MEGA LECTURE

IB DP BIOLOGY

Theme B: Form and Function

B2.3 Cell Specialization

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Biology course (2025 syllabus)

What the syllabus requires

By the end of B2.3 you should be able to explain how a single fertilised egg gives rise to the many specialised cell types of a multicellular organism, and how those cells are organised into larger functional units. Use this checklist before the exam.

Understanding	You should be able to...
Differentiation	Define differentiation and explain how it produces specialised cells from unspecialised precursors.
Basis of differentiation	Explain that all body cells share one genome but express different subsets of genes.
Stem cells	State the two defining properties (self-renewal and potency) and distinguish totipotent, pluripotent, multipotent and unipotent cells.
Sources of stem cells	Compare embryonic and adult (tissue) stem cells, including their potency and ethical status.
Specialised cells	Relate the structure of named specialised cells to their functions.
Cell size and SA:V	Explain how the surface-area-to-volume ratio limits cell size and shapes specialised cells.
Levels of organisation	Sequence cells → tissues → organs → organ systems → organism, and describe emergent properties.
(HL) Control of differentiation	Outline how gene regulation directs differentiation and why it is usually irreversible.

> **Exam note:** Most of B2.3 is common to SL and HL. HL candidates must also account for *how* differentiation is controlled at the level of gene expression (linking to D2.2) and why it is normally permanent. HL-only material is flagged “(HL)” below.

1. From one cell to many types

A human body contains on the order of 37 trillion cells and around 200 recognisably different cell types, yet all of them descend by mitosis from a single fertilised egg (the zygote). **Differentiation** is the process by which a relatively unspecialised cell develops the distinct structure and function of a particular cell type. A differentiated cell is committed: it carries out one narrow role especially well and usually loses the ability to become other types.

Multicellularity and division of labour

A single-celled organism must perform every life function itself. In a multicellular organism, groups of cells specialise and share the work — a **division of labour**. This brings clear advantages, and is only possible because cells can differentiate.

- Each cell type becomes highly efficient at one task, because its structure is optimised for that task rather than compromised across many.
- Larger body sizes become possible, because specialised transport and exchange tissues overcome the limits that face a lone cell.

- Internal conditions can be regulated (homeostasis), because dedicated cells monitor and adjust the internal environment.
- There is a cost: specialised cells become interdependent, so no single cell can survive alone, and the organism needs systems to coordinate and supply them.

> **Key definition: Differentiation** is the process during development in which cells become structurally and functionally specialised as a result of expressing some of their genes but not others.

2. Gene expression: the basis of differentiation

Every cell produced by mitosis from the zygote receives a complete, identical copy of the organism's **genome** — the same full set of genes. A muscle cell and a nerve cell in the same person therefore contain the same DNA. What makes them different is **which genes they express** (transcribe and translate into proteins) and which they keep switched off.

Because proteins determine a cell's structure and chemistry, expressing a different set of genes builds a different cell:

- A red blood cell expresses the haemoglobin genes strongly, filling with that oxygen-binding protein.
- A pancreatic β-cell (written beta-cell) expresses the insulin gene, so it can synthesise and secrete insulin.
- A muscle cell expresses the genes for actin and myosin, building the contractile filaments that let it shorten.

The unexpressed genes are still present — they are switched off, not deleted. In principle the insulin gene sits inside a muscle cell too; it is simply never transcribed there. This point is examined repeatedly, so state it precisely: **differentiation is a difference in gene expression, not a difference in genes.**

> **Analogy:** The genome is like a single large cookbook given to every kitchen. Each kitchen cooks only a few recipes from it. Different dishes appear not because the books differ, but because different pages are used.

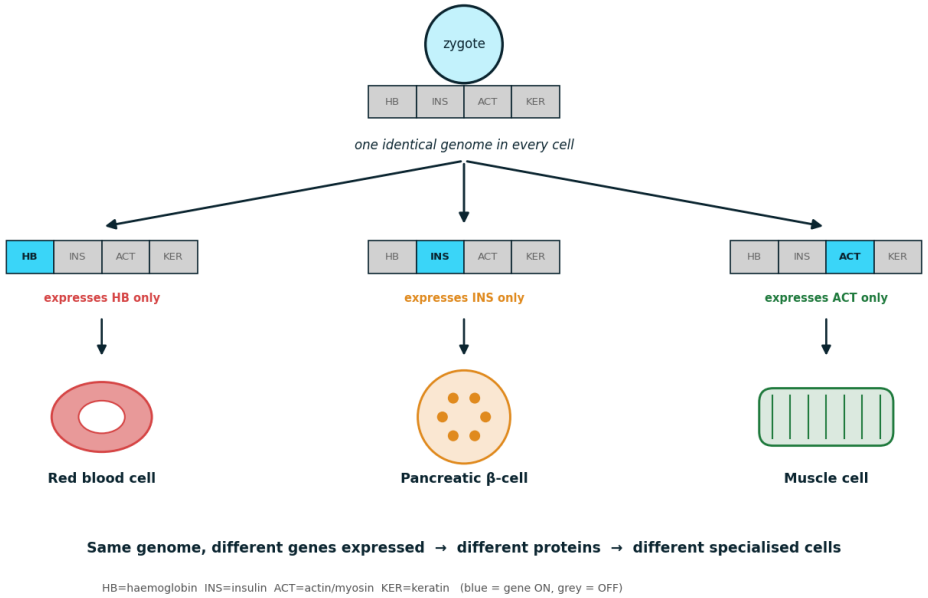

Figure 2. Differentiation is a difference in gene expression, not in genes. Every cell holds the same genome but expresses a different subset, building a different cell (same genome → different proteins → different cells).

3. Stem cells

Stem cells are unspecialised cells that retain the ability to divide and to give rise to differentiated cells. They are defined by two properties that must both be present:

- **Self-renewal** — they can divide repeatedly by mitosis to produce more stem cells, maintaining a supply.
- **Potency** — they can differentiate into one or more specialised cell types.

Types of stem cell by potency

Potency describes the range of cell types a stem cell can become. It narrows as development proceeds.

Potency	Can form...	Example
Totipotent	Every cell type of the body *and* the extra-embryonic tissues (e.g. placenta); a whole organism	The zygote and the cells of the very early embryo (first few divisions)
Pluripotent	All cell types of the body proper, but not extra-embryonic tissues	Embryonic stem cells of the blastocyst inner cell mass
Multipotent	A limited related family of cell types	Haematopoietic (bone-marrow) stem cells, which form the range of blood cells
Unipotent	Only one cell type, but can still self-renew	Epidermal (skin) stem cells; muscle satellite cells

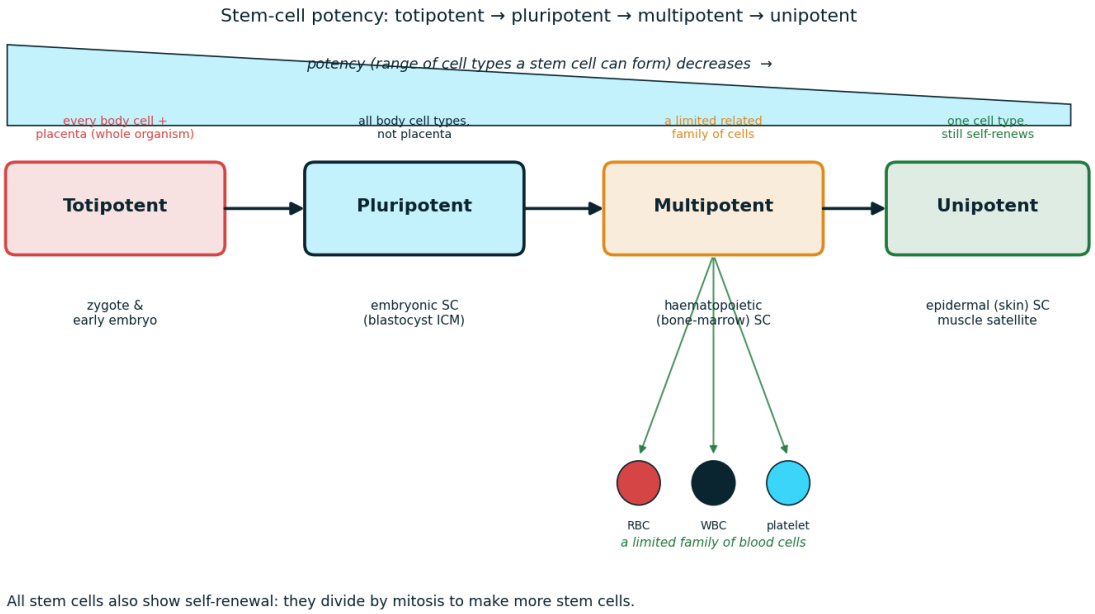

Figure 1. Potency narrows as development proceeds: totipotent → pluripotent → multipotent → unipotent. Multipotent haematopoietic stem cells form a limited family of blood cells.

Embryonic versus adult (tissue) stem cells

Feature	Embryonic stem cells	Adult / tissue stem cells
Source	Inner cell mass of the blastocyst (early embryo)	Specific tissues of the body after birth (e.g. bone marrow, skin, gut lining)
Potency	Pluripotent — very wide range	Usually multipotent or unipotent — narrow range
Division	Divide rapidly and almost indefinitely in culture	Divide more slowly; often replace worn-out cells
Ethics	Obtaining them typically destroys an embryo — ethically contested	Taken from the patient's own tissue — fewer ethical concerns

> **Exam tip:** Learn the four potency terms as a sequence of narrowing ability: totipotent → pluripotent → multipotent → unipotent. A common slip is to call embryonic stem cells "totipotent" — the blastocyst cells are *pluripotent*.

4. Therapeutic uses and ethics of stem cells

Because stem cells can be directed to differentiate, they offer a way to replace cells that are lost or faulty — the basis of **regenerative medicine**. Established and researched uses include:

- Bone-marrow (haematopoietic stem cell) transplants to rebuild the blood and immune system after leukaemia treatment — already routine.
- Skin grafts grown from a patient's own epidermal stem cells to treat severe burns.
- Research into replacing cells lost in Parkinson's disease, type 1 diabetes, spinal-cord injury and macular degeneration of the retina.

Ethical considerations

Stem cell work raises genuine arguments on both sides, and a balanced answer should note them.

Arguments in favour	Arguments against / cautions
Could cure currently untreatable diseases and reduce suffering	Harvesting embryonic stem cells destroys an embryo, which some regard as a human life
Adult and induced stem cells can often be taken from the patient, avoiding rejection	Long-term safety is uncertain — cultured cells may divide uncontrollably and form tumours
Spare embryos from IVF would otherwise be discarded	Concerns about consent, commercialisation and access to costly therapies

Induced pluripotent stem cells (iPS cells) — ordinary body cells reprogrammed back to a pluripotent state — sidestep much of the embryo debate and are an active area of research.

5. Specialised cells and their adaptations

Examiners frequently ask you to link a cell's structure to its function. The rule to apply every time: identify the job, then explain how each named feature makes that job easier. The table gives well-adapted examples.

Cell	Function	Key adaptations (structure → function)
Red blood cell	Transport oxygen	Biconcave disc → large surface area for gas exchange; no nucleus/mitochondria → more room for haemoglobin; flexible → squeezes through capillaries
Sperm cell	Deliver male DNA to the egg	Flagellum (tail) → swims; many mitochondria in midpiece → ATP for movement; acrosome → enzymes to penetrate the egg; haploid nucleus
Egg cell (ovum)	Provide the female gamete and nutrients	Large cytoplasm → food store for the early embryo; haploid nucleus; zona pellucida → blocks extra sperm after fertilisation
Root hair cell	Absorb water and mineral ions	Long thin extension → greatly increased surface area; thin wall → short diffusion path; many mitochondria → active uptake of ions
Palisade mesophyll	Photosynthesis in the leaf	Many chloroplasts → absorb light; tall column shape packed near the upper surface → maximise light capture
Neuron	Transmit electrical impulses	Long axon → carries signals over distance; dendrites → receive from many cells; myelin sheath → speeds conduction
Muscle fibre	Contract to produce movement	Actin and myosin filaments → sliding produces force; many mitochondria → ATP; multiple nuclei in skeletal fibres
White blood cell	Defend against pathogens	Phagocytes change shape → engulf microbes; lymphocytes → make specific antibodies; flexible for movement through tissues

> **Marking point:** Do not merely name a feature — always follow it with “which allows / so that...”. “The red blood cell has no nucleus, which leaves more space for haemoglobin so it can carry more oxygen” scores; “it has no nucleus” alone often does not.

6. Surface-area-to-volume ratio and cell size

Cells cannot grow without limit. Materials enter and leave a cell across its surface (the plasma membrane), while the demand for those materials, and the waste produced, depend on the cell's volume. As a cell grows, volume increases faster than surface area, so the **surface-area-to-volume ratio (SA:V)** falls.

For a cube of side L, surface area = $6L^2$ and volume = L^3, so SA:V = $6/L$. Doubling the size roughly halves the ratio.

Cube side L	Surface area ($6L^2$)	Volume (L^3)	SA : V ratio
1 unit	6	1	6 : 1
2 units	24	8	3 : 1
4 units	96	64	1.5 : 1

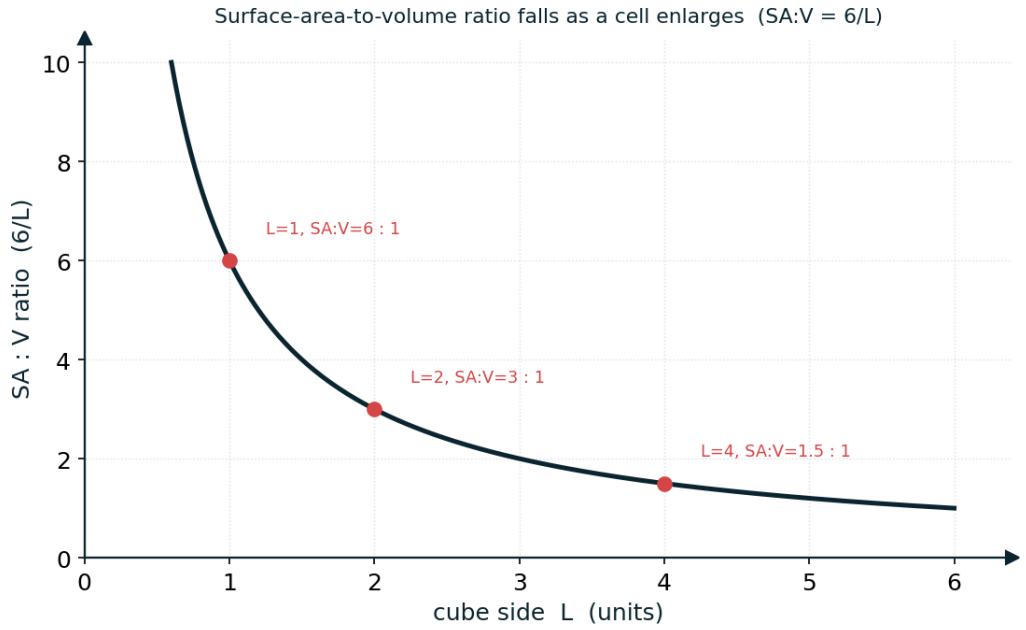

Figure 3. For a cube of side L, SA:V = 6/L, so the ratio falls as a cell enlarges: L = 1 → 6:1, L = 2 → 3:1, L = 4 → 1.5:1. Cells therefore stay small or adopt high-SA:V shapes.

Why this drives specialisation and shape

- A low SA:V means the surface can no longer supply the interior fast enough by diffusion, so cells stay small — typically 10–100 µm across.
- Cells that need high exchange rates adopt shapes that raise SA:V: root hair cells form long projections, and the epithelial cells lining the small intestine carry microvilli.
- The red blood cell's biconcave shape gives more surface area than a sphere of the same volume, speeding oxygen loading and unloading.
- Thin, flat cells (such as the alveolar cells of the lungs) keep every part of the cytoplasm close to the surface, shortening diffusion distances.

> **Concept link:** A large organism cannot solve its own exchange problem simply by having bigger cells. Instead it has *more* small, specialised cells and dedicated exchange surfaces (lungs, gut lining, roots) — another reason specialisation and multicellularity go together.

7. Levels of organisation

Once cells are specialised, they are organised into a hierarchy of increasing complexity. Each level is built from the one below and shows abilities the parts do not have alone.

- **Cell** — the basic unit of life; e.g. a single muscle cell.
- **Tissue** — a group of similar cells working together on one function; e.g. cardiac muscle tissue.
- **Organ** — several tissues combined into a structure with a defined role; e.g. the heart, containing muscle, nervous and connective tissue.
- **Organ system** — a set of organs cooperating on a broad function; e.g. the circulatory system (heart and blood vessels).
- **Organism** — all the organ systems together forming a complete, independent living thing.

Emergent properties

At each level, new properties **emerge** from the interactions of the parts — properties that none of the individual components possesses on its own. A single heart-muscle cell can twitch, but the coordinated interaction of millions of them produces a rhythmic pumping heartbeat; no lone neuron is conscious, yet the interactions of billions produce thought. Emergent properties are why “the whole is more than the sum of its parts.”

8. (HL) How differentiation is controlled

HL candidates must go beyond “different genes are expressed” and outline how that expression is controlled. This links directly to gene regulation in D2.2.

- Signals from a cell's position and its neighbours (chemical gradients of signalling molecules during development) tell a cell where it is and therefore what to become.
- These signals switch on particular **regulatory genes** that code for **transcription factors** — proteins that bind DNA and turn sets of target genes on or off.
- The pattern of active transcription factors determines which structural genes are transcribed, and so which proteins the cell makes — fixing its identity.
- Longer-term control comes from **epigenetic** changes (such as DNA methylation and histone modification) that lock genes in an on or off state and are copied to daughter cells at mitosis.

Why differentiation is usually irreversible

Once a cell has differentiated, these epigenetic marks and stable patterns of transcription factors keep the “wrong” genes silenced and the “right” genes active. The marks are inherited through each cell division, so the specialised state is maintained and passed on. Reversing it normally requires deliberate laboratory reprogramming (as in producing iPS cells). This stability is useful: a liver cell must not spontaneously turn into a nerve cell.

Cell size limits and the need for specialisation (HL emphasis)

The SA:V argument in section 6 also explains why highly active differentiated cells stay small and adopt exaggerated shapes: their high metabolic rate demands a high SA:V, which only a small or elongated/flattened cell can provide. Specialisation of shape is therefore partly a direct consequence of the geometry of exchange.

> **(HL) exam link:** If a question asks *how* the same genome yields different cells, name transcription factors and regulatory genes, and mention epigenetic marks as the reason the state is stable and heritable.

9. Worked examples, skills and pitfalls

Worked example 1 — match adaptation to function

A cell is described as long and thin with a very large surface area, a thin cell wall and many mitochondria, and it lacks chloroplasts. Identify the cell and justify each feature.

It is a **root hair cell**. Large surface area → faster absorption of water and ions; thin wall → short diffusion path; many mitochondria → ATP for active transport of mineral ions against a gradient; no chloroplasts → it is underground and does not photosynthesise.

Worked example 2 — identify the potency type

A stem cell taken from adult bone marrow can form red blood cells, white blood cells and platelets, but not nerve or muscle cells. Which type of potency is this, and is it embryonic or adult?

It forms a limited, related family of cell types, so it is **multipotent**. Being taken from bone marrow after birth, it is an **adult (tissue) stem cell**, not embryonic.

Worked example 3 — same genome, different cells

Explain how a neuron and a pancreatic cell in the same person can be so different despite having identical DNA. (HL: extend the explanation.)

Both descend by mitosis from the zygote and so contain the same genome. They differ because they express different subsets of that genome: the neuron transcribes genes for ion channels and neurotransmitters, while the pancreatic cell transcribes the insulin gene. The genes for the other cell's proteins are present but switched off, not absent.

(HL) The choice of which genes are active is set by transcription factors made from regulatory genes and is locked in by epigenetic marks (e.g. DNA methylation) that are copied at each cell division.

Worked example 4 — interpret an SA:V-driven shape

Cells lining the small intestine are covered in microvilli. Two neighbouring cells have the same volume, but cell X has microvilli and cell Y does not. Which absorbs faster, and why?

Cell X absorbs faster. Microvilli greatly increase the surface area without increasing the volume, raising the SA:V ratio. A higher SA:V means more membrane area for absorption per unit of cytoplasm, so digested nutrients are taken up more quickly.

Common pitfalls

- Saying differentiated cells have “different genes” — they have the *same* genes but express *different* ones.
- Claiming differentiation involves “losing” genes — unexpressed genes are silenced, not deleted (a rare exception is the mature red blood cell losing its whole nucleus, which is unusual).
- Confusing the potency terms — remember totipotent forms a whole organism including placenta, while pluripotent forms all body cells but not placenta.
- Calling embryonic (blastocyst) stem cells totipotent — they are pluripotent.
- Naming a structural feature without stating its function — always add the “so that...”.
- Saying big cells solve exchange problems — the opposite is true; large size lowers SA:V and worsens exchange.

Quick-reference table

Term	One-line meaning
Differentiation	Cells becoming specialised through selective gene expression
Genome	The complete set of genes; identical in (almost) all body cells
Gene expression	Transcribing and translating a gene into protein
Stem cell	Unspecialised cell with self-renewal + potency
Totipotent	Forms all cell types plus extra-embryonic tissue (whole organism)
Pluripotent	Forms all body cell types, not extra-embryonic tissue
Multipotent	Forms a limited related family of cell types
Unipotent	Forms one cell type; still self-renews
SA : V ratio	Surface area ÷ volume; falls as cells enlarge, limiting size
Emergent property	A property arising from interactions, absent in the parts alone

Test yourself

Attempt these without notes; full answers follow.

1. Define differentiation and state what causes cells to differ from one another.

2. A muscle cell and a skin cell contain identical DNA. Explain how they can look and behave so differently.

3. State the two properties that define a stem cell.

4. Place these in order of decreasing potency and give an example of each: multipotent, totipotent, unipotent, pluripotent.

5. Give two structural adaptations of a sperm cell and explain each.

6. Explain, using SA:V, why cells do not grow to a very large size.

7. List the levels of organisation from cell to organism, and define “emergent property”.

8. (HL) Outline how differentiation is controlled and why it is usually irreversible.

Answers

1. Differentiation is the process by which an unspecialised cell becomes structurally and functionally specialised. Cells differ because they express different subsets of the shared genome, making different proteins.

2. Both arose by mitosis from the zygote and share the same genome. They express different genes: the muscle cell makes actin and myosin; the skin cell makes keratin. The unused genes are switched off, not removed.

3. Self-renewal (can divide to make more stem cells) and potency (can differentiate into one or more specialised types).

4. Totipotent (zygote/early embryo) → pluripotent (embryonic stem cells of the blastocyst) → multipotent (bone-marrow/haematopoietic stem cells) → unipotent (skin/epidermal stem cells).

5. Any two: flagellum → propels the cell to swim to the egg; midpiece packed with mitochondria → supplies ATP for movement; acrosome → releases enzymes to digest a path through the egg's coat.

6. As a cell enlarges, volume grows faster than surface area, so SA:V falls. Beyond a certain size the surface cannot exchange materials (bring in nutrients/O_2, remove waste) fast enough for the volume, so cells stay small.

7. Cell → tissue → organ → organ system → organism. An emergent property is one that arises from the interactions between components and is not shown by any component alone (e.g. a heartbeat from many muscle cells).

8. (HL) Positional signals switch on regulatory genes coding for transcription factors, which activate or silence sets of target genes and so fix the cell's protein profile and identity. Epigenetic marks (DNA methylation, histone modification) lock this pattern and are copied at mitosis, so the specialised state is stable and heritable — making differentiation normally irreversible without deliberate reprogramming.