MEGA LECTURE

IB DP BIOLOGY

Theme D: Continuity and Change

D2.1 Cell and Nuclear Division

Revision Notes · Standard and Higher Level

Fahad H. Ahmad

+92 323 509 4443 | Megalecture.com

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

What the syllabus requires

By the end of D2.1 you should be able to work confidently with each of the following. Use this list as a final checklist before the exam. Items marked **(HL)** are examined at Higher Level only.

Understanding	You should be able to...
Reasons for division	Explain that cells divide for growth, tissue repair and replacement, and reproduction (asexual and the formation of gametes).
Two steps of division	Distinguish nuclear division (mitosis or meiosis) from cytokinesis (division of the cytoplasm).
The cell cycle	Describe interphase (G1, S, G2) and the mitotic phase, and outline the role of checkpoints.
Mitosis	Describe prophase, metaphase, anaphase and telophase, and state that mitosis produces two genetically identical diploid nuclei.
Meiosis	Describe meiosis as a reduction division producing four haploid, genetically varied cells through two divisions.
Variation	Explain crossing over, independent assortment and random fertilisation as sources of genetic variation.
Mitotic index	Calculate the mitotic index and interpret its meaning in a tissue sample.
Cancer	Relate uncontrolled cell division to tumour formation, mutation and metastasis.
Non-disjunction (HL)	Explain how non-disjunction produces chromosome-number changes such as Down syndrome, and interpret a karyotype.

> **Exam note:** The core of D2.1 is common to SL and HL. Non-disjunction, karyotypes and the more detailed treatment of variation are the parts most likely to appear in HL-only questions and in extended-response answers.

1. Why cells divide

A cell cannot simply keep growing. As a cell enlarges, its volume increases faster than its surface area, so the surface-area-to-volume ratio falls and the membrane can no longer exchange materials fast enough for the larger cytoplasm. Dividing restores a favourable ratio. Beyond this limit, cell division serves three broad biological purposes.

- **Growth.** A multicellular organism develops from a single fertilised egg into trillions of cells by repeated division; the organism gets larger because cell number increases.
- **Repair and replacement.** Damaged or worn-out cells (for example skin, gut lining and blood cells) are continually replaced by division of neighbouring cells or of stem cells.
- **Reproduction.** In asexual reproduction, division produces new genetically identical organisms. In sexual reproduction, a special form of division produces the gametes (sex cells) that fuse at fertilisation.

Nuclear division then cytokinesis

Cell division happens in two distinct steps that should never be confused. First the nucleus divides (**nuclear division**), so that each new nucleus receives a complete and correct set of chromosomes. Then the cytoplasm splits (**cytokinesis**), separating the cell into two. There are two types of nuclear division, and choosing between them is the theme of this topic:

Nuclear division	Main purpose	Product
Mitosis	Growth, repair, asexual reproduction	Two nuclei genetically identical to the parent (diploid stays diploid)
Meiosis	Production of gametes for sexual reproduction	Four nuclei that are haploid and genetically varied

> **Key distinction:** Nuclear division shares out the chromosomes; cytokinesis shares out the cytoplasm and organelles. A question about “what divides” usually wants you to name both steps.

2. The cell cycle

The cell cycle is the ordered sequence of events by which one cell becomes two. It is dominated by **interphase** (a long period of growth and preparation) followed by a short **mitotic (M) phase** in which division actually occurs.

Stage	What happens
G_1 (first gap)	The cell grows, makes proteins and organelles, and carries out its normal functions. Each chromosome is a single DNA molecule.
S (synthesis)	DNA replication: every chromosome is copied, so each now consists of two identical sister chromatids joined at a centromere. The DNA amount doubles.
G_2 (second gap)	Further growth; the cell checks the replicated DNA and makes the proteins needed for division (for example spindle proteins).
M phase	Nuclear division (mitosis or meiosis) followed by cytokinesis.

Cells that stop dividing (such as mature neurons) leave the cycle and enter a resting state, sometimes called G_0.

Checkpoints

The cycle is controlled at **checkpoints** where the cell verifies that conditions are correct before continuing. A checkpoint late in G_1 confirms the cell is large enough and the DNA undamaged before committing to S phase; a checkpoint at the end of G_2 confirms replication is complete; and a checkpoint during mitosis confirms every chromosome is correctly attached to the spindle before separation. Checkpoints act as quality control: they prevent damaged or incompletely copied DNA from being passed on, and their failure is central to cancer (Section 8).

Chromosomes, chromatids and centromeres

Getting this vocabulary right is essential, because the same chromosome looks different before and after S phase.

Term	Meaning
Chromosome	A single molecule of DNA wound around proteins (histones). Before S phase it is one chromatid; after S phase it is two.
Sister chromatids	The two identical copies of a chromosome produced by replication, held together until they are separated during division.
Centromere	The constricted region where sister chromatids are joined and where spindle fibres attach.
Homologous chromosomes	A matching pair carrying the same genes in the same order (one inherited from each parent), but possibly different alleles.

> **Watch the count:** Replication does not change the chromosome number. A replicated chromosome made of two chromatids is still counted as one chromosome, because the chromatids share one centromere.

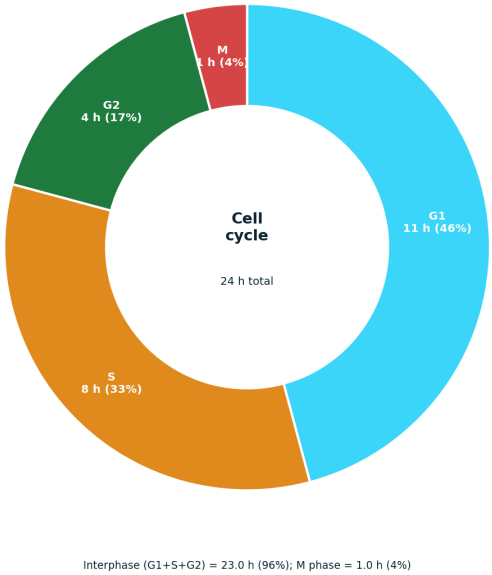

Figure 1. A representative 24-hour somatic cell cycle: interphase (G_1+S+G_2) = 23 h (96%), M phase = 1 h (4%), computed from stage durations of 11 h, 8 h, 4 h and 1 h that sum to 24 h.

3. Mitosis

Mitosis is nuclear division that produces two genetically identical nuclei. It is conventionally divided into four phases in the order **P**rophase, **M**etaphase, **A**naphase, **T**elophase (mnemonic: PMAT). The phases flow continuously; the boundaries are simply useful markers.

Phase	What happens
Prophase	Chromosomes condense (supercoil) and become visible as two sister chromatids. The nuclear membrane breaks down and the spindle, made of microtubules, begins to form from opposite poles.
Metaphase	Spindle fibres attach to the centromeres and line the chromosomes up single-file along the equator (metaphase plate) of the cell.

Phase	What happens
Anaphase	The centromeres split and the spindle fibres shorten, pulling the sister chromatids apart to opposite poles. Each chromatid is now an independent chromosome.
Telophase	Chromosomes arrive at the poles and decondense; a nuclear membrane re-forms around each group, producing two nuclei. The spindle breaks down.

Cytokinesis in animal and plant cells

Cytokinesis usually overlaps with telophase and completes the division of one cell into two, but the mechanism differs between the two cell types.

- **Animal cells** have no cell wall. A ring of protein filaments just under the membrane contracts, pulling the membrane inward to form a **cleavage furrow** that pinches the cell in two.
- **Plant cells** have a rigid wall, so the cell cannot pinch. Vesicles line up along the equator and fuse to build a new **cell plate** that grows outward into a new cell wall and membrane between the two daughter cells.

Outcome and roles of mitosis

Mitosis followed by cytokinesis produces **two daughter cells that are genetically identical to each other and to the parent cell**, each with the full diploid chromosome number. This genetic constancy is exactly what growth and repair require: every body cell must carry the same genome. Mitosis therefore underlies growth of tissues, replacement of dead or damaged cells, and asexual reproduction (for example runners in strawberry plants or budding in yeast and Hydra), all of which need faithful copies of the original cell.

> **Exam phrasing:** “Genetically identical” and “diploid” are the two marks examiners want when you state the product of mitosis. Do not forget “two” cells.

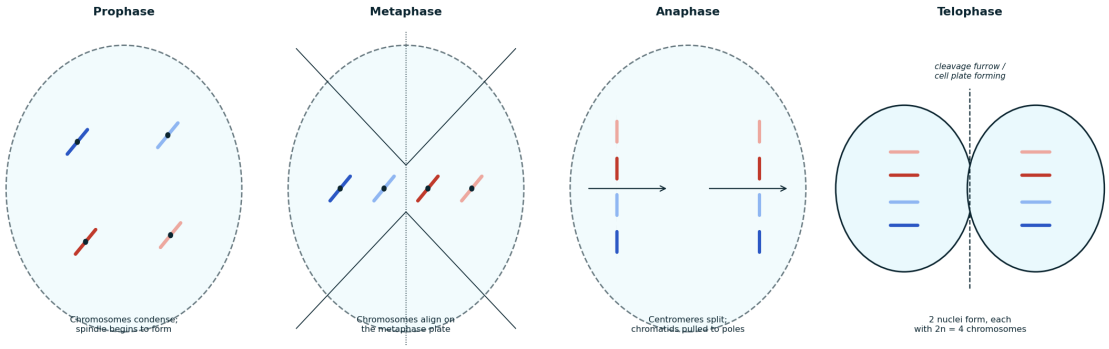

Figure 2. Mitosis (PMAT) tracked for a cell with 2n = 4: at anaphase the 4 dyad chromosomes split into 8 single-chromatid chromosomes (8 = 2 → 4), 4 moving to each pole, so each daughter nucleus again has 2n = 4.

4. Meiosis

Meiosis is the special nuclear division that makes gametes. It is a **reduction division**: the chromosome number is halved, from diploid (2*n*) to haploid (*n*). Halving is essential, because at fertilisation two gametes fuse; if each still carried the full number, the chromosome count would double every generation. In humans, diploid body cells have 46 chromosomes and gametes have 23.

Two divisions, four cells

Meiosis consists of **two divisions** in succession, with DNA replicated only once beforehand (in S phase).

- **Meiosis I** is the reduction division. Homologous chromosomes pair up and then are separated into different cells, so the chromosome number halves. This is where crossing over and independent assortment occur.
- **Meiosis II** resembles mitosis: the sister chromatids of each chromosome are separated. No further halving of chromosome number occurs.

The net result is **four haploid cells**, each with one chromosome from each homologous pair, and each **genetically different** from the others and from the parent cell.

Stage	Key event
Prophase I	Chromosomes condense; homologues pair to form bivalents; crossing over occurs at chiasmata; the spindle forms and the nuclear membrane breaks down.
Metaphase I	Bivalents line up on the equator; each homologous pair orients independently of the others (independent assortment).
Anaphase I	Whole homologous chromosomes (each still two chromatids) are pulled to opposite poles — this is where the chromosome number is halved.
Telophase I	Two haploid nuclei form; usually followed by cytokinesis into two cells.
Meiosis II (P, M, A, T)	Behaves like mitosis in each of the two cells: sister chromatids are separated, giving four haploid cells in total.

Homologous chromosomes and bivalents

Early in meiosis I, each chromosome pairs with its homologous partner. The two homologues lying alongside each other, each already made of two sister chromatids, form a group of four chromatids called a **bivalent** (or tetrad). Pairing brings the homologues close enough for chromatids to exchange segments, and it is the separation of these paired homologues in anaphase I that halves the chromosome number. Bivalents form only in meiosis, never in mitosis, which is one clear way to tell the two divisions apart.

> **Common error:** Meiosis I separates whole homologous chromosomes; meiosis II separates sister chromatids. Mixing up which division does which is a frequent cause of lost marks.

5. Sources of variation in meiosis

Sexual reproduction generates offspring that differ genetically from their parents and from one another. Three processes are responsible: two occur during meiosis, and one at fertilisation.

Crossing over (chiasmata)

While homologues are paired as bivalents in prophase I, non-sister chromatids can break and rejoin, exchanging equivalent segments of DNA. The points where chromatids cross and exchange material are called **chiasmata** (singular: chiasma). Crossing over shuffles alleles between the maternal and paternal chromosomes, producing **recombinant** chromatids that carry new combinations of alleles not present in either parent chromosome.

Independent (random) assortment

At metaphase I, each bivalent lines up on the equator independently of the others, so which homologue of a pair faces which pole is random and unlinked to the orientation of every other pair. The number of possible combinations is 2^n, where n is the number of chromosome pairs. In humans (n = 23) this gives 2^{23}, about 8.4 million, different gametes from assortment alone, before crossing over is even considered.

Random fertilisation

Any one of a father's millions of genetically distinct sperm can fertilise any one of a mother's genetically distinct eggs. This **random fertilisation** multiplies the variation: for humans, roughly $2^{23} \times 2^{23}$ possible zygotes, and that is before crossing over. Together these three processes make each individual (except identical twins) genetically unique.

Source	When it occurs	Effect
Crossing over	Prophase I (at chiasmata)	New allele combinations within a chromosome
Independent assortment	Metaphase I (and II)	New combinations of whole chromosomes
Random fertilisation	At fusion of gametes	Random combination of two varied gametes

6. Mitosis compared with meiosis

This comparison is one of the most commonly examined parts of the topic. Learn it as a table so you can retrieve any row quickly.

Feature	Mitosis	Meiosis
Number of divisions	One	Two (meiosis I and II)
Number of daughter cells	Two	Four
Chromosome number	Kept the same ($2n \rightarrow 2n$)	Halved ($2n \rightarrow n$)
Genetic identity	Identical to parent	Genetically varied
Homologues pair (bivalents)?	No	Yes, in meiosis I
Crossing over?	No	Yes
Purpose	Growth, repair, asexual reproduction	Production of gametes
Where in the body	Most body (somatic) cells	Reproductive organs (gonads)

> **Memory hook:** Mi**t**osis makes **t**wins (identical); meiosis makes gametes and halves the number. “Meiosis” and “reduction” both start with a downward idea — the number goes down.

7. Mitotic index

The **mitotic index** is the proportion of cells in a sample that are undergoing mitosis at a given moment. It is measured from a stained micrograph by counting how many cells show visible condensed chromosomes (that is, are in prophase, metaphase, anaphase or telophase) as a fraction of all cells counted.

Mitotic index = (number of cells in mitosis) / (total number of cells)

The value has no units (it is a ratio, often expressed as a decimal or a percentage). A high mitotic index means a large fraction of cells are dividing. This is useful in two contexts:

- In a growing tissue (such as a root tip or embryo), a high index indicates rapid growth.
- In medicine, an unusually high mitotic index in a tissue sample can signal uncontrolled division and is used to help diagnose and grade tumours.

Mitotic index and the length of a phase

Because cells move through the cycle continuously, the fraction of cells caught in a stage is proportional to the fraction of the cycle spent in that stage. So the mitotic index also estimates the proportion of the cycle occupied by mitosis: multiplying it by the total cycle time gives the approximate time a cell spends in mitosis. This is why a tissue with a longer M phase, or with more cells triggered to divide, shows a higher index.

Worked example — calculating a mitotic index

A student examines a field of view of an onion root tip and counts 60 cells in total, of which 15 show condensed chromosomes. Find the mitotic index as a decimal and as a percentage.

Mitotic index = 15 / 60 = **0.25**.

As a percentage: 0.25 × 100 = **25%**. One quarter of the cells are in mitosis, consistent with the rapid growth expected at a root tip.

Method tip: Count every cell in the field, including those clearly in interphase (uniform nucleus, no visible chromosomes). Forgetting the interphase cells in the denominator inflates the index.

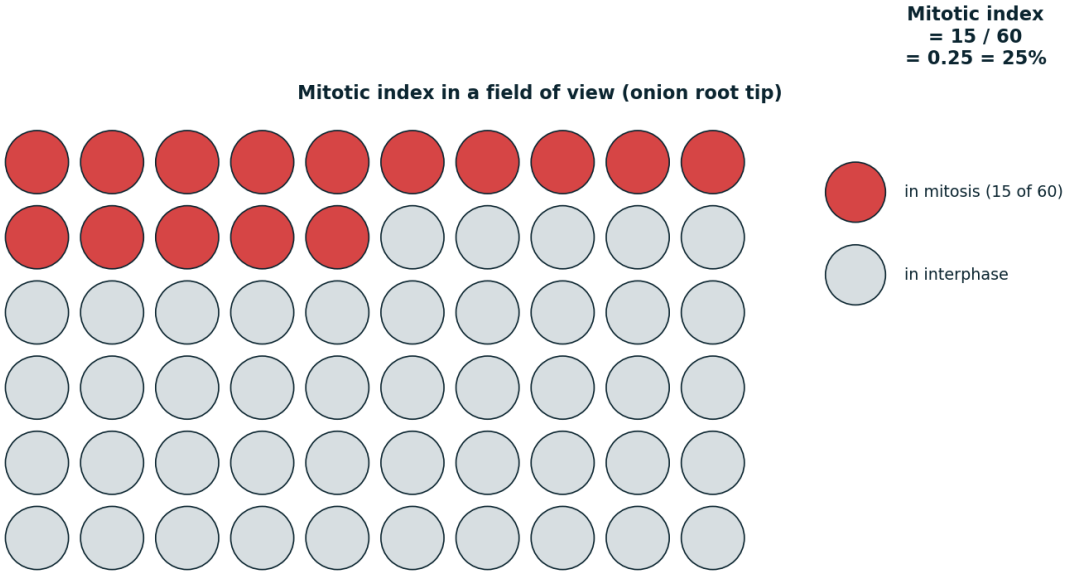

Figure 3. Mitotic index worked and audited: 15 of 60 cells in a field of view show condensed chromosomes, giving a mitotic index of 0.25 (25%), matching the worked example in the text.

8. Uncontrolled division and cancer

Normally the cell cycle is tightly controlled: cells divide only when signalled to and only when checkpoints are satisfied. Cancer arises when this control is lost and cells divide in an **uncontrolled** way.

Mutations and the loss of control

Control is lost when the genes that regulate the cell cycle become mutated. Two categories matter: **proto-oncogenes**, which normally promote division and, when mutated into over-active **oncogenes**, drive it too fast; and **tumour suppressor genes**, which normally restrain division and, when disabled by mutation, remove the brakes. Cancer usually requires several such mutations to accumulate in one cell line, which is why risk rises with age.

Tumours and metastasis

A cell dividing without control produces a mass of cells called a **tumour**. A **benign** tumour stays in one place and is usually harmless once removed. A **malignant** tumour is cancerous: its cells can invade surrounding tissue and, crucially, break away, travel in the blood or lymph and start secondary tumours elsewhere in the body — a process called **metastasis**, which makes cancer so dangerous to treat.

Carcinogens

Agents that increase the mutation rate and therefore the risk of cancer are called **carcinogens**. They include certain chemicals (such as components of tobacco smoke), ionising radiation (such as X-rays and radon) and ultraviolet light, and some viruses. Because most carcinogens act by damaging DNA, they are also **mutagens**.

> **Link back:** Cancer is a failure of the checkpoints in Section 2. When checkpoint proteins that would normally halt a damaged cell are themselves faulty, mutated cells continue through the cycle and divide.

9. Non-disjunction and karyotypes (HL)

(HL) Meiosis normally separates chromosomes precisely, but errors happen. **Non-disjunction** is the failure of chromosomes to separate correctly during meiosis: either homologues fail to separate in anaphase I, or sister chromatids fail to separate in anaphase II. The result is a gamete with one chromosome too many or too few.

Down syndrome (trisomy 21)

(HL) If a gamete carrying an extra copy of chromosome 21 is fertilised by a normal gamete, the zygote has three copies of chromosome 21 (47 chromosomes in total) instead of two. This condition, **trisomy 21**, causes **Down syndrome**. The frequency of non-disjunction, and hence of Down syndrome, increases with maternal age. Non-disjunction of other chromosomes and of the sex chromosomes produces other recognised conditions.

Karyotypes

(HL) A **karyotype** is a display of all of an individual's chromosomes arranged in homologous pairs and ordered by size. It is prepared from cells arrested in metaphase, when chromosomes are most condensed and visible. Reading a karyotype allows biologists to count the chromosomes and check their structure: 47 chromosomes with three copies of number 21 confirms trisomy 21, and the sex chromosomes (XX or XY) reveal the chromosomal sex. Samples for karyotyping can be obtained before birth by amniocentesis or

chorionic villus sampling.

Term (HL)	Meaning
Non-disjunction	Failure of chromosomes or chromatids to separate in meiosis, giving gametes with abnormal chromosome numbers
Trisomy	Three copies of a particular chromosome instead of two (for example trisomy 21)
Karyotype	The complete set of an individual's chromosomes arranged in ordered homologous pairs

10. Worked examples and exam skills

These build the specific skills examiners test: identifying phases, tracking chromosome and DNA content, and explaining variation.

Worked example 1 — identify the phase

A cell is observed with its chromosomes lined up single-file across the middle of the cell, each still made of two chromatids, with spindle fibres attached to the centromeres. Name the phase of mitosis and justify your answer.

Metaphase. The defining feature is chromosomes aligned on the equator (metaphase plate) with spindle fibres attached but not yet shortened, so the chromatids have not yet been pulled apart (that would be anaphase).

Worked example 2 — calculate a mitotic index

In a micrograph, 8 cells are in prophase, 3 in metaphase, 2 in anaphase and 1 in telophase, and the remaining 36 cells are in interphase. Calculate the mitotic index.

Cells in mitosis = 8 + 3 + 2 + 1 = 14. Total cells = 14 + 36 = 50.

Mitotic index = 14 / 50 = **0.28** (or 28%).

Worked example 3 — track chromosomes and DNA through the cycle

A diploid cell has 2*n* = 8 chromosomes. State the number of chromosomes and the number of DNA molecules (chromatids) present at the end of G_1, at the end of G_2, and in each daughter cell after mitosis.

End of G_1: **8 chromosomes, 8 DNA molecules** (each chromosome is one chromatid, before replication).

End of G_2 (after S phase): **8 chromosomes, 16 DNA molecules** (each chromosome now has two sister chromatids; the number of chromosomes is unchanged).

Each daughter cell after mitosis: **8 chromosomes, 8 DNA molecules** — identical to the original G_1 cell.

Worked example 4 — explain a source of variation

Explain how independent assortment during meiosis leads to genetic variation in gametes.

At metaphase I each bivalent (homologous pair) lines up on the equator independently of the other pairs. The maternal and paternal homologue of each pair can face either pole, and the orientation of one pair does not influence any other. Different orientations send different combinations of maternal and paternal chromosomes into each gamete, giving 2^n possible combinations and therefore genetically varied gametes.

Worked example 5 — compare the two divisions

A student states: “Meiosis produces four cells and mitosis produces two, so meiosis just does mitosis twice.” Identify the flaw in this statement.

The number of cells is correct, but the reasoning is wrong. Meiosis I is a **reduction** division that separates homologous chromosomes and halves the chromosome number, and it includes pairing, crossing over and independent assortment — none of which happen in mitosis. Only meiosis II resembles mitosis. So the products are haploid and genetically varied, not diploid and identical.

Worked example 6 — count gamete combinations

An organism has a diploid number of $2n = 6$. Ignoring crossing over, how many genetically different gametes can it produce through independent assortment?

Number of chromosome pairs $n = 3$, so combinations = $2^n = 2^3 =$ **8** genetically different gametes.

Worked example 7 — estimate time spent in mitosis

In a root-tip sample the mitotic index is 0.20 and the complete cell cycle lasts 24 hours. Estimate the time an average cell spends in mitosis.

Time in mitosis ≈ mitotic index × cycle time = 0.20 × 24 h = **4.8 hours**.

This assumes cells are randomly distributed through the cycle, so the fraction in mitosis reflects the fraction of the cycle spent there.

11. Common pitfalls

- **Chromatids vs chromosomes.** After replication a chromosome has two chromatids but still counts as one chromosome. Chromatids become separate chromosomes only once the centromere splits (anaphase).
- **Diploid vs haploid.** Diploid ($2n$) means chromosomes in homologous pairs; haploid (n) means one of each. Mitosis keeps the number; meiosis halves it.
- **When does DNA replicate?** Once, in S phase, before either division. Meiosis does not replicate DNA again between meiosis I and II.

- **Where variation comes from.** Mitosis produces no variation (barring rare mutation). All the shuffling — crossing over and independent assortment — happens in meiosis, and random fertilisation adds more.
- **Which division separates what.** Meiosis I separates homologues; meiosis II and mitosis separate sister chromatids.
- **Nuclear division is not the whole story.** Cytokinesis (splitting the cytoplasm) is a separate step; naming only mitosis or meiosis is incomplete.

12. Quick reference

Item	Key point
Reasons cells divide	Growth; repair and replacement; reproduction
Two steps	Nuclear division (mitosis / meiosis) then cytokinesis
Cell cycle	Interphase (G_1, S, G_2) + M phase; DNA replicates in S; checkpoints control progress
Mitosis phases	Prophase → Metaphase → Anaphase → Telophase (PMAT)
Mitosis product	2 genetically identical diploid cells
Meiosis product	4 haploid, genetically varied cells (two divisions)
Variation sources	Crossing over; independent assortment; random fertilisation
Mitotic index	cells in mitosis / total cells (a ratio, no units)
Cancer	Uncontrolled division → tumour; malignant tumours metastasise; carcinogens raise mutation risk
Non-disjunction (HL)	Failed separation in meiosis → abnormal chromosome number (for example trisomy 21)

13. Practice questions

Attempt each question fully before reading the worked answer beneath it.

Q1. State two reasons, other than reproduction, why cells in a multicellular organism divide by mitosis. [2]

Answer 1

Growth — an increase in the number of cells enlarges the organism; and repair or replacement of damaged, dead or worn-out cells (for example skin or blood cells). Each point earns one mark.

Q2. Distinguish between nuclear division and cytokinesis. [2]

Answer 2

Nuclear division is the division of the nucleus, sharing the chromosomes into new nuclei (by mitosis or meiosis). Cytokinesis is the division of the cytoplasm that follows, splitting the cell into two separate daughter cells.

Q3. Describe what happens to the DNA during S phase and explain why the chromosome number does not change. [3]

Answer 3

During S phase every chromosome is replicated, so each ends up as two identical sister chromatids joined at a centromere; the total amount of DNA doubles. The chromosome number is unchanged because the two chromatids remain attached at a single centromere and are therefore still counted as one chromosome, not two.

Q4. A dividing animal cell shows sister chromatids being pulled to opposite poles by shortening spindle fibres. Name the phase and describe how cytokinesis will differ from that in a plant cell. [3]

Answer 4

The phase is **anaphase** (centromeres have split and chromatids are moving to the poles). In the animal cell, cytokinesis occurs by a contracting ring of filaments that forms a cleavage furrow, pinching the membrane inward. In a plant cell the rigid wall prevents pinching, so instead vesicles fuse at the equator to build a cell plate that becomes a new wall and membrane.

Q5. A tissue sample of 200 cells contains 24 cells with visible condensed chromosomes. Calculate the mitotic index and comment on what a high value would suggest in a clinical sample. [3]

Answer 5

Mitotic index = 24 / 200 = **0.12** (12%).

A high mitotic index indicates that a large proportion of cells are actively dividing. In a clinical (tissue biopsy) sample this can suggest uncontrolled cell division and helps in the diagnosis or grading of a tumour.

Q6. Explain two ways in which meiosis generates genetic variation. [4]

Answer 6

Crossing over: while homologous chromosomes are paired as bivalents in prophase I, non-sister chromatids exchange segments at chiasmata, producing recombinant chromatids with new allele combinations.

Independent assortment: at metaphase I each bivalent orients randomly and independently of the others, so gametes receive different combinations of maternal and paternal chromosomes (2^n combinations).

Q7. A diploid cell has $2n = 10$. State the number of chromosomes in (a) each cell produced by mitosis and (b) each cell produced by meiosis. Explain the difference. [3]

Answer 7

(a) Mitosis: **10 chromosomes** per cell (the diploid number is maintained).

(b) Meiosis: **5 chromosomes** per cell (the haploid number). The difference arises because meiosis I separates homologous chromosomes, halving the number, whereas mitosis separates only sister chromatids and keeps the number constant.

Q8. (HL) Explain how non-disjunction during meiosis can result in a child with Down syndrome. [3]

Answer 8 (HL)

Non-disjunction is the failure of chromosomes to separate correctly — here the two copies of chromosome 21 fail to separate (in anaphase I) or the chromatids fail to separate (in anaphase II). This produces a gamete carrying an extra chromosome 21. When this gamete is fertilised by a normal gamete, the zygote has three copies of chromosome 21 (trisomy 21), a total of 47 chromosomes, which causes Down syndrome.