Cell Biology

Unit 3 · Lesson 3 · Ribosomes, mitochondria and chloroplasts

The notes for Lesson 3 of Unit 3: chapters 3.5 to 3.7 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 3 of 4 | 3 chapters | Chapters 3.5 to 3.7

About these notes

These are the notes for **Lesson 3 · Ribosomes, mitochondria and chloroplasts** of the University free n easy video lessons on Cell Biology Unit 3, Cell Organelles and Cytoskeleton. They are chapters 3.5 to 3.7 of the unit book, unchanged, so a page here is the same page in the full book.

3.5 Ribosomes

A ribosome is the machine that reads an mRNA and joins amino acids into a protein. It is made of two subunits of ribosomal RNA (rRNA) and protein, has no membrane, and is found in every living cell, which is why it is often counted as an organelle even in bacteria. The key fact for modern biology is that the ribosome is a **ribozyme**: the bond between amino acids is made by its RNA, not by its proteins. Because bacterial and human ribosomes differ, many antibiotics can block the first without harming the second.

You need: the nucleolus from Chapter 3.1. The genetic code and the steps of translation in full belong to molecular biology; this chapter covers the ribosome as a structure.

Size, subunits and the Svedberg unit

Ribosomes are named by how fast they sink in an ultracentrifuge. The **sedimentation coefficient** s is the sinking speed divided by the centrifugal acceleration, and is measured in **Svedberg units** (S), where 1 S = 10^{-13} s. A larger s means faster sinking. It depends on mass *and* shape, so values do not add up: a 50S and a 30S subunit together make a 70S ribosome, not 80S, because the joined particle is more compact than two separate ones.

FEATURE	PROKARYOTIC (70S)	EUKARYOTIC CYTOSOLIC (80S)
Large subunit	50S: 23S + 5S rRNA, about 33 proteins	60S: 28S + 5.8S + 5S rRNA, about 47 proteins
Small subunit	30S: 16S rRNA, 21 proteins	40S: 18S rRNA, about 33 proteins
Where made	in the cytoplasm	rRNA and assembly in the nucleolus
Also found in	mitochondria and chloroplasts have bacteria-like ribosomes	free in cytosol or bound to rough ER

Protein counts vary by a few between species and sources, so learn them as "about". In both kinds, rRNA forms most of the mass and the core of the active sites; the proteins sit mostly on the surface. The 16S rRNA of the small subunit pairs with the Shine–Dalgarno sequence of a bacterial mRNA to place the start codon, and its sequence is the standard tool for identifying bacteria.

Ribosomes need magnesium ions to hold the two subunits together. If Mg^{2+} is removed in the lab, the ribosome falls apart into its subunits.

The working parts: three tRNA sites and a tunnel

The two subunits clamp the mRNA between them. The **small subunit** holds the mRNA and checks that each codon pairs correctly with the anticodon of its tRNA (decoding). The **large subunit** holds the **peptidyl transferase centre**, which makes the peptide bond. Three tRNA sites lie across both subunits:

- **A site** (aminoacyl): the incoming tRNA carrying the next amino acid binds here.
- **P site** (peptidyl): the tRNA holding the growing chain sits here.
- **E site** (exit): the empty tRNA leaves from here.

1. An aminoacyl-tRNA, brought by an elongation factor with GTP, enters the A site if its anticodon matches the codon.
2. The peptidyl transferase centre moves the whole growing chain from the P-site tRNA on to the amino acid of the A-site tRNA, making a new peptide bond.
3. Another elongation factor, using GTP, moves the ribosome three nucleotides along the mRNA (translocation): the A-site tRNA moves to P, the P-site tRNA to E.
4. The empty tRNA leaves from E and the A site is free for the next codon. A stop codon brings a release factor instead of a tRNA, and the chain is freed.

The new chain leaves through an **exit tunnel** in the large subunit. This is where SRP meets the signal sequence for ER targeting (Chapter 3.2). Several ribosomes can read one mRNA at the same time, spaced along it like beads; this string is a **polysome** (polyribosome).

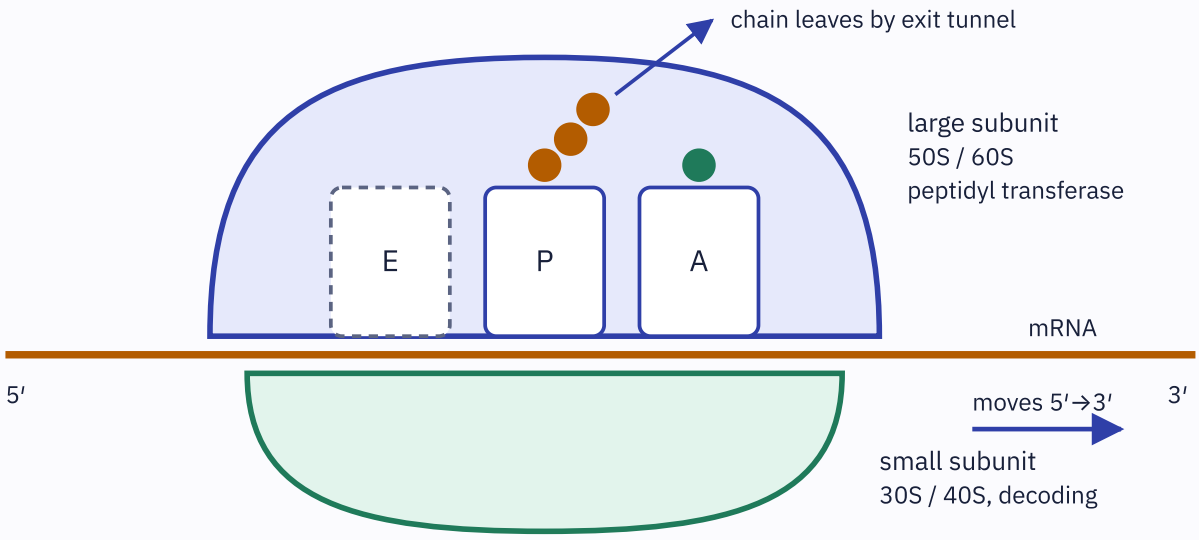


Figure 3.5.1 A ribosome during elongation. The mRNA runs between the two subunits; the E, P and A sites span both. The new peptide bond forms in the large subunit, and the chain threads out through the exit tunnel. The ribosome steps toward the 3′ end of the mRNA, one codon at a time.

Antibiotics and the endosymbiont link

Because 70S and 80S ribosomes differ, many antibiotics hit only the bacterial kind:

- **Streptomycin** binds the 30S subunit and causes misreading of codons.
- **Tetracycline** binds the 30S subunit and blocks aminoacyl-tRNA from entering the A site.
- **Chloramphenicol** binds the 50S subunit and blocks peptidyl transferase.
- **Erythromycin** (a macrolide) binds the 50S subunit and blocks the exit tunnel.
- **Cycloheximide** blocks eukaryotic 80S ribosomes and is used in the lab, not as a drug.

Mitochondria and chloroplasts carry their own ribosomes, which resemble bacterial ones and are sensitive to some of these antibiotics. This is one piece of evidence for their bacterial origin (Chapter 3.6), and it explains some side effects of chloramphenicol.

WORKED EXAMPLE

Question (6 marks). The coding region of an mRNA is 1,203 nucleotides long, including the start codon AUG and one stop codon. (a) How many amino acids are in the protein? (b) Assume a eukaryotic ribosome adds 6 amino acids per second. How long does one ribosome take to make the protein? (c) If ribosomes start on this mRNA every 4 seconds and it stays in use for 10 minutes, about how many protein copies does it give?

Solution.

1. Codons = 1,203 ÷ 3 = 401. The stop codon codes for no amino acid, so the protein has **400 amino acids** (the first is methionine, from AUG).
2. Time = 400 amino acids ÷ 6 per second ≈ **67 s**, a little over one minute.
3. Ten minutes = 600 s. A new ribosome starts every 4 s, so about 600 ÷ 4 = 150 ribosomes start. Allowing the last ones about 67 s to finish, about **150 copies** are made from the single mRNA, and at any moment about 67 ÷ 4 ≈ 17 ribosomes sit on it as a polysome.

Answer: 400 amino acids; about 67 s; about 150 copies. The polysome is how one mRNA becomes many proteins quickly.

EXAM TRAPS

- 50S + 30S = 70S, and 60S + 40S = 80S. Svedberg values are not additive; say why (shape and mass, not mass alone).
- Mitochondrial ribosomes are not 80S. They are bacteria-like (in mammals about 55S).
- The peptide bond is made by rRNA (23S or 28S), not by a ribosomal protein. This is the most asked "ribozyme" question.
- The 5.8S rRNA is found only in eukaryotes, in the large subunit, paired with the 28S rRNA.
- Free and ER-bound ribosomes are the same; only the protein being made decides where they sit.

CHECK YOURSELF

– REMEMBER **List the rRNAs of the eukaryotic large subunit.** 2 marks

28S, 5.8S and 5S rRNA.

– REMEMBER **What do the A, P and E sites hold?** 3 marks

A: the incoming aminoacyl-tRNA. P: the tRNA carrying the growing peptide. E: the empty tRNA about to leave.

– UNDERSTAND **Why is the ribosome called a ribozyme?** 2 marks

Its catalytic step, forming the peptide bond, is carried out by rRNA in the large subunit. Atomic structures show that the active site is built of rRNA.

– UNDERSTAND **Explain why a 70S ribosome dissociates into 50S and 30S rather than into two 35S halves.** 2 marks

The subunits are different particles of different mass and composition; the S value of each reflects its own mass and shape, and the joined particle's S is not the sum.

– APPLY **A protein has 250 amino acids. What is the minimum length of its coding region including the stop codon?** 2 marks

(250 + 1) × 3 = 753 nucleotides.

– APPLY **Why can tetracycline treat a bacterial infection without stopping protein synthesis in the patient's cytosol?** 2 marks

It binds the 30S subunit of the bacterial 70S ribosome; the human cytosolic 80S ribosome has a different 40S small subunit that it does not block effectively.

– ANALYZE **What would you expect if a drug blocked the exit tunnel in a pancreatic acinar cell? Reason about the ER.** 4 marks

Chains could not leave the tunnel, so no signal sequence would appear for SRP to bind. Ribosomes would not be targeted to the ER, digestive enzymes would not enter the secretory pathway, and secretion would stop. Synthesis of all other proteins would also stall.

BEYOND THE SYLLABUS

The 2009 Nobel Prize in Chemistry went to Ramakrishnan, Steitz and Yonath for atomic structures of the ribosome, which are now used to design antibiotics that avoid resistance. 16S rRNA sequencing is the standard method in microbiome studies, from gut bacteria to soil. Ribosome profiling (Ribo-seq) maps which mRNAs are being translated in a cell at a given moment. Search "ribosome profiling" and "16S rRNA amplicon sequencing". Not for the exam.

3.6 Mitochondria: structure and function

Mitochondria are the organelles that make most of a eukaryotic cell's ATP by using oxygen to burn food molecules. They have two membranes, their own small genome and their own ribosomes, because they descend from bacteria that lived inside an ancient host cell. Their central trick, the **chemiosmotic** mechanism, is to pump protons across the inner membrane and let them flow back through ATP synthase, much like water stored behind a dam turning a turbine. Beyond ATP, mitochondria also control apoptosis, buffer calcium and make heme.

You need: active transport and ATP pumps from **Unit 2, Active transport**. The detailed reactions of glycolysis and the citric acid cycle belong to your biochemistry course.

Structure: four compartments

A mitochondrion is often drawn as a bean about 0.5–1 µm wide and a few µm long, but in living cells many mitochondria join into a branching network that keeps splitting (**fission**) and joining (**fusion**). The number per cell follows energy demand: heart muscle and liver cells hold hundreds to thousands. Mature red blood cells have none.

- **Outer membrane:** smooth and leaky. Channel proteins called **porins** (VDAC) let molecules up to about 5 kDa pass, so ions and small metabolites cross freely.
- **Intermembrane space:** the narrow gap between the membranes; it holds cytochrome c and becomes rich in protons when the electron transport chain runs.
- **Inner membrane:** folded into **cristae**, which raise its area. It is about three-quarters protein, holds the electron transport chain and ATP synthase, and is rich in the lipid **cardiolipin**. It is impermeable to most ions, including H^+; every metabolite crosses on a specific carrier (for example the ADP/ATP translocase).
- **Matrix:** the inner space, a dense gel holding the enzymes of pyruvate oxidation, the **citric acid cycle** and fatty-acid **β-oxidation**, plus mitochondrial DNA, ribosomes and tRNAs.

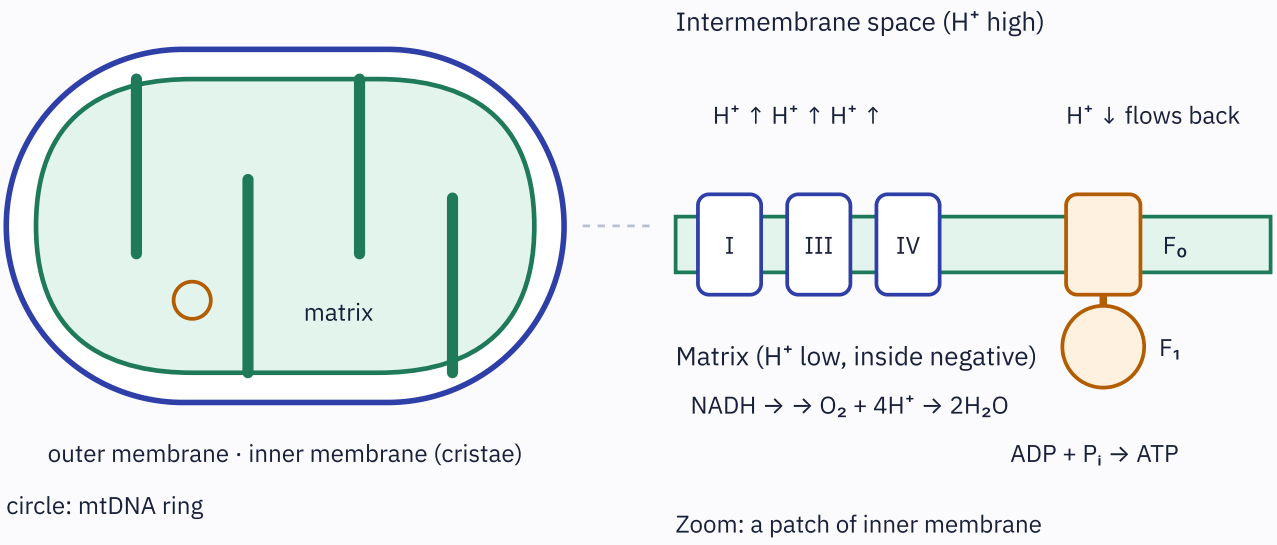


Figure 3.6.1 Left, a mitochondrion in section. Right, a patch of inner membrane: complexes I, III and IV pump protons into the intermembrane space as electrons pass from NADH to oxygen; protons return through the F_o part of ATP synthase, and its F_1 head in the matrix makes ATP. Complex II, which feeds electrons from $FADH_2$, pumps none and is left out.

How mitochondria make ATP

1. **Fuel in.** Pyruvate from glycolysis and fatty acids enter the matrix and are oxidised to acetyl-CoA, which the citric acid cycle burns to CO_2. The energy is captured as the reduced carriers NADH and $FADH_2$.
2. **Electron transport.** NADH gives electrons to **complex I**; $FADH_2$ (from succinate) gives them to **complex II**. Ubiquinone carries them to **complex III**, cytochrome c carries them to **complex IV**, which passes them to O_2, forming water. Oxygen is the final electron acceptor.
3. **Proton pumping.** Complexes I, III and IV use the energy released to move protons from the matrix to the intermembrane space: about 10 H^+ for each NADH and 6 for each $FADH_2$.
4. **Proton-motive force.** The result is a pH difference (matrix more alkaline) and a voltage (matrix negative). Together they form the **proton-motive force**, Δp.
5. **ATP synthesis.** Protons flow back through **ATP synthase**. Its membrane part F_o includes a ring of c subunits that rotates as protons pass; the rotation turns a central stalk inside the F_1 head (three α and three β subunits), and each β subunit in turn binds ADP and P_i, makes ATP and releases it. This is Paul Boyer's **binding-change mechanism**.

Peter Mitchell proposed the chemiosmotic hypothesis in 1961 and received the 1978 Nobel Prize for it. In modern accounting, one NADH gives about 2.5 ATP and one $FADH_2$ about 1.5 ATP (the P/O ratios), and complete oxidation of one glucose gives about 30–32 ATP.

$$\Delta p = \Delta\psi + (2.303\ RT / F) \cdot \Delta pH$$

Here $\Delta\psi$ is the membrane potential (size of the voltage, matrix negative), ΔpH = pH(matrix) − pH(intermembrane space), $R = 8.314\ J\ mol^{-1}\ K^{-1}$, T is the temperature in kelvin, and $F = 96{,}485\ C\ mol^{-1}$ (Faraday constant). At 37 °C, $2.303RT/F \approx 61.5$ mV per pH unit. The energy released when one mole of H^+ flows back is $\Delta G = -F \cdot \Delta p$.

Blocking the chain. Rotenone blocks complex I, antimycin A complex III, and cyanide, azide and carbon monoxide complex IV; oligomycin blocks ATP synthase. **Uncouplers** such as 2,4-dinitrophenol carry protons across the inner membrane, so oxygen is used but no ATP is made and the energy is lost as heat. Brown fat does this on purpose with **UCP1** (thermogenin) to keep newborns warm.

Genome, origin and other roles

Human mitochondrial DNA (mtDNA) is a circle of 16,569 base pairs with 37 genes: 13 for proteins of the respiratory chain and ATP synthase, 22 for tRNAs and 2 for rRNAs. All other mitochondrial proteins, more than a thousand, are coded in the nucleus, made in the cytosol and imported through the **TOM** (outer) and **TIM** (inner) complexes, guided by an N-terminal presequence. mtDNA is inherited from the mother, and mutations in it cause disorders such as Leber hereditary optic neuropathy.

The **endosymbiotic theory**, argued strongly by Lynn Margulis from 1967, says mitochondria came from α-proteobacteria taken in by an ancestral host cell. Evidence: two membranes, circular DNA without histones, 70S-type ribosomes sensitive to some antibiotics, and division by fission. Mitochondria also release **cytochrome c** to start apoptosis (Unit 4), take up Ca^{2+}, and make heme and iron–sulfur clusters.

WORKED EXAMPLE

Question (8 marks). In a liver mitochondrion at 37 °C, the membrane potential is 160 mV (matrix negative) and the matrix pH is 0.75 units higher than the intermembrane space. (a) Find the proton-motive force. (b) Find the free energy released per mole of H^+ flowing into the matrix. (c) Making one mole of ATP inside the cell needs about 50 kJ. What is the minimum number of protons per ATP?

Solution.

1. Chemical part: 61.5 mV × 0.75 = 46.1 mV.
2. Δp = 160 + 46.1 = **206 mV** = 0.206 V.
3. $\Delta G = -F \cdot \Delta p = -96{,}485\ \text{C mol}^{-1} \times 0.206\ \text{V} = -19{,}876\ \text{J mol}^{-1} \approx$ **−19.9 kJ per mol H^+** (C × V = J).
4. Minimum protons = 50 ÷ 19.9 ≈ 2.5, so at least **3 protons** must flow per ATP (a whole number above 2.5).

Answer: Δp ≈ 206 mV; about 19.9 kJ per mole of H^+; at least 3 H^+ per ATP. The real figure is a little higher, because protons are also spent bringing ADP and phosphate into the matrix; this is why NADH gives 2.5 ATP and not more. Note that the voltage contributes more than the pH gradient in mitochondria.

EXAM TRAPS

- Protons are pumped into the intermembrane space, not into the matrix. The matrix is the alkaline, negative side.
- Glycolysis happens in the cytosol, not in the mitochondrion. The citric acid cycle is in the matrix; the electron transport chain is in the inner membrane.
- Complex II pumps no protons, which is why $FADH_2$ gives less ATP than NADH.
- The outer membrane is permeable to small molecules; the inner membrane is the barrier. Students often swap them.
- Most mitochondrial proteins are coded by the nucleus, not by mtDNA.

CHECK YOURSELF

– REMEMBER **Name the four compartments of a mitochondrion.** 2 marks

Outer membrane, intermembrane space, inner membrane (with cristae) and matrix.

– REMEMBER **What does human mtDNA code for?** 2 marks

37 genes: 13 proteins of oxidative phosphorylation, 22 tRNAs and 2 rRNAs.

– UNDERSTAND **Why are cristae important?** 2 marks

They fold the inner membrane and raise its area, so more electron transport chains and ATP synthases fit in one mitochondrion; very active cells have densely packed cristae.

– UNDERSTAND **Explain how an uncoupler causes fever-like heat.** 3 marks

It lets protons leak back across the inner membrane without passing through ATP synthase. The chain keeps running and using oxygen to rebuild the gradient, but the energy is released as heat instead of being stored in ATP.

– APPLY **At 37 °C, Δψ = 150 mV and ΔpH = 0.5. Find Δp.** 2 marks

61.5 × 0.5 = 30.8 mV; Δp = 150 + 30.8 ≈ 181 mV.

– APPLY **A cell is poisoned with cyanide. What happens to oxygen use and ATP synthesis, and why?** 3 marks

Both stop: cyanide blocks complex IV, so electrons cannot reach O_2, the chain backs up, no protons are pumped and the gradient that drives ATP synthase collapses.

– ANALYZE **Evaluate the evidence that mitochondria were once bacteria.** 5 marks

Supporting: double membrane, circular DNA without histones, 70S-type ribosomes sensitive to chloramphenicol, division by fission, and gene sequences closest to α-proteobacteria. Complication: most of their genes have moved to the nucleus, so they cannot live alone; this is explained by gene transfer after the endosymbiosis.

BEYOND THE SYLLABUS

Mitochondrial replacement therapy ("three-parent IVF") lets a mother with an mtDNA disease have a child with healthy mitochondria from a donor egg; the UK made it legal in 2015. Cryo-EM structures of the full respiratory supercomplexes and the rotating ATP synthase are a fast-moving research area. In bioprocessing, the mitochondrial activity of CHO and yeast cells limits how much protein they make. Search "mitochondrial replacement therapy" and "respirasome cryo-EM". Not for the exam.

3.7 Chloroplasts: structure and function

Chloroplasts are the organelles of plants and algae that capture light energy and use it to turn carbon dioxide and water into sugar, releasing oxygen. Like mitochondria they have two envelope membranes, their own DNA and bacteria-like ribosomes, and they also make ATP with a proton gradient and an ATP synthase. The difference is the energy source (light instead of food) and a third membrane system inside, the **thylakoids**, where the light is caught. Almost all the food and oxygen on Earth come from this one organelle.

> You need: the proton-motive force and ATP synthase from Chapter 3.6.

Structure

A typical leaf chloroplast is a lens-shaped disc about 5–10 µm long, and a leaf mesophyll cell holds dozens of them. From outside in:

- **Envelope:** an outer membrane, permeable to small molecules, and an inner membrane with specific transporters (for example the triose-phosphate/phosphate translocator that exports sugar). The inner envelope has **no** electron transport chain, unlike the inner mitochondrial membrane.
- **Stroma:** the fluid inside the envelope. It holds the enzymes of the **Calvin cycle**, including RuBisCO, plus chloroplast DNA, 70S ribosomes and starch grains.
- **Thylakoids:** flattened membrane sacs. Stacks of them are **grana** (one stack is a granum); single thylakoids joining the stacks are **stroma lamellae** (intergranal thylakoids). The space inside every thylakoid is one connected compartment, the **thylakoid lumen**.

The thylakoid membrane carries the pigments: **chlorophyll a** (the main pigment), **chlorophyll b** and **carotenoids**, held by proteins in light-harvesting complexes around two **photosystems**. The membrane is rich in galactolipids rather than phospholipids.

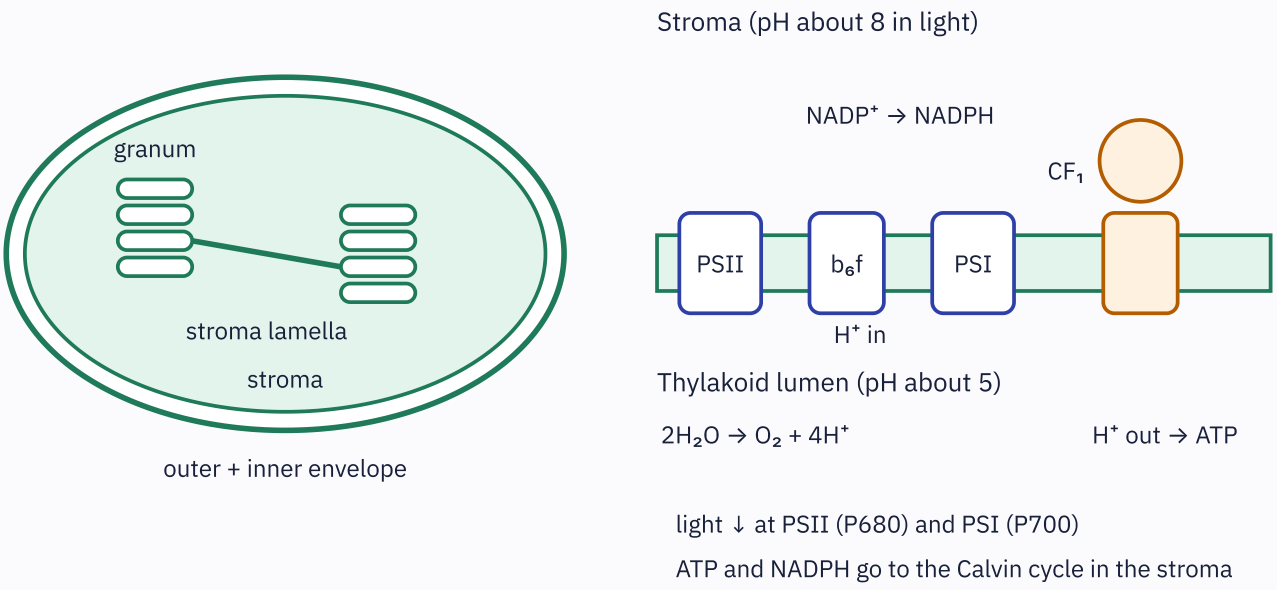


Figure 3.7.1 Left, a chloroplast with grana joined by stroma lamellae. Right, a patch of thylakoid membrane: water is split on the lumen side, protons collect in the lumen, NADPH is made on the stroma side, and protons flow out through ATP synthase whose CF_1 head faces the stroma. Compare with Figure 3.6.1: the head points into the matrix there and into the stroma here.

The light reactions in the thylakoid

1. **Light capture.** Pigments in the antenna absorb photons and pass the energy to a special chlorophyll pair at a reaction centre: **P680** in photosystem II (PSII) and **P700** in photosystem I (PSI), named for the wavelength in nm they absorb best.
2. **Water splitting.** Excited P680 gives up an electron. It takes a replacement from water through the manganese-containing oxygen-evolving complex: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$. The O_2 we breathe comes from water, and the protons stay in the lumen.
3. **Electron flow.** Electrons pass through plastoquinone, the **cytochrome b_6f complex** (which pumps more protons into the lumen) and plastocyanin to PSI. Light excites P700, and its electrons go via ferredoxin to the enzyme ferredoxin–$NADP^+$ reductase, which makes **NADPH** in the stroma. Drawn on an energy scale this path is the **Z-scheme**.
4. **ATP synthesis.** Protons flow from the lumen back to the stroma through **CF_oCF_1 ATP synthase**, making ATP in the stroma. This is **photophosphorylation**. When only PSI runs and electrons cycle back to b_6f (cyclic flow), the cell makes extra ATP without NADPH or O_2.

The Calvin cycle in the stroma

The ATP and NADPH power carbon fixation. **RuBisCO** (ribulose-1,5-bisphosphate carboxylase/oxygenase) joins CO_2 to ribulose-1,5-bisphosphate (RuBP), giving two molecules of

3-phosphoglycerate. These are reduced to glyceraldehyde-3-phosphate (G3P), and most G3P is used to rebuild RuBP. To make one G3P (3 carbons) the cycle fixes 3 CO_2 and uses **9 ATP and 6 NADPH**. RuBisCO also reacts with O_2, starting **photorespiration**, which wastes carbon and involves chloroplasts, peroxisomes and mitochondria together (Chapter 3.4). RuBisCO is thought to be the most abundant protein on Earth.

Genome, origin and other plastids

Chloroplast DNA is a circle of roughly 120–160 kb in most land plants, coding for rRNAs, tRNAs and around a hundred proteins, including the large subunit of RuBisCO; the small subunit is coded in the nucleus and imported. Chloroplasts came from a **cyanobacterium** taken in by an early eukaryote, the same endosymbiotic story as mitochondria. All plastids grow from **proplastids**: **chloroplasts** (green, photosynthetic), **chromoplasts** (carotenoid colours of tomato and chilli fruit), **amyloplasts** (starch stores, as in potato), and other **leucoplasts**. Seedlings grown in the dark have **etioplasts**, which turn into chloroplasts in light.

FEATURE	MITOCHONDRION	CHLOROPLAST
Energy source	oxidation of food	light
Where the chain sits	inner membrane	thylakoid membrane
Protons pumped into	intermembrane space	thylakoid lumen
ATP made in	matrix	stroma
Main part of Δp	voltage (Δψ)	pH difference
Ancestor	α-proteobacterium	cyanobacterium

WORKED EXAMPLE

Question (6 marks). (a) Find the energy of one photon of 680 nm light and of one mole of such photons. (b) In bright light the thylakoid lumen is 3.0 pH units more acidic than the stroma, with almost no voltage across the membrane. Find the free energy released per mole of H^+ flowing out at 25 °C. Take $h = 6.626 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m s^{-1}, $N_a = 6.022 \times 10^{23}$ mol^{-1}, $R = 8.314$ J mol^{-1} K^{-1}.

Solution.

1. $E = hc/\lambda$, where λ is the wavelength in metres: $\lambda = 680 \times 10^{-9}$ m.
2. $E = (6.626 \times 10^{-34} \times 3.00 \times 10^{8}) \div (6.80 \times 10^{-7}) = 1.988 \times 10^{-25} \div 6.80 \times 10^{-7} =$ **2.92×10^{-19} J per photon**.
3. Per mole: $2.92 \times 10^{-19} \times 6.022 \times 10^{23} = 1.76 \times 10^{5}$ J = **176 kJ per mole of photons**.
4. For a pure pH gradient, $\Delta G = -2.303\ RT \times \Delta pH$. $T = 298$ K, so $2.303 \times 8.314 \times 298 = 5{,}706$ J ≈ 5.71 kJ per pH unit.
5. $\Delta G = -5.71 \times 3.0 =$ **-17.1 kJ per mole of H^+**.

Answer: 2.92×10^{-19} J per photon, 176 kJ mol^{-1}; about 17 kJ per mole of H^+. One mole of red photons carries roughly ten times the energy of one mole of protons crossing the membrane, which is why each photon can drive several steps.

EXAM TRAPS

- Protons collect in the thylakoid lumen, not in the stroma, and not between the two envelope membranes.
- The light reactions happen on the thylakoid membrane; the Calvin cycle happens in the stroma. "Dark reactions" do not need darkness; several of their enzymes are activated by light.
- The O_2 released comes from water, not from CO_2.
- PSII acts before PSI in the electron path; the numbering follows the order of discovery.
- Chloroplasts have bacteria-like 70S ribosomes, not the 80S ribosomes of the cytosol.

CHECK YOURSELF

– REMEMBER **Name the three membrane systems of a chloroplast.** 2 marks

Outer envelope membrane, inner envelope membrane and thylakoid membrane.

– REMEMBER **What are the reaction-centre chlorophylls of PSII and PSI?** 1 mark

P680 (PSII) and P700 (PSI).

– UNDERSTAND **Why is ATP made in the stroma and not in the lumen?** 2 marks

The CF_1 head of ATP synthase faces the stroma; protons flow from the lumen out to the stroma through it, and the Calvin cycle that uses ATP is also in the stroma.

– UNDERSTAND **What is the advantage of cyclic electron flow?** 2 marks

It pumps protons and makes ATP without making NADPH, adjusting the ATP:NADPH ratio to the 9:6 the Calvin cycle needs.

– APPLY **How much ATP and NADPH are needed to make one glucose (6 carbons) from CO_2?** 2 marks

Two G3P are needed, so 2 × 9 = 18 ATP and 2 × 6 = 12 NADPH, fixing 6 CO_2.

– APPLY **Find the energy per mole of photons at 700 nm.** 2 marks

$E = 1.988 \times 10^{-25} \div 7.00 \times 10^{-7} = 2.84 \times 10^{-19}$ J; × 6.022×10^{23} = about 171 kJ mol^{-1}.

– ANALYZE **Compare how mitochondria and chloroplasts build and use the proton gradient.** 5 marks

Both pump protons across an inner membrane with an electron transport chain and use an F-type ATP synthase. Mitochondria pump from matrix to intermembrane space using food oxidation and make ATP in the matrix; Δp is mostly voltage. Chloroplasts pump into the thylakoid lumen using light and make ATP in the stroma; Δp is mostly pH, because ions such as Cl^- and Mg^{2+} move to cancel the voltage.

BEYOND THE SYLLABUS

Engineering RuBisCO, or adding bypasses for photorespiration, is a major goal in crop science; field trials in tobacco reported higher biomass. Projects to move C4 photosynthesis into rice aim at higher yields for Asian farmers. Chloroplast transformation is used to make vaccines and enzymes in plants because the plastid genome is not spread by pollen in most crops. Search "photorespiration bypass" and "C4 rice project". Not for the exam.

Key terms of this lesson

TERM	MEANING OR FORMULA	CHAPTER
Ribosomes	70S = 50S + 30S; 80S = 60S + 40S; S values not additive	3.5
Proton-motive force	$\Delta p = \Delta\psi + (2.303RT/F)\cdot\Delta pH$; 61.5 mV per pH unit at 37 °C; $\Delta G = -F\Delta p$	3.6
Photon energy	$E = hc/\lambda$; 680 nm → 176 kJ mol^{-1}	3.7
Calvin cycle cost	3 CO_2 → 1 G3P uses 9 ATP + 6 NADPH	3.7

Glossary (terms used in this lesson)

Cristae Folds of the inner mitochondrial membrane.

Endosymbiotic theory The idea that mitochondria and chloroplasts descend from bacteria living inside an ancestral cell.

Granum A stack of thylakoids in a chloroplast.

Nucleolus Membraneless nuclear region where rRNA is made and ribosome subunits assembled.

Polysome Several ribosomes translating the same mRNA at once.

Proton-motive force Energy stored in a proton gradient across a membrane, from voltage and pH difference.

Stroma Fluid inside the chloroplast envelope, site of the Calvin cycle.

Thylakoid Membrane sac inside a chloroplast carrying pigments, photosystems and ATP synthase.

The full unit book

Every chapter of Unit 3, the unit summary, the exam question bank with model answers and the full glossary: Cell Biology · Unit 3 · Cell Organelles and Cytoskeleton (one file, works offline).

Sources and further reading

Standard textbooks

- Bruce Alberts and others, *Molecular Biology of the Cell* (W. W. Norton / Garland Science): chapters on intracellular compartments and protein sorting, intracellular membrane traffic, energy conversion in mitochondria and chloroplasts, and the cytoskeleton. (from memory; check)
- Harvey Lodish and others, *Molecular Cell Biology* (W. H. Freeman / Macmillan). (from memory; check)
- Geoffrey M. Cooper, *The Cell: A Molecular Approach* (Sinauer / Oxford University Press). (from memory; check)
- Gerald Karp, *Cell and Molecular Biology: Concepts and Experiments* (Wiley). (from memory; check)
- P. S. Verma and V. K. Agarwal, *Cell Biology, Genetics, Molecular Biology, Evolution and Ecology* (S. Chand), widely prescribed in Indian universities. (from memory; check)

Open resources

- OpenStax, *Biology 2e*, Chapter 4 "Cell Structure", section 4.3 "Eukaryotic Cells" and 4.4 "The Endomembrane System and Proteins" (CC BY 4.0): an open textbook covering the organelles of this unit at an introductory level. Reached through the course pages below; section titles from memory; check.
- Penn State DuBois, Biology 110 course pages built on OpenStax *Biology 2e*: psu.pb.unizin.org/biol110/part/cell-structure/
- City Tech OpenLab, Biology 1101 Course Hub, Lecture 11 "The Eukaryotic Cell", with readings and slides: openlab.citytech.cuny.edu/bio1101coursehub/?p=3597

Numbers in this book (pore size limit, ribosome protein counts, mtDNA size, filament diameters, motor step sizes) are standard textbook values written from memory; check them against your prescribed book. Worked-example inputs such as step rates and translation speeds are given in the question and are for practice.

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