



Cell specialization

Revision notes · IB Biology B2.3: differentiation, stem cells, niches and potency, cell size and SA:V, and HL adaptations of pneumocytes, muscle cells and gametes.

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

Cell specialization

Spec B2.3

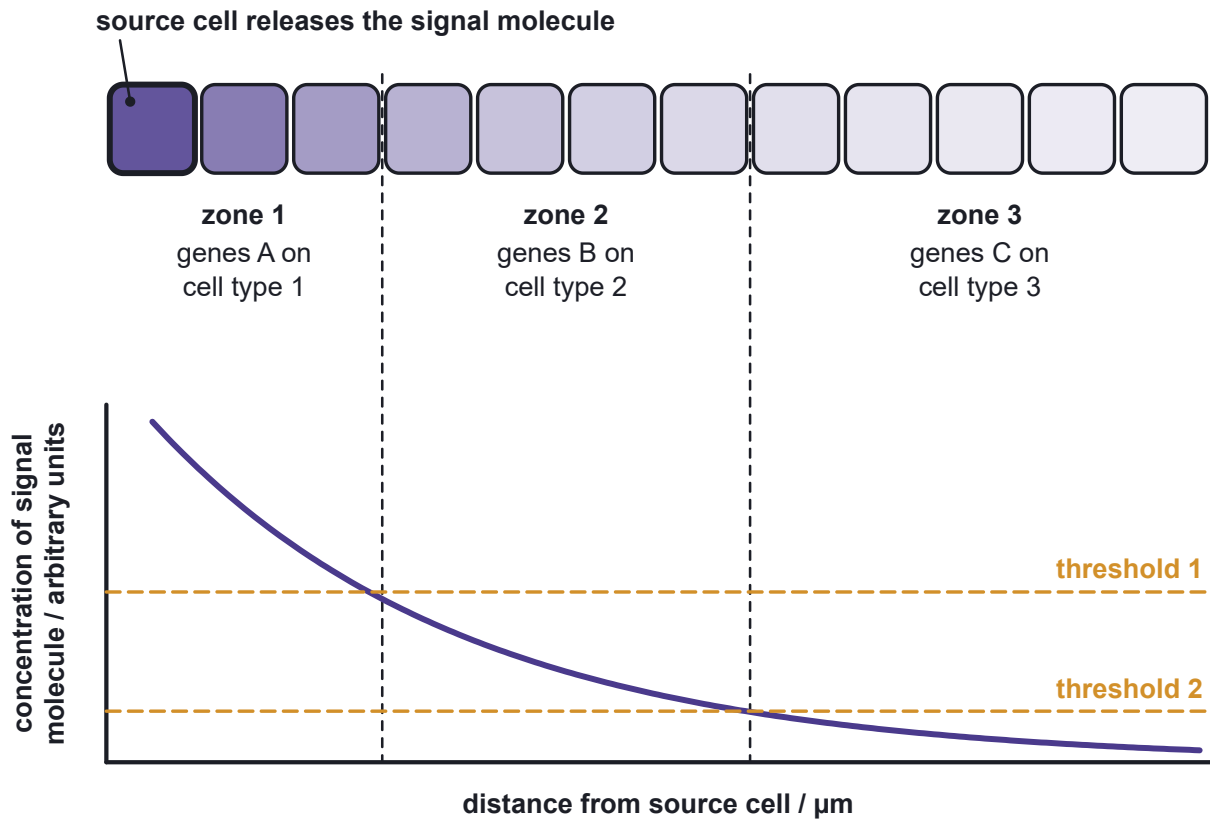
Differentiation and stem cells

Spec B2.3.1-B2.3.4

From zygote to specialized cells

Fertilization produces a **zygote**, which divides by mitosis to form an embryo of unspecialized cells. These cells then develop into specialized cells by **differentiation**: each cell type expresses a different set of genes, so it makes different proteins and develops a different structure and function. All the cells still contain the same genes.

In an early-stage embryo, certain cells release signal molecules (morphogens). These diffuse away from their source, forming a **concentration gradient** across the embryo. The concentration a cell receives depends on its position, and this determines which genes it expresses. Cells in different positions therefore follow different developmental pathways, which is how body axes such as head-to-tail are set up.



[\(opens full size in a new tab\)](#)

A **concentration gradient** of signal molecule tells each cell its position, so different genes are expressed in each zone (illustrative).

Properties of stem cells

Stem cells have two properties: they can **divide endlessly**, and they can **differentiate along different pathways** to become different cell types.

Stem cell niches in adult humans

A stem cell niche is a location in the body where stem cells are found. Conditions in the niche can either maintain the stem cells or promote their proliferation and differentiation, depending on the body's needs.

Two stem cell niches in adult humans		
Niche	Stem cells	Function
Bone marrow	Blood-forming (haematopoietic) stem cells	Produce red blood cells, white blood cells and platelets throughout life
Hair follicles	Stem cells in a region of the follicle called the bulge	Regenerate the hair follicle in each growth cycle and help repair the skin after wounding

Totipotent, pluripotent and multipotent stem cells

Potency of stem cells		
Type	Can form	Example
Totipotent	Any type of cell, including the placenta and other tissues outside the embryo; can form a whole organism	The zygote and cells of the very early embryo
Pluripotent	Any type of cell in the body, but not a whole organism	Embryonic stem cells, from the embryo a few days after fertilization
Multipotent	A limited range of related cell types	Adult stem cells, such as those in bone marrow, which form the different types of blood cell

Common mistake: Differentiated cells do not lose genes. Differentiation changes which genes are expressed, not which genes are present.

Cell size and surface area-to-volume ratio Spec B2.3.5, B2.3.6

Cell size as an aspect of specialization

Human cells vary greatly in size, and the size of each type suits its function.

Approximate sizes of some human cells		
Cell	Approximate size	Link to function
Sperm (male gamete)	Head about 5 μm long; whole cell about 50–60 μm long	Small and streamlined, with little cytoplasm, so it can swim to the egg
Egg (female gamete)	About 110 μm (0.1 mm) in diameter, at the limit of what the naked eye can see	Large, with cytoplasm and nutrients for the early embryo
Red blood cell	About 7–8 μm in diameter	Small and flexible, so it can squeeze through narrow capillaries
White blood cells	About 7–20 μm in diameter, from small lymphocytes (similar to a red blood cell) to monocytes	Most are larger than red blood cells; phagocytes are large enough to engulf bacteria
Neuron	Cell body up to about 100 μm across; axons up to about 1 m long	Long axons carry impulses over long distances, such as from the spinal cord to the foot
Striated muscle fibre	Up to about 100 μm wide and many centimetres long	Long fibres contract along their whole length

Surface area-to-volume ratio

A cell exchanges materials such as oxygen, nutrients and waste across its surface, so the rate of exchange depends on its **surface area**. The need for exchange depends on how much cytoplasm is carrying out metabolism, which is the cell's **volume**.

As a cell gets larger, its volume increases faster than its surface area. For a cube of side length L , surface area = $6L^2$ but volume = L^3 , so the **surface area-to-volume ratio** ($6 \div L$) falls as L increases. A large cell may not be able to exchange materials fast enough to meet its needs, and the distance from the surface to the centre becomes long for diffusion. This constrains cell size.

surface area-to-volume ratio = surface area ÷ volume

Calculating SA:V

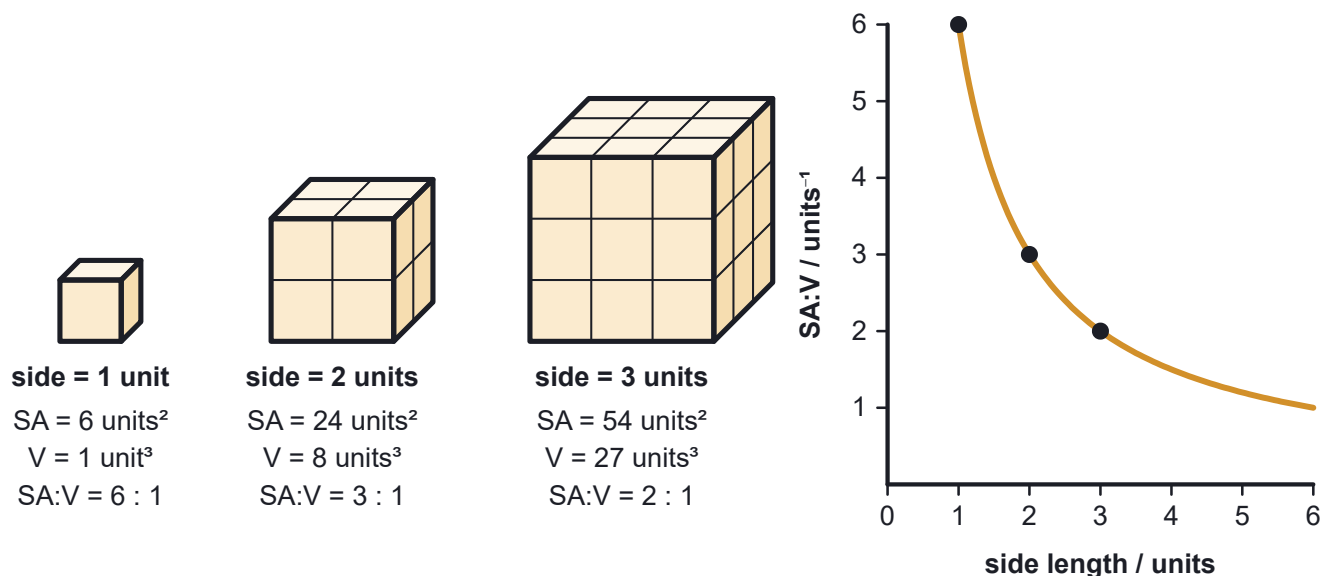
Model two cells as cubes with sides of 10 μm and 20 μm . Calculate the surface area-to-volume ratio of each and state the effect of doubling the side length.

1. 10 μm cube: surface area = $6 \times 10^2 = 600 \mu\text{m}^2$; volume = $10^3 = 1000 \mu\text{m}^3$
2. SA:V = $600 \div 1000 = 0.6 \mu\text{m}^{-1}$ (0.6 : 1)
3. 20 μm cube: surface area = $6 \times 20^2 = 2400 \mu\text{m}^2$; volume = $20^3 = 8000 \mu\text{m}^3$
4. SA:V = $2400 \div 8000 = 0.3 \mu\text{m}^{-1}$ (0.3 : 1)

Answer: Doubling the side length multiplies surface area by 4 but volume by 8, so SA:V halves, from 0.6 to 0.3 μm^{-1} .

Maths skill: Give SA:V in μm^{-1} (or cm^{-1}) or as a ratio such as 0.6 : 1. Work out surface area (squared units) and volume (cubed units) separately before dividing.

Practical skill: Model SA:V with agar cubes of different side lengths containing an indicator, placed in acid. The percentage of each cube's volume that changes colour in a fixed time shows how exchange falls behind as cubes get larger. Models are simplified: cubes are simpler than real cells, but scale factors work in the same way.



[\(opens full size in a new tab\)](#)

As side length increases, volume grows faster than surface area, so the SA:V ratio falls.

Exam tip: Linking question: what are the advantages of small size and large size in biological systems? Small cells exchange materials quickly; large organisms need extra adaptations such as lungs and a circulatory system.

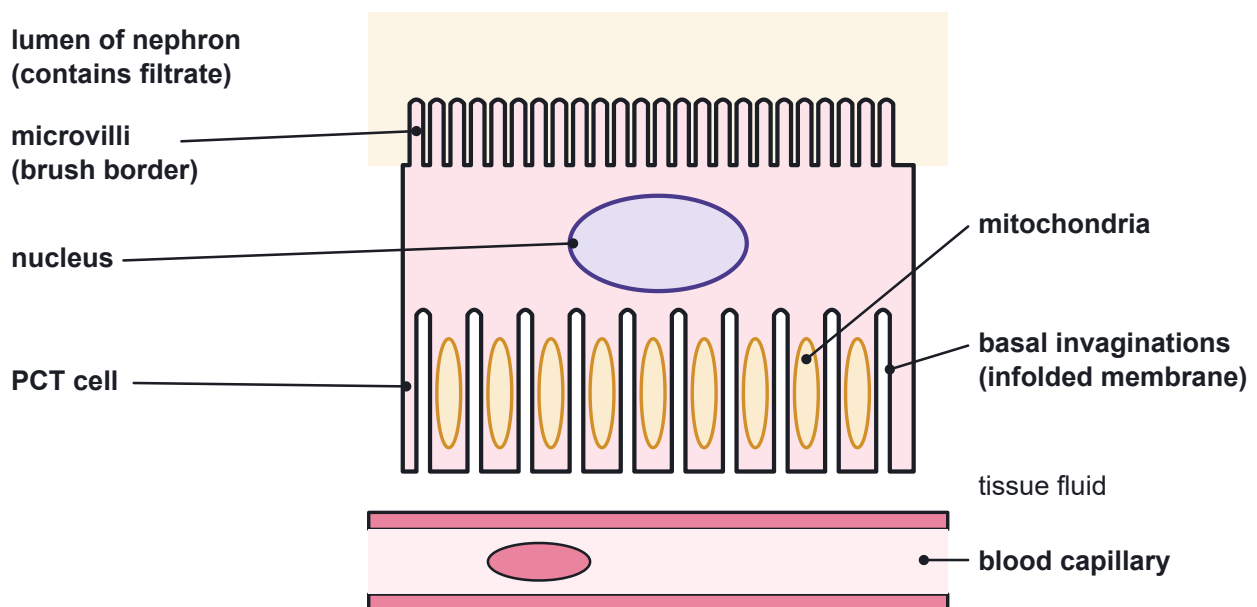
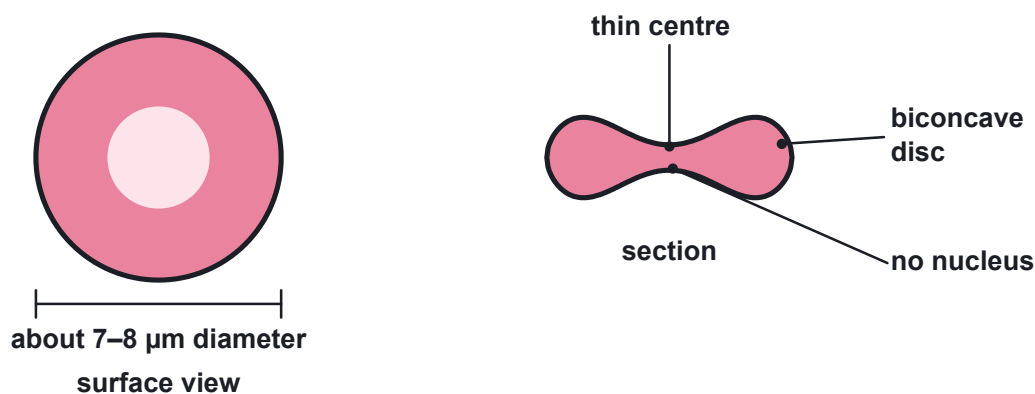
Surface area adaptations and pneumocytes

Spec B2.3.7, B2.3.8

HL only

Adaptations that increase SA:V

Increasing the surface area-to-volume ratio of cells		
Adaptation	Example	How it helps
Flattening	Erythrocytes (red blood cells) are biconcave discs	A larger surface area for the same volume, and no part of the cytoplasm is far from the surface, so oxygen loads and unloads quickly
Microvilli	Proximal convoluted tubule (PCT) cells in the nephron have a brush border of microvilli on the membrane facing the filtrate	Greatly increases the area for reabsorbing substances such as glucose, ions and water from the filtrate
Invagination	In PCT cells, the basal membrane facing the tissue fluid and blood capillaries is folded inwards	Increases the area for pumping reabsorbed substances out of the cell; many mitochondria nearby supply ATP



[\(opens full size in a new tab\)](#)

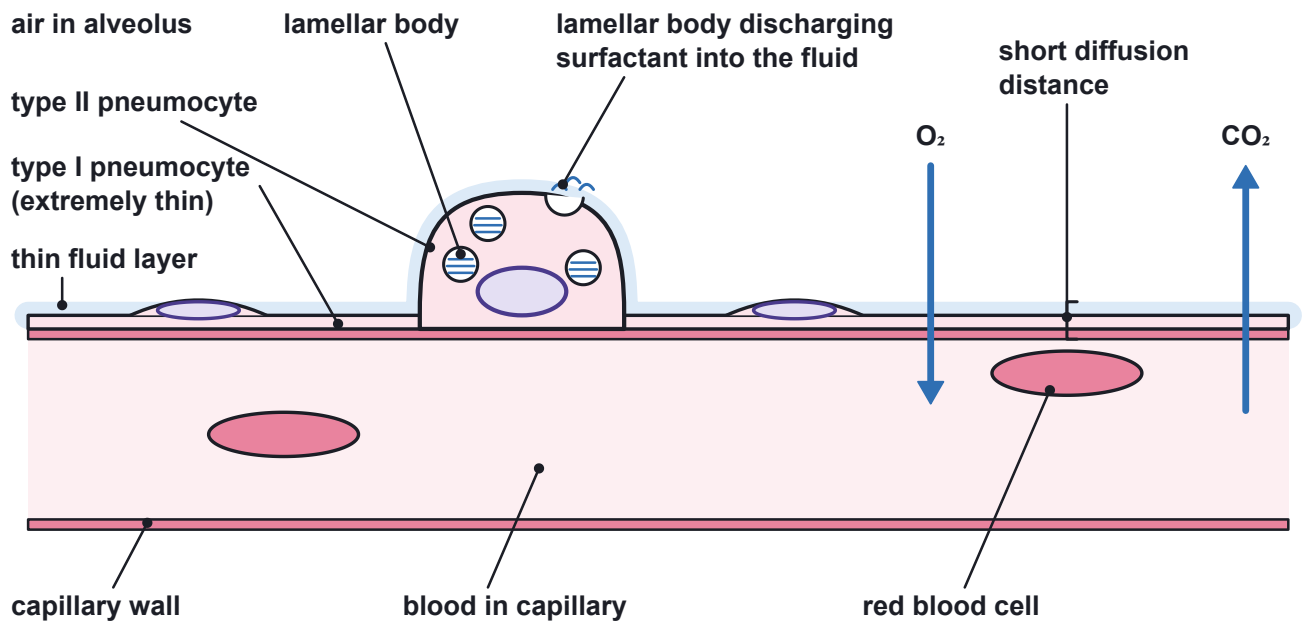
Flattening (**biconcave erythrocytes**), **microvilli** and **basal invaginations** all increase the SA:V ratio.

Type I and type II pneumocytes

The alveolar epithelium is an example of a tissue with **more than one cell type**, because different adaptations are needed for the overall function of the tissue.

Pneumocytes in the alveolar wall

Feature	Type I pneumocytes	Type II pneumocytes
Shape	Extremely thin, flattened cells covering about 95% of the alveolar surface	Rounded (cuboidal) cells; at least as numerous as type I cells but covering only about 5% of the surface
Key adaptation	Extreme thinness: the cytoplasm is much less than 1 µm thick	Many secretory vesicles, called lamellar bodies , in the cytoplasm
Function	A short distance for diffusion of O ₂ and CO ₂ between air in the alveolus and blood in the capillaries	Lamellar bodies discharge surfactant into the alveolar lumen; surfactant reduces surface tension in the moist lining, which helps stop the alveoli collapsing



[\(opens full size in a new tab\)](#)

Thin **type I pneumocytes** give a short diffusion distance; **type II pneumocytes** secrete surfactant from lamellar bodies.

Exam tip: Name the vesicles: type II pneumocytes contain lamellar bodies that discharge surfactant. Gas exchange happens mainly across the type I cells.

Cardiac muscle cells and striated muscle fibres Spec B2.3.9 HL only

Both types contain **contractile myofibrils**, which give a striped (striated) appearance and shorten when the muscle contracts. They differ in branching, length and number of nuclei.

Comparing cardiac muscle cells and striated muscle fibres

Feature	Cardiac muscle cells	Striated (skeletal) muscle fibres
Contractile myofibrils	Present	Present
Branching	Branched	Unbranched
Length	Short (about 0.1 mm)	Very long (up to many centimetres)
Nuclei	Usually one, near the centre	Many, near the edge of the fibre
Connections	Joined end to end at intercalated discs	Lie side by side, each stimulated by a motor neuron

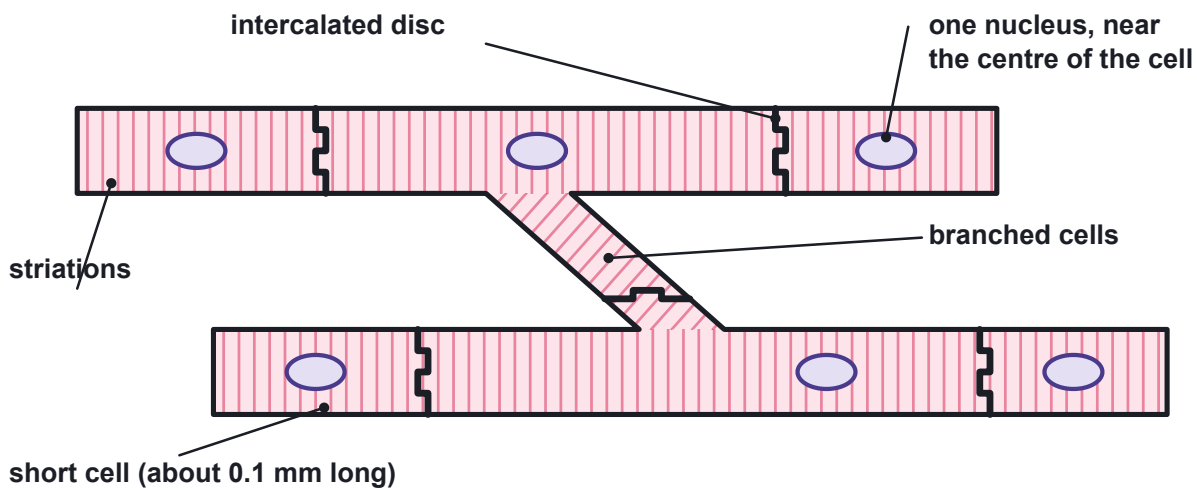
Hypotheses for the differences

- Branching: cardiac cells branch and join at intercalated discs, forming a network, so impulses spread quickly through the heart wall and the heart contracts as a coordinated unit.
- Length: a striated muscle fibre is long so that one stimulus makes the whole fibre contract along its length at the same time.
- Number of nuclei: one nucleus may not be able to supply enough mRNA for the proteins of a very large volume of cytoplasm, so a long fibre has many nuclei spread along it. A short cardiac cell needs only one.

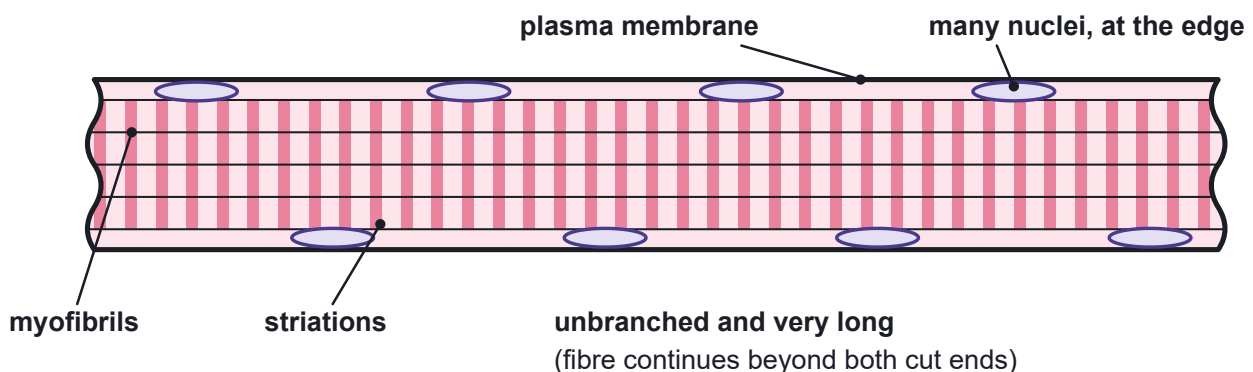
Is a striated muscle fibre a cell?

A striated muscle fibre is surrounded by one continuous plasma membrane, as a cell is. But it forms during development when many muscle precursor cells **fuse** together, and it contains many nuclei, so it does not fit the usual idea of a cell as a unit with one nucleus. It can be argued either way: it is often described as an **atypical cell**, an exception to the cell theory, or as a fused structure rather than a single cell.

Cardiac muscle



Striated (skeletal) muscle fibre



[\(opens full size in a new tab\)](#)

Cardiac cells are short, **branched** and joined by **intercalated discs**; striated fibres are long, unbranched and **multinucleate**.

Exam tip: In a 'discuss' question on whether a muscle fibre is a cell, give evidence on both sides and finish with a reasoned conclusion.

Adaptations of sperm and egg cells

Spec B2.3.10

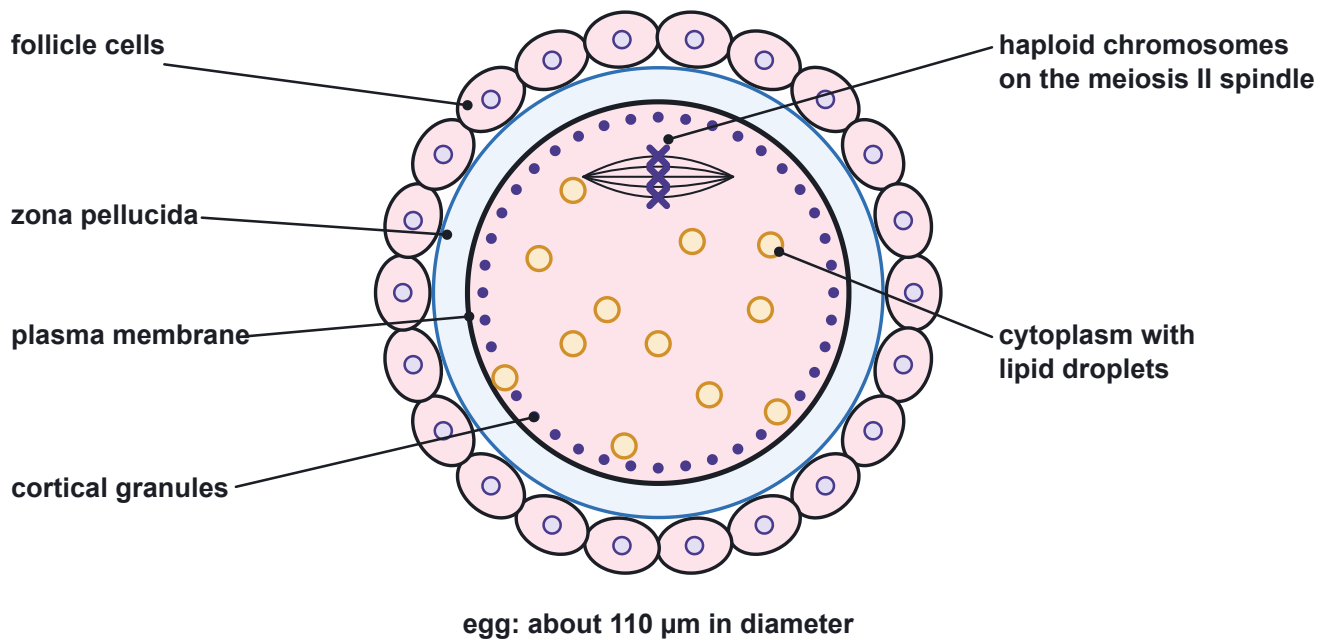
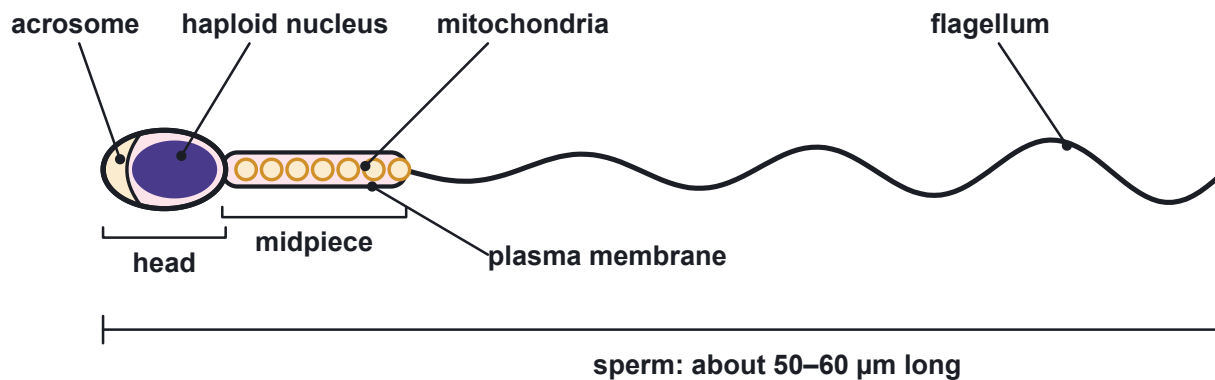
HL only

Adaptations of the human sperm

Structure	Adaptation
Haploid nucleus in the head	Carries one set of chromosomes; the DNA is tightly packed so the head is small
Acrosome	A large vesicle at the tip of the head containing enzymes that digest a path through the zona pellucida
Midpiece	Packed with mitochondria that produce ATP by aerobic respiration to power the flagellum
Flagellum (tail)	Beats to propel the sperm through fluid in the female reproductive tract
Little cytoplasm	A small, streamlined cell that swims efficiently; very large numbers are produced

Adaptations of the human egg

Structure	Adaptation
Large size (about 110 μm)	Plenty of cytoplasm, with nutrients such as lipid droplets and organelles, to support the early embryo
Haploid set of chromosomes	One set of chromosomes, combined with the sperm's set at fertilization (the ovulated egg is a secondary oocyte that completes meiosis II only after a sperm enters)
Zona pellucida	A layer of glycoprotein around the egg; sperm bind to it, and it protects the egg
Cortical granules	Vesicles under the plasma membrane; after one sperm enters, they release their contents by exocytosis, which hardens the zona pellucida and prevents polyspermy
Follicle cells	A layer of cells around the egg that supports it



The sperm and the egg are not drawn to the same scale.

[\(opens full size in a new tab\)](#)

Sperm and egg are adapted for **movement** and **supporting the early embryo**; not drawn to the same scale.

Exam tip: Pair each structure with its function, for example 'many mitochondria in the midpiece, to provide ATP for movement of the flagellum'. A structure alone rarely earns the mark.

Quick check

1. State the two properties of stem cells.
2. Name two stem cell niches in adult humans.
3. What type of stem cell is found in adult bone marrow?
4. What happens to the SA:V of a cube when its side length doubles?
5. **HL only** What do type II pneumocytes secrete?

Quick check answers

Cell specialization

1. They can divide endlessly and differentiate along different pathways.
2. Bone marrow and hair follicles.
3. Multipotent.
4. It halves.
5. Surfactant, from lamellar bodies.