

B2.3 CELL SPECIALIZATION

Ver. 2

Guiding Questions

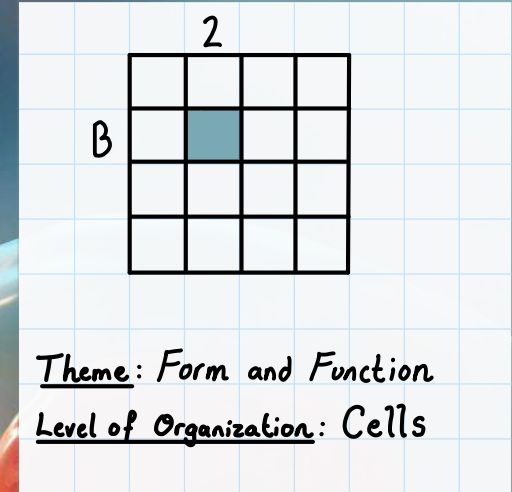
What are the roles of stem cells in multicellular organisms?

How are differentiated cells adapted to their specialized functions?

Linking Questions

What are the advantages of small size and large size in biological systems?

How do cells become differentiated?



Written and drawn by:
PETER MARIER



SL LEARNING OUTCOMES

B2.3.1	Production of unspecialized cells following fertilization and their development into specialized cells by differentiation	Students should understand the impact of gradients on gene expression within an early-stage embryo.
B2.3.2	Properties of stem cells	Limit to the capacity of cells to divide endlessly and differentiate along different pathways.
B2.3.3	Location and function of stem cell niches in adult humans	Limit to two example locations and the understanding that the stem cell niche can maintain the cells or promote their proliferation and differentiation. Bone marrow and hair follicles are suitable examples.
B2.3.4	Differences between totipotent, pluripotent and multipotent stem cells	Students should appreciate that cells in early-stage animal embryos are totipotent but soon become pluripotent, whereas stem cells in adult tissue such as bone marrow are multipotent.
B2.3.5	Cell size as an aspect of specialization	Consider the range of cell size in humans including male and female gametes, red and white blood cells, neurons and striated muscle fibres.
B2.3.6	Surface area-to-volume ratios and constraints on cell size	Students should understand the mathematical ratio between volume and surface area and that exchange of materials across a cell surface depends on its area whereas the need for exchange depends on cell volume. NOS: Students should recognize that models are simplified versions of complex systems. In this case, surface-area-to-volume relationship can be modelled using cubes of different side lengths. Although the cubes have a simpler shape than real organisms, scale factors operate in the same way.

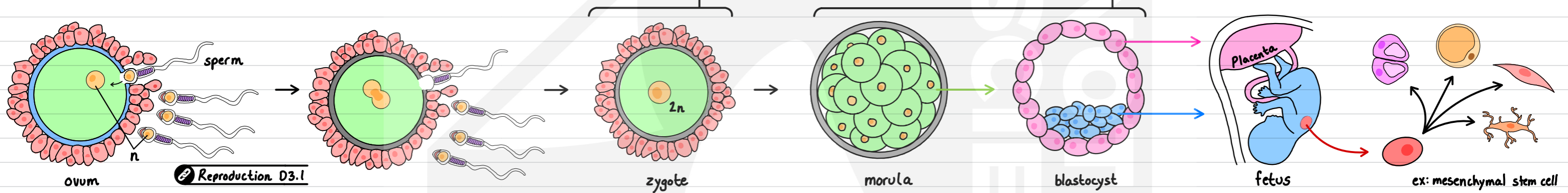
HL LEARNING OUTCOMES

B2.3.7	Adaptations to increase surface area-to-volume ratios of cells	Include flattening of cells, microvilli and invagination. Use erythrocytes and proximal convoluted tubule cells in the nephron as examples.
B2.3.8	Adaptations of type I and type II pneumocytes in alveoli	Limit to extreme thinness to reduce distances for diffusion in type I pneumocytes and the presence of many secretory vesicles (lamellar bodies) in the cytoplasm that discharge surfactant to the alveolar lumen in type II pneumocytes. Alveolar epithelium is an example of a tissue where more than one cell type is present, because different adaptations are required for the overall function of the tissue.
B2.3.9	Adaptations of cardiac muscle cells and striated muscle fibres	Include the presence of contractile myofibrils in both muscle types and hypotheses for these differences: branching (branched or unbranched), and length and numbers of nuclei. Also include a discussion of whether a striated muscle fibre is a cell.
B2.3.10	Adaptations of sperm and egg cells	Limit to gametes in humans.

B2.3.1 – Production of unspecialized cells following fertilization and their development into specialized cells by differentiation.

B2.3.2 – Properties of stem cells. B2.3.3 – Location and function of stem cell niches in adult humans. B2.3.4 – Differences between totipotent, pluripotent and multipotent stem cells. B2.3.5 – Cell size as an aspect of specialization

Fertilization: fusion of nuclei from male and female haploid gametes (sperm and ovum), forming a **zygote**. This unspecialized cell divides many times forming an **embryo** and then differentiates into specialized cells as it grows



Stem cell: undifferentiated cell with the capacity to divide endlessly and differentiate into specialized cells along different pathways.
Classified according to their potential to differentiate: **toti** > **pluri** > **multi**

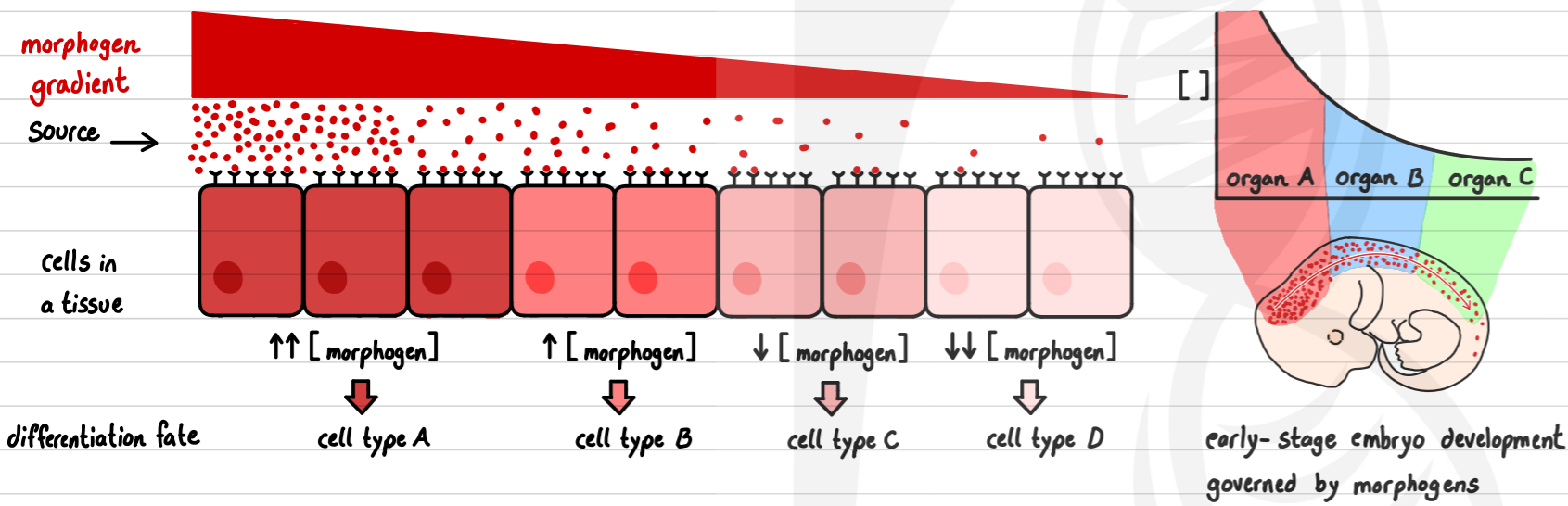
totipotent: capacity to differentiate into all cell types (embryo and placenta)
* found only in early embryos and not adults

pluripotent: capacity to differentiate into most cell types (embryo)

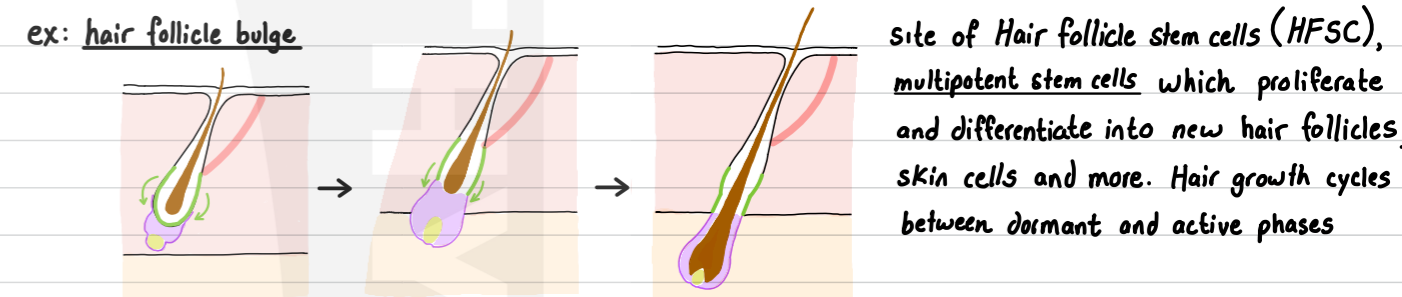
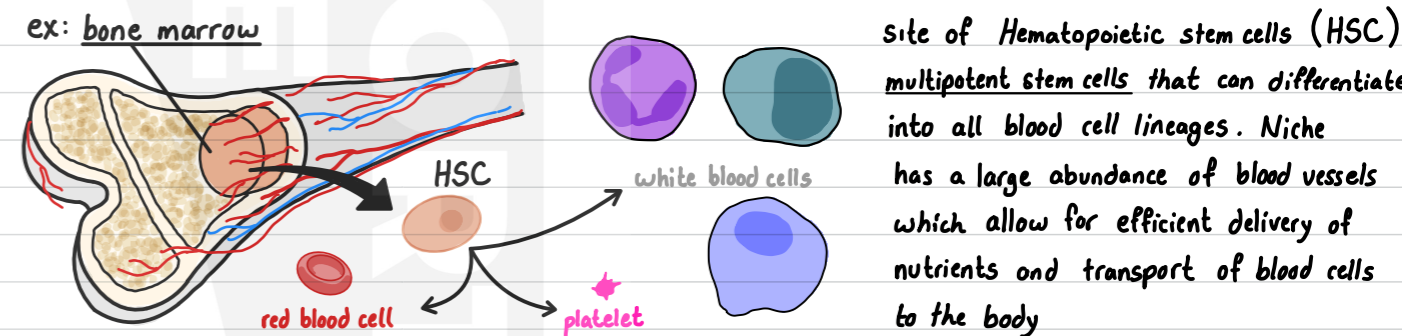
multipotent: capacity to differentiate into cells of specific tissue/type
* remain in adults

morphogens: signal molecules whose concentration alters gene expression and controls differentiation of stem cells in a developing embryo

→ morphogens bind to cells and if a certain concentration threshold is reached, cause some genes to be expressed inducing specialization



Stem cell niche: area of a tissue that provides a specific environment that can both maintain stem cells in an undifferentiated state and promote their proliferation and differentiation



In humans, specialized cells range tremendously in terms of size (length and volume) as an adaptive feature related to their function:

<p>→ sperm cells</p> <ul style="list-style-type: none"> 5µm head with 50µm long flagellum Small size reduces resistance, and increases efficiency, allowing it to swim easier within narrow spaces of female reproductive tract to egg 	<p>→ ova</p> <ul style="list-style-type: none"> 110µm diameter - very large large cytoplasm allows ovum to store a lot of nutrients and organelles needed for early embryonic growth prior to implantation 	<p>→ red blood cells</p> <ul style="list-style-type: none"> 7µm width, 1µm thick small size allows passage through narrow capillaries and increases SA:V, increasing rate of O₂ diffusion 	<p>→ B-lymphocyte</p> <ul style="list-style-type: none"> 10µm (inactive) 30µm (active) Once activated, cells produce large amounts of antibodies from increased rER and Golgi, causing its size to increase 	<p>→ cerebellar granule cells</p> <ul style="list-style-type: none"> cell body 5µm with long protruding axons - 3000µm small volume but long, thin axons allow them to be packed densely, forming many connections in brain 	<p>→ motor neurons</p> <ul style="list-style-type: none"> cell body 20µm with very long axon - some >1000000µm very long axons allows signals to be sent great distances in body at high speed 	<p>→ striated muscle fibres</p> <ul style="list-style-type: none"> 20-100µm diameter and lengths can be >300,000µm long fibres allow contractions to occur over large distances in a coordinated manner
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B2.3.6—Surface area-to-volume ratios and constraints on cell size

Cell surface area is the size of its outer surface, i.e. its membrane surface area
 → as materials are exchanged using the membrane, the greater the area, the higher the rate of exchange

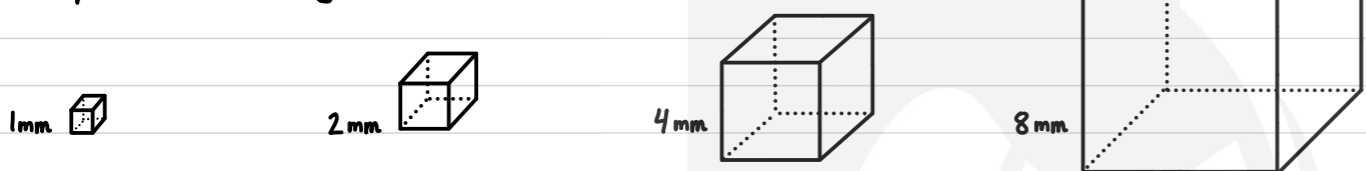
Cell volume is the size of its interior, i.e. mainly its cytoplasm
 → metabolic reactions occur within cytoplasm, thus the larger the volume the greater the metabolic rate, i.e. its need for reactants and generation of products and waste

Cell size is constrained by its surface area (SA) to volume (V) ratio

$$\text{Cell SA:V} = \frac{\text{Cell surface area } (\mu\text{m}^2)}{\text{Cell volume } (\mu\text{m}^3)} \rightarrow \text{limits rate of exchange with cell and its environment}$$

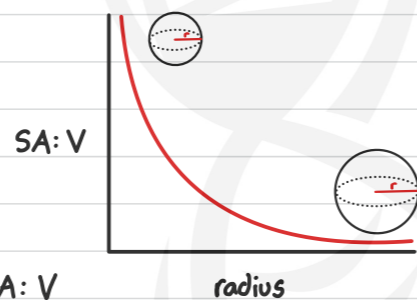
$$\rightarrow \text{limits metabolic rate and need for exchange}$$

NOS: To better understand how SA:vol changes with increasing complex cellular shapes, cubes of increasing side lengths are used as a simplified model since scale factors operate the same regardless of shape

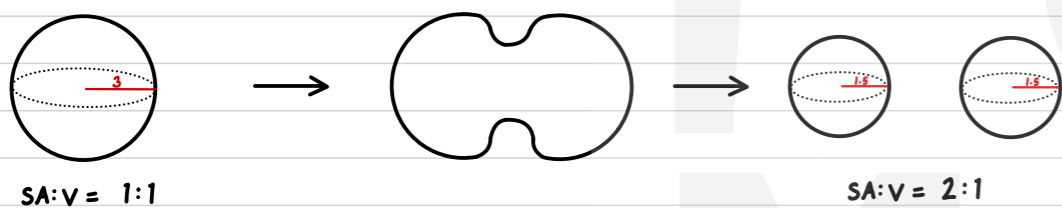


Side Length	SA	V	SA:V
1mm	$(1\text{mm} \times 1\text{mm}) \times 6 = 6\text{mm}^2$	$1\text{mm} \times 1\text{mm} \times 1\text{mm} = 1\text{mm}^3$	6:1
2mm	$(2\text{mm} \times 2\text{mm}) \times 6 = 24\text{mm}^2$	$2\text{mm} \times 2\text{mm} \times 2\text{mm} = 8\text{mm}^3$	3:1
4mm	$(4\text{mm} \times 4\text{mm}) \times 6 = 96\text{mm}^2$	$4\text{mm} \times 4\text{mm} \times 4\text{mm} = 64\text{mm}^3$	1.5:1
8mm	$(8\text{mm} \times 8\text{mm}) \times 6 = 384\text{mm}^2$	$8\text{mm} \times 8\text{mm} \times 8\text{mm} = 512\text{mm}^3$	0.75:1

✗ as the cell grows in size:
 its volume increases much faster than its surface area
 the SA:V decreases

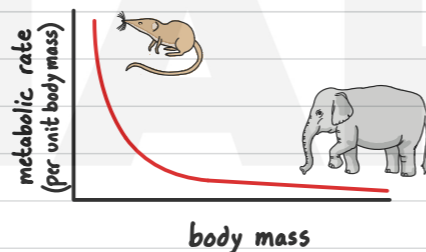


→ eventually a cell will grow so large that its metabolic demand for exchange > exchange rate forcing it to divide in order to increase its SA:V ensuring the rate it imports nutrients and exports waste and heat meets cellular demands



In multicellular organisms:

- larger animals have lower SA:V and more difficulty exchanging heat from their core to their surroundings. ∴ lower metabolic rate per unit mass
- smaller animals have higher SA:V and lose heat from their core to their surroundings too quickly ∴ higher metabolic rate per unit mass



HL

B2.3.7—Adaptations to increase surface area-to-volume ratios of cells

Cells whose function involves exchange of materials have adaptations to maximize surface area (SA) to volume (V)

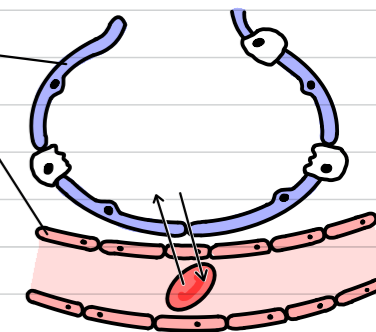
→ **Flattening** →

Some cells are very flattened (wide and thin); large surface area relative to a small volume and short diffusion distance

ex: Erythrocytes (Red blood cells) circulate in blood vessels, carrying and exchanging O_2 with cells. Cell has a flattened biconcave shape, increasing SA:V which increases rate of diffusion and exchange



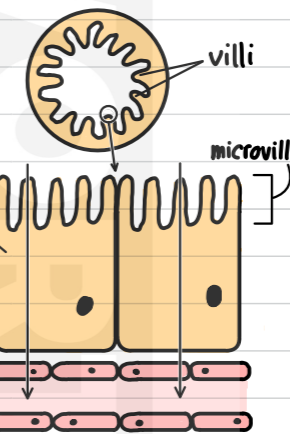
ex: Type I pneumocytes and capillary endothelium cells allow the diffusion and exchange of O_2 and CO_2 between air in lungs and erythrocytes in blood



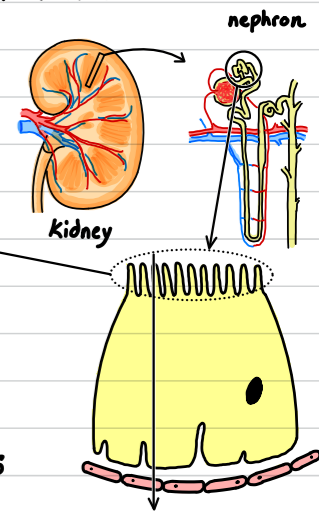
→ **Microvilli** →

Cells in tissues involved in absorption greatly increase their SA through projections called microvilli

ex: tissue in the small intestine is folded in structures called villi which are composed of a single layer of intestinal epithelial cells which are themselves folded, massively increasing SA:V for nutrient absorption from intestinal lumen to blood in capillaries



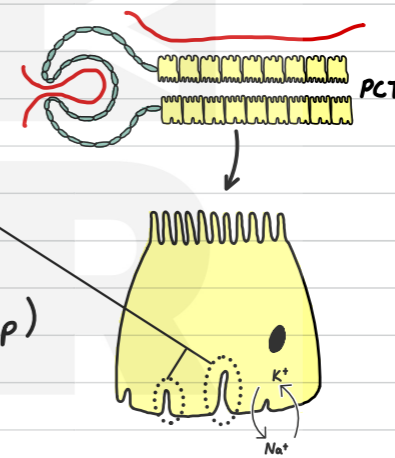
ex: tissue in kidneys called the proximal convoluted tubule are lined with cells with microvilli in order to increase the rate of reabsorption of sugars, salts, amino acids, and water from filtrate to the blood in capillaries



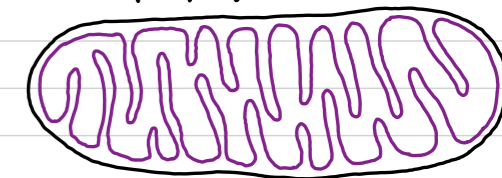
→ **Invagination** →

Cell membranes can fold inward, forming invaginations and increasing SA

ex: Cells in the kidney proximal convoluted tubule (PCT) not only have microvilli to increase absorption but invaginations on the other (basal) end in order to increase the rate of active transport (Na^+/K^+ pump)



ex: the inner membrane of the mitochondrion has many invaginations called cristae in order to increase the surface area for the electron transport chain and oxidative phosphorylation

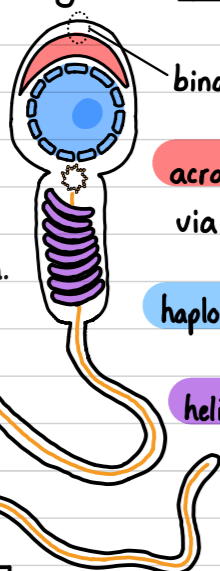


Reproduction D3.1

Specialized cells for sexual reproduction - gametes

Sperm : male reproductive cells (gametes) produced in the testes. Function is to deliver genetic material to and fuse with female ovum in order to produce a zygote. Very little cytoplasm. Shape is very small and streamlined

axoneme
microtubules and proteins move flagellum



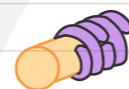
binding proteins allow sperm to bind to zona and ovum membrane

acrosome : a sac containing digestive enzymes which are released via exocytosis in order to break down ovum's zona pellucida

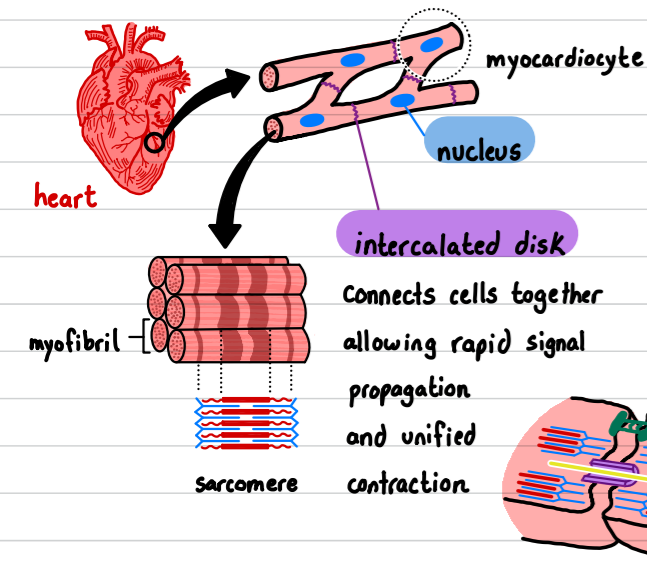
haploid nucleus : contains 1 unique set of chromosomes

helical mitochondria : site of aerobic respiration in order to supply ATP for flagellum movement. wound around axoneme

flagellum : 9+2 microtubules propels sperm



Specialized cells for motility - muscles



Cardiac muscle cells / myocardiocytes

heart only
Involuntary - contraction initiated by heart pacemaker cells
contract heart chambers (atria and ventricles) to pump blood
shorter, 50-100µm
branched, single nucleus near center of cell

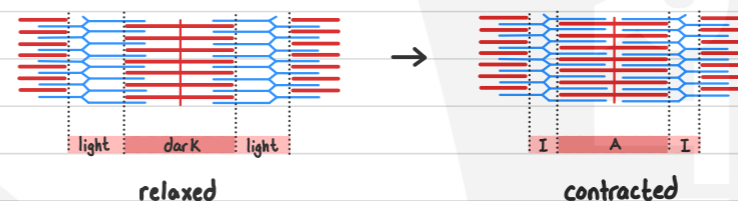
both striated (striped) due to many contractile myofibrils made primarily of **actin** and **myosin** - forming light and dark bands

differences

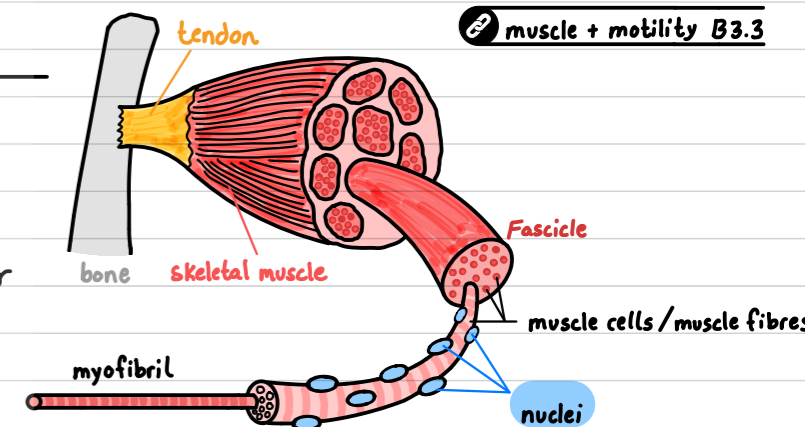
location
contraction
function
length
structure

Skeletal muscle fibres

attached to bones via tendons
Voluntary - contraction initiated by brain
contract to move bones of skeleton
long, 30,000µm on average but can be larger
unbranched, many nuclei on periphery of cell

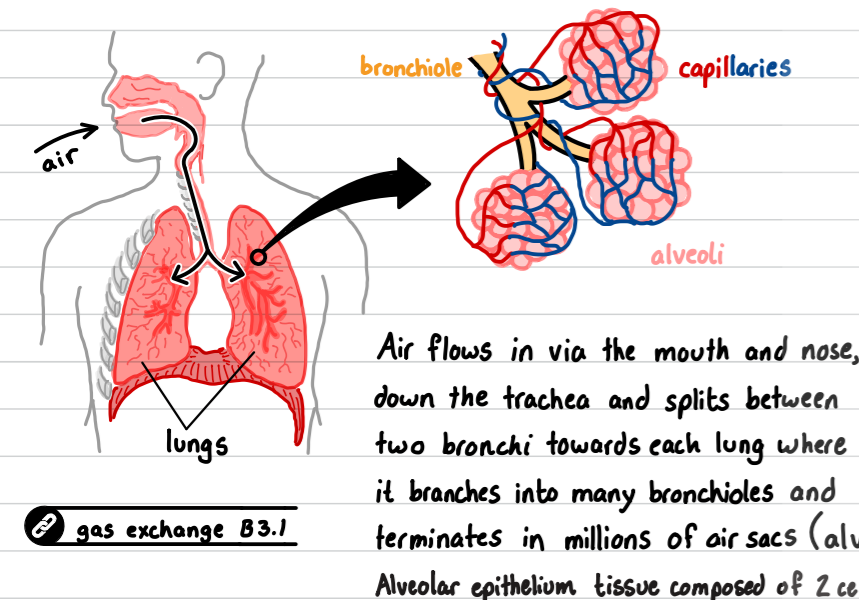


muscle + motility B3.3

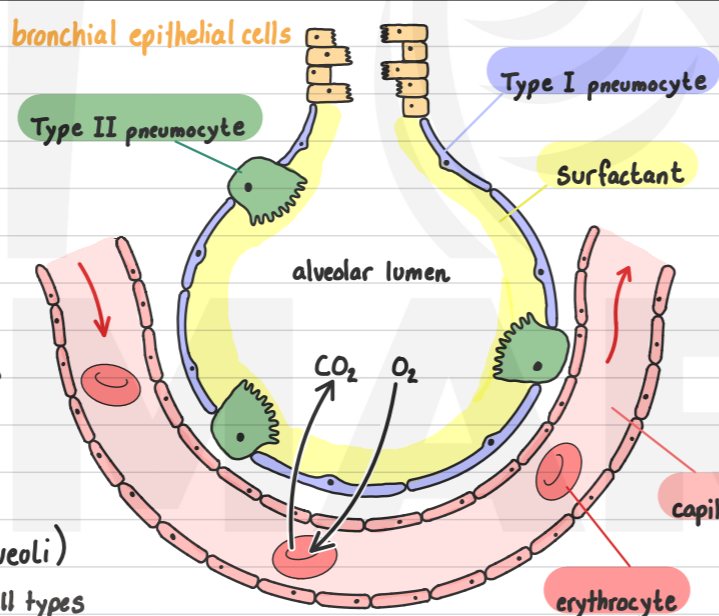


* as discussed in A2.2, debatable if striated muscle fibre is a "cell" due to enormous length and multinucleation.

Specialized cells for ventilation and gas exchange - pneumocytes

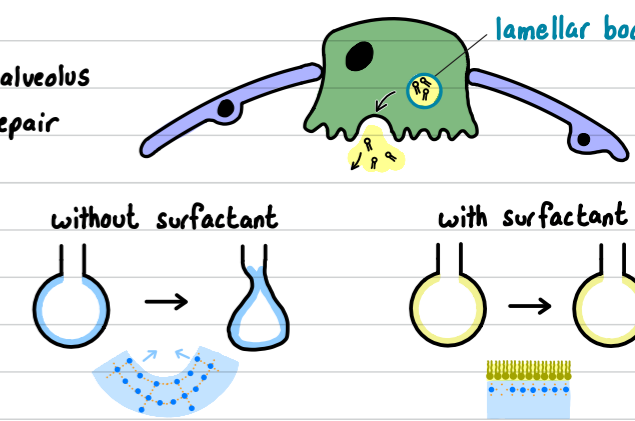


Air flows in via the mouth and nose, down the trachea and splits between two bronchi towards each lung where it branches into many bronchioles and terminates in millions of air sacs (alveoli)
Alveolar epithelium tissue composed of 2 cell types



Type I pneumocyte : alveolar cells adapted for gas exchange (CO₂ and O₂) making up most of alveolar surface
• very long (200µm) and extremely thin (<0.2µm), reducing diffusion distance and increasing rate
• cytoplasm volume is very small, to save space, the few organelles it has are clustered around nucleus

Type II pneumocyte : cuboidal secretory alveolar cells which support alveolus
• can proliferate and differentiate into Type I pneumocytes for repair
• contain many **lamellar bodies**, vesicles which secrete **pulmonary surfactant** into alveolus via exocytosis
→ keep lining moist allowing gases to dissolve and diffuse
→ contains phospholipids which form monolayer which reduces surface tension, preventing alveolar walls sticking together and collapsing during expiration.

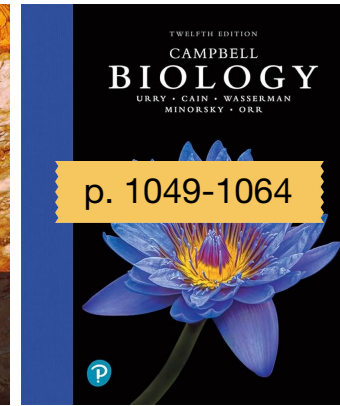
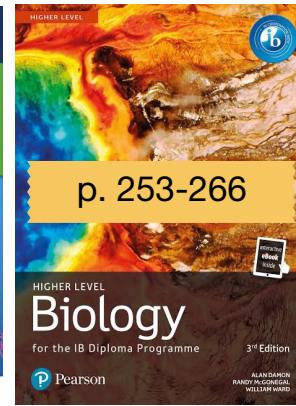
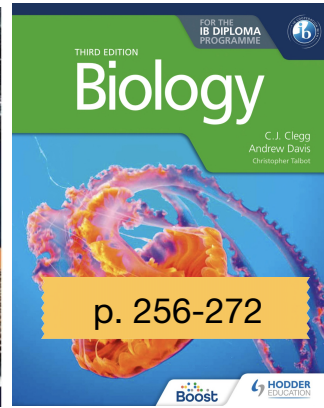
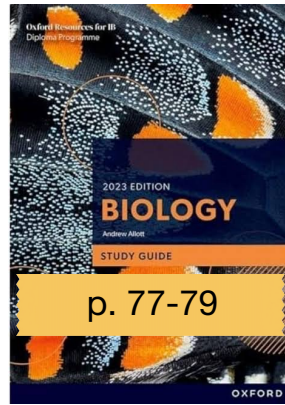
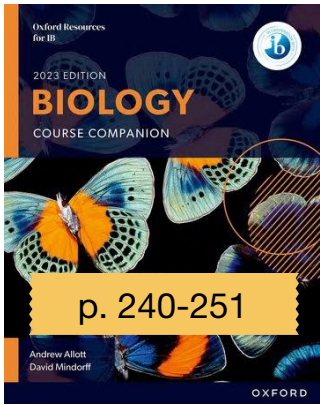


Resource Links

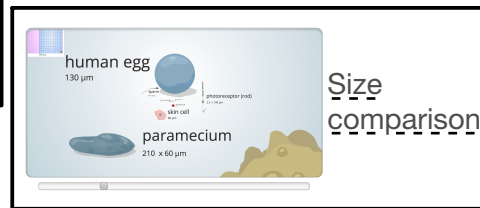
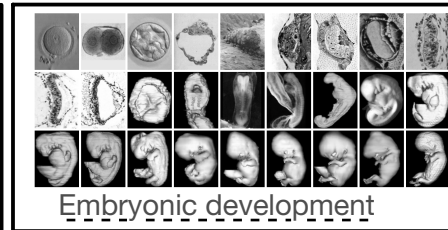
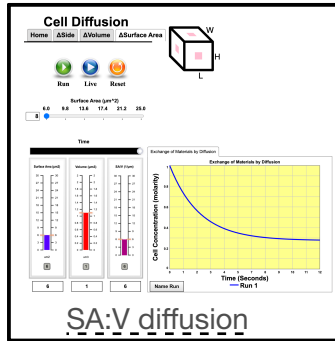
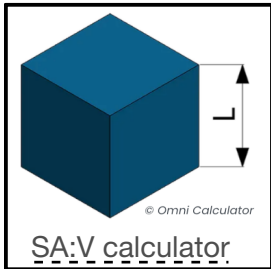
each resource is hyperlinked



Textbooks



Simulators / Interactives



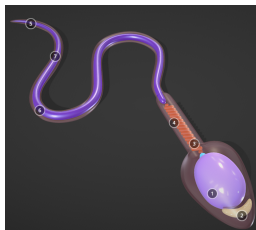
Articles

Hatton, I. A., Galbraith, E. D., Merleau, N. S. C., Miettinen, T. P., Smith, B. M., & Shander, J. A. (2023). The human cell count and size distribution. *Proceedings of the National Academy of Sciences*, 120(39). <https://doi.org/10.1073/pnas.2303077120>

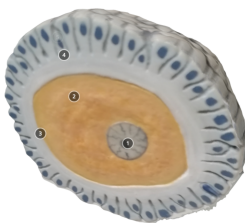
Kicheva, A., & Briscoe, J. (2023). Control of tissue development by morphogens. *Annual Review of Cell and Developmental Biology*, 39(1), 91–121. <https://doi.org/10.1146/annurev-cellbio-020823-011522>

Li, L., & Xie, T. (2005). STEM CELL NICHE: Structure and function. *Annual Review of Cell and Developmental Biology*, 21(1), 605–631. <https://doi.org/10.1146/annurev.cellbio.21.012704.131525>

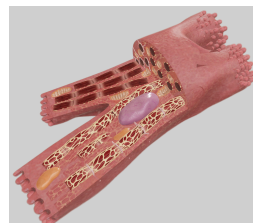
3D models



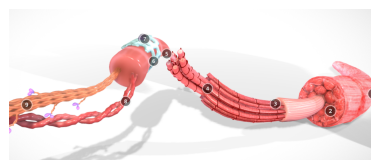
Sperm cell



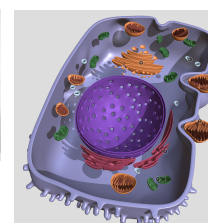
Ovum



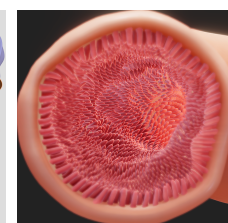
Myocardiocyte



Skeletal muscle



Type 2 pneumocyte



Intestinal villi