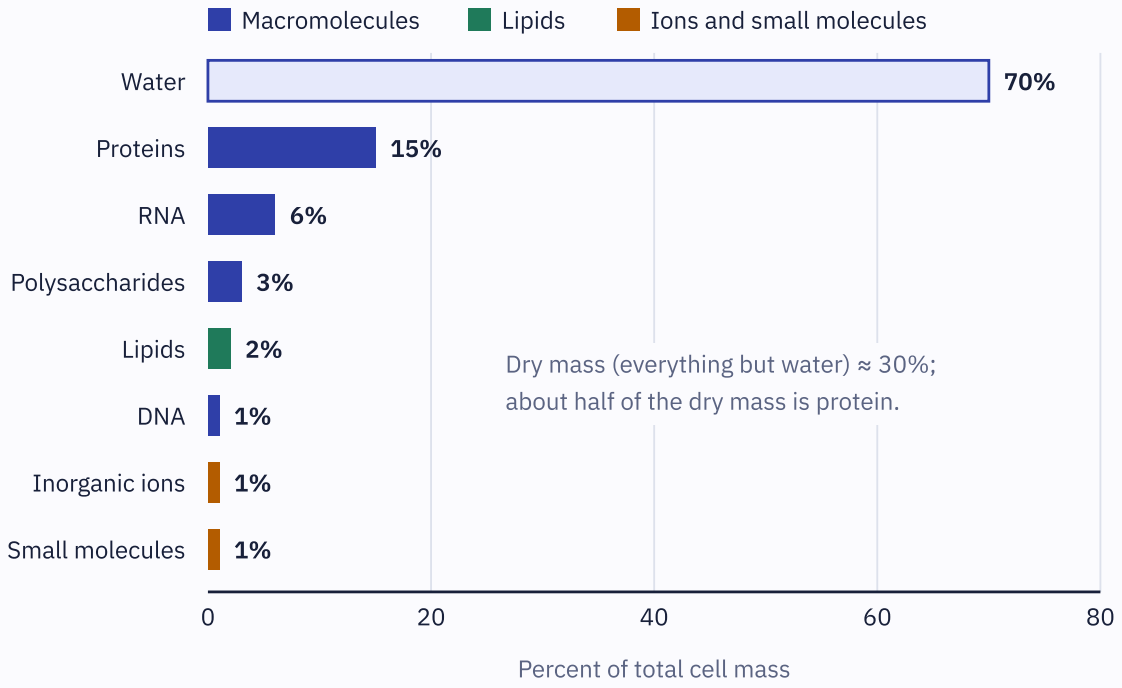


Figure 1.4.1 Approximate composition of a bacterial cell by mass, from a classic textbook table (University of Hamburg course page, see Sources). Water dominates; among the rest, protein is the largest share, and RNA outweighs DNA six to one because the cell's tens of thousands of ribosomes are built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

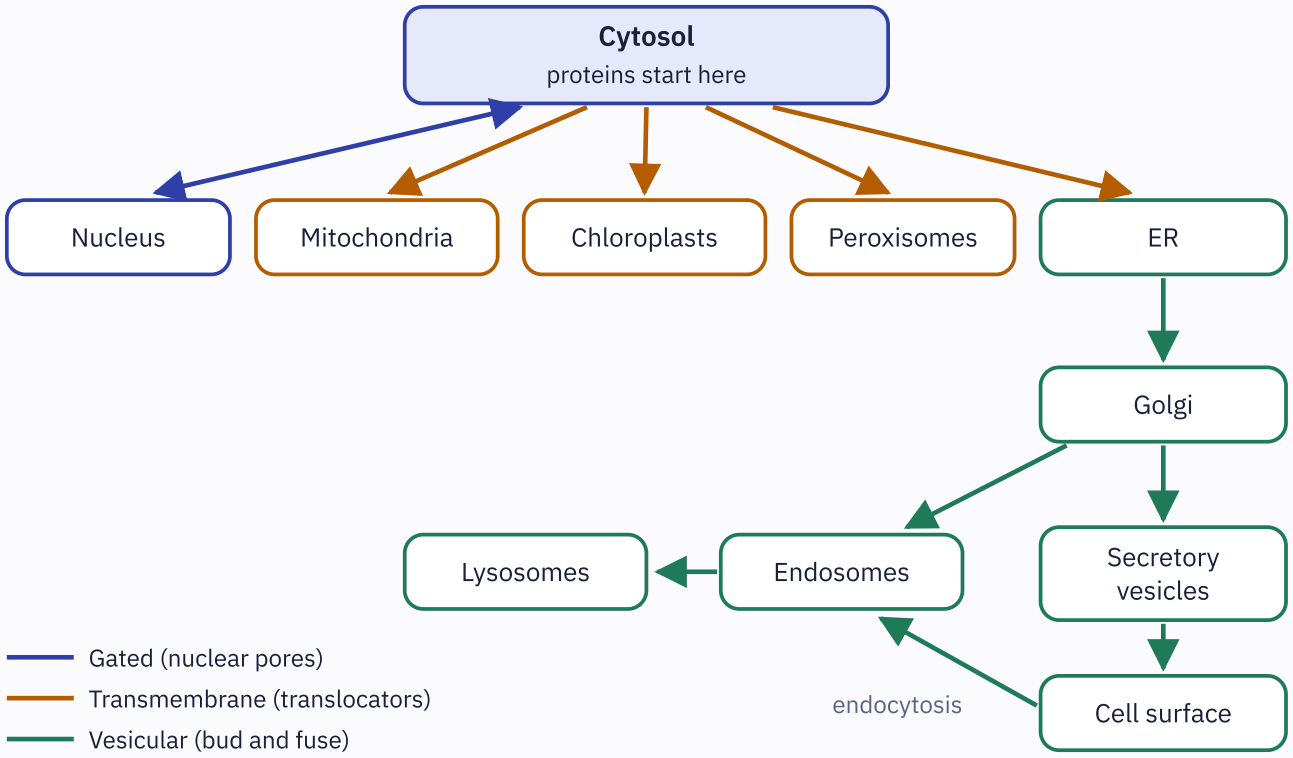


Figure 1.5.1 The protein traffic map of a eukaryotic cell. Blue: gated transport through nuclear pores (two-way). Orange: transmembrane transport by translocators from the cytosol into mitochondria, chloroplasts, peroxisomes and the ER. Green: vesicular transport inside the endomembrane system, from 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.

Key terms of this lesson

TERM	MEANING OR FORMULA	CHAPTER
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

Glossary (terms used in this lesson)

Centriole Small cylinder of microtubules; a pair forms the centrosome of animal cells.

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.
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.
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.
Signal sequence	Short stretch of amino acids that directs a protein to its compartment.
Tonoplast	Membrane around the central vacuole of a plant cell.

The full unit book

Every chapter of Unit 1, the unit summary, the exam question bank with model answers and the full glossary: Cell Biology · Unit 1 · Foundations: Cell Theory and Cell Types (one file, works offline).

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.