Cell specialization

B2.3 · SL and HL

How can one genome support different cell structures?

Different functions require different products and arrangements

A fertilized egg gives rise to oxygen-carrying, contracting and signalling cells. Most retain essentially the same genome while expressing different combinations of genes.

Common content: differentiation, stem cells and niches, potency, cell-size diversity and surface area-to-volume constraints.

AHL: exchange geometry, pneumocytes, cardiac/skeletal muscle and human gametes.

Numerical models and practice datasets are invented.

Different gene use can change a cell without deleting its genes

Position-dependent signals can influence cell fate

Differentiation develops specialized structures and functions through changes in gene expression and functional products.

Most nucleated body cells retain broadly the same genome. Mature mammalian erythrocytes lose their nucleus; do not apply this exception to all mature cells.

Cells at different embryo positions can encounter different signal concentrations and activate different programmes. Shape differences alone do not identify the signalling mechanism.

Apply each threshold including its boundary

1. **Invented rules.** Below 2 units: A. From 2 to below 5: B. At 5 or above: C.
2. **Predict.** Exposures 1, 2, 3, 5 and 6 give A, B, B, C and C. A concentration exactly on a boundary belongs to the stated inclusive interval.
3. **Test.** Measure **gene expression** under controlled exposure. The thresholds are an original model, not universal embryonic concentrations.

Self-renewal and differentiation are different properties

Maintaining a stem-cell population differs from producing specialized cells

Stem cells can supply stem-cell descendants and specialized descendants under suitable conditions.

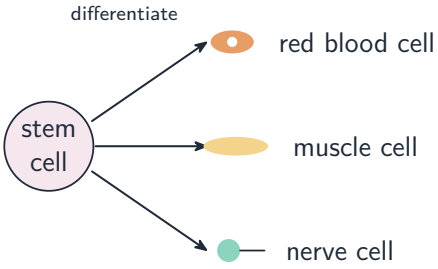
Long-term renewal does not mean every stem cell divides continuously, survives forever or works under any culture condition.

Repeated division by an already specialized cell does not establish broad developmental potency.

Choose the division model before using powers of two

1. **Asymmetric model.** Each round along one continuing stem-cell line produces one stem cell and one non-dividing specialized descendant.
2. **After four rounds.** One stem cell plus four specialized descendants: five cells total, assuming survival.
3. **Different model.** If every stem cell produces two stem cells each round, four rounds give $2^4 = 16$ stem cells and no specialized descendants.

Stem cells differentiate



Different genes are expressed in each

A niche supplies local signals and contacts

Compare bone marrow with hair follicles

Bone marrow supports blood-forming stem cells. Hair-follicle niches support relevant epithelial stem cells during tissue renewal.

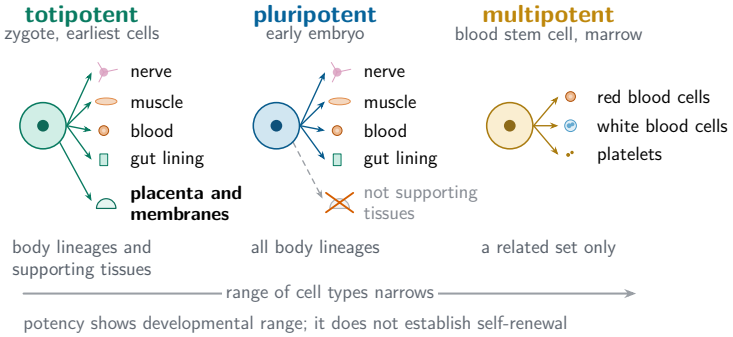
Neighbouring cells, extracellular material and signals can maintain a stem-cell population or promote proliferation and differentiation.

A niche is not an empty space that makes any cell pluripotent. Its effects depend on cells, signals and conditions.

Distinguish a marker response from full functional differentiation

1. **Invented counts.** Controls: 8, 10, 12 marker-positive cells; treated: 38, 40, 42. Each dish has 100 viable cells at measurement.
2. **Calculate.** Mean proportions are 10% and 40%. Difference: 30 percentage points; treated/control ratio: $40/10 = 4$.
3. **Evaluate.** Control starting cells, medium, time and marker threshold. A marker alone need not prove full function; also measure total cells and viability.

Compare the range of developmental outcomes



Potency describes possible developmental outcomes; self-renewal describes maintenance of stem-cell descendants.

Classify stated capacity rather than donor age

1. **X.** Body and supporting lineages of a complete conceptus: totipotent.
2. **Y.** Diverse body lineages without independently supplying every necessary supporting lineage: pluripotent.
3. **Z.** Several related blood-cell types: multipotent. Several measured markers alone do not establish every possible lineage or a complete organism.

State which dimension is being compared

Human cell example	Size interpretation
Red and white blood cells	Representative red cells: about 7–8 μm across; many white cells: roughly 10–20 μm
Egg and sperm	Egg: approximately 100–120 μm across; distinguish sperm head from whole length
Neuron	A long axon is different from cell-body width
Skeletal muscle fibre	Can extend centimetres while remaining much narrower than its length

A long cell need not have a long diffusion path across its width

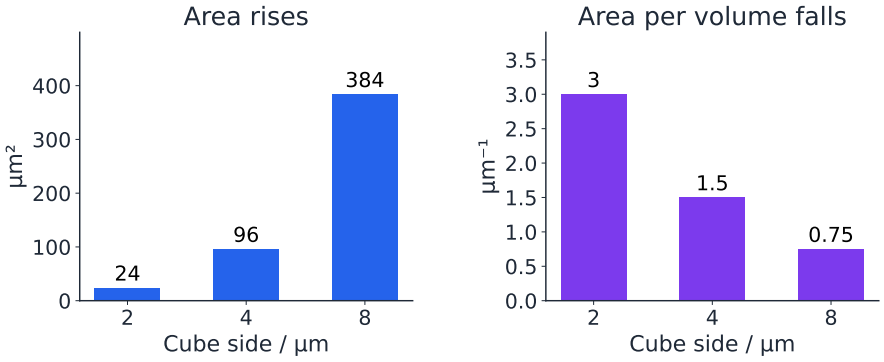
Size offers benefits as well as constraints

Egg cytoplasm supplies material for early development. Long neuronal processes support communication over distance.

An elongated muscle fibre supports force along its length. Narrow regions, shape and internal transport can help meet exchange demands.

Compare the same dimension in common units. There is no single best size for every cell function.

Area can rise while area per volume falls



Exchange area scales with length squared; volume scales with length cubed in geometrically similar shapes.

Calculate the cube model and its scaling

1. **Relations.** Area $= 6a^2$, volume $= a^3$, area/volume $= 6/a$.
2. **Sides 2, 4, 8 μm.** Areas 24, 96, 384 μm^2; volumes 8, 64, 512 μm^3; ratios 3.0, 1.5, 0.75 μm^{-1}.
3. **Doubling.** Area increases fourfold, volume eightfold, ratio halves. More total area does not imply more area per unit volume.

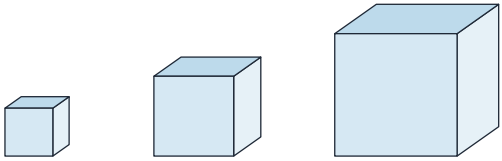
Hold total volume constant when comparing subdivision

1. **One cube.** Side 4 μm gives volume 64 μm^3 and area 96 μm^2.
2. **Eight smaller cubes.** Each side 2 μm: combined volume $8(8) = 64$ μm^3; area $8(24) = 192$ μm^2, twice the original.
3. **Assumptions.** All faces are exposed. Touching tissue cells may not expose every face; cutting a cell does not automatically create viable daughter cells.

Check radius, units and the limits of a shape model

1. **Sphere.** Area/volume $= 3/r$. Radii 2, 4, 6 and 10 give 1.5, 0.75, 0.50 and 0.30 per length unit.
2. **Diameter trap.** Diameter 4 means radius 2: correct ratio 1.5. Using 4 as the radius gives 0.75, half the correct value.
3. **Real cells.** Permeability, transport proteins, gradients, metabolic demand, diffusion distances and internal transport matter. Geometry alone cannot predict an exact maximum cell size.

Surface area to volume



side $L = 1$ side $L = 2$ side $L = 3$

SA : V $= 6 : 1$ SA : V $= 3 : 1$ SA : V $= 2 : 1$

a bigger cube (or cell) has a **smaller** surface area : volume ratio

Large cells struggle to exchange enough

Compare equal volume with different shapes

1. **Cube.** $2 \times 2 \times 2$ μm: volume 8 μm^3, area 24 μm^2, ratio 3 μm^{-1}, shortest centre-to-face distance 1 μm.
2. **Flattened model.** $0.5 \times 4 \times 4$ μm: volume 8 μm^3, area 40 μm^2, ratio 5 μm^{-1}, shortest centre-to-face distance 0.25 μm.
3. **Interpret.** Flattening increases exchange area and reduces the shortest diffusion distance at fixed volume. These cuboids are models, not exact cell shapes.

Area works with transport proteins and energy supply

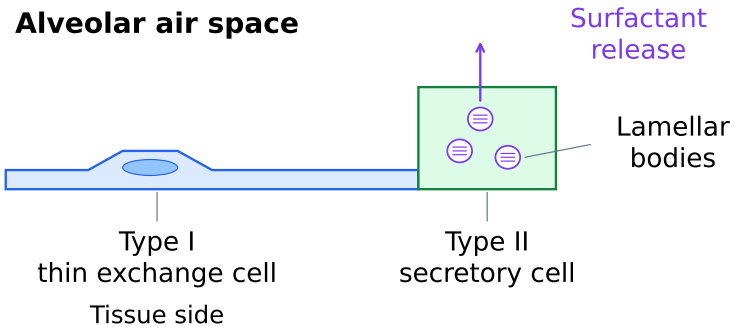
Use erythrocytes and proximal-tubule cells as named examples

Erythrocytes have flexible biconcave forms and thin regions, supporting exchange and movement through capillaries. Haemoglobin and organelle loss contribute different functions.

Proximal-tubule microvilli increase apical area facing filtrate; basolateral infoldings add area for transport machinery. Mitochondria support energy demands.

Microvilli do not beat like cilia. Extra area does not replace carriers, pumps or maintained gradients.

Different alveolar cell types solve different problems



Thin type I cells support a short diffusion path; type II cells release surfactant from lamellar bodies.

Surfactant stabilizes the lining rather than supplying oxygen

Efficient exchange requires a functioning tissue

Type I pneumocytes spread thinly over the exchange surface. The complete air–blood barrier also includes other structures.

More cuboidal type II cells contain lamellar bodies releasing surfactant into the alveolar lumen. Lower surface tension helps stabilize alveoli during breathing.

Do not say every alveolar cell has the same adaptation. Ventilation, blood flow, thickness and area also influence gas exchange.

Striations alone do not identify skeletal muscle

Feature	Cardiac cells versus skeletal fibres
Contractile machinery	Both have myofibrils with repeating contractile units and striations
Shape and length	Cardiac: shorter, branched; skeletal: long, generally unbranched
Nuclei	Cardiac: commonly one, sometimes two, central; skeletal: many near periphery
Organization	Cardiac connections support coordinated network activity; parallel skeletal fibres support directed force

A multinucleate fibre still has one continuous cell boundary

Cell identity is not defined by one nucleus per cell

Skeletal fibres form by fusion of precursor cells into continuous cytoplasm within one plasma membrane. A fibre is a multinucleate cell, or syncytium.

Cardiac intercalated discs connect cells mechanically and electrically. Their network differs from a continuous multinucleate skeletal fibre.

Link structure to a testable function hypothesis. One still image cannot measure contraction strength or prove the whole developmental history.

Compare gamete adaptations without changing chromosome accounting

Feature	Human sperm versus egg
Movement	Sperm flagellum supports movement; egg does not swim with a flagellum
Contents	Sperm head carries nucleus and acrosome; egg has much larger cytoplasm and early-development resources
Energy and secretion	Sperm midpiece mitochondria contribute ATP, alongside other pathways; egg cortical granules contribute changes reducing additional sperm entry
Nuclear chromosomes	Each gamete contributes a haploid set of 23; the usual diploid zygote has 46

Common practice: gene expression, stem cells and data

1. **Questions 1–4.** Explain differential gene use, threshold responses A/B/B/C/C, renewal versus **differentiation**, and bone-marrow/hair-follicle niches.
2. **Question 5.** 10% versus 40% gives 30 percentage points and a fourfold ratio. A marker response alone is not a full functional cell assay.
3. **Questions 6–7.** Classify X/Y/Z as totipotent/pluripotent/multipotent from capacity. Compare like dimensions rather than axon length with egg diameter.

Common practice: geometry and its assumptions

1. **Questions 8–9.** Cube ratios 3, 1.5 and 0.75 μm^{-1}. Equal-volume subdivision doubles exposed area under the all-faces-exposed assumption.
2. **Question 10.** Sphere ratios 1.5, 0.75, 0.50 and 0.30 per length unit. Using diameter as radius halves the calculated ratio.
3. **Question 11.** State named transport, gradient, distance and metabolic factors. Calibrate scaled drawings and connect an observed feature to its mechanism.

AHL practice: exchange surfaces, muscle and gametes

1. **Question 12.** Equal volumes 8 μm^3; areas 24 versus 40 μm^2; ratios 3 versus 5 μm^{-1}; shortest distances 1 versus 0.25 μm.
2. **Question 13.** Type I thinness and type II lamellar bodies serve different tissue functions. Both muscle types have myofibrils; branching, nuclei and cell boundaries distinguish them.
3. **Question 14.** Compare sperm motility/acrosome with egg cytoplasm/cortical granules. Lamellar bodies belong to pneumocytes; each human gamete contributes 23 nuclear chromosomes.

Check yourself

Name the cell, feature, mechanism and function

Separate potency from division rate, percentage points from fold change, and length from diameter.

Report total area and area per volume. State geometric assumptions and biological limits.

AHL: compare cell types within tissues, rather than assigning one adaptation to every cell.