REVISION GUIDE

One cell, then *two*

Cell and nuclear division

Every cell in your body came from one cell dividing, again and again. Watch the cytoplasm split three different ways, follow the chromosomes through mitosis and meiosis, find the error behind Down syndrome, count dividing cells down a microscope, and at higher level see how cyclins control the cycle and what happens when that control fails.

11 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division

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By the end you can

- [ ] Outline how new cells are made by a parent cell dividing into two daughter cells D2.1.1
- [ ] Compare cytokinesis in animal cells and plant cells D2.1.2
- [ ] Explain why cytokinesis is usually equal, give two examples of unequal cytokinesis, and say what every daughter cell must receive D2.1.3
- [ ] Explain why nuclear division comes before cell division, and the different roles of mitosis and meiosis D2.1.4
- [ ] Explain why DNA replication must happen before mitosis or meiosis, and what a chromosome is made of afterwards D2.1.5
- [ ] Outline how chromosomes condense and how they are moved D2.1.6
- [ ] Describe the phases of mitosis and explain how mitosis produces genetically identical nuclei D2.1.7
- [ ] Identify the phases of mitosis in diagrams and micrographs D2.1.8
- [ ] Explain meiosis as a reduction division, using the terms diploid and haploid D2.1.9
- [ ] Explain how non-disjunction can cause Down syndrome D2.1.10
- [ ] Explain how random orientation and crossing over make meiosis a source of variation D2.1.11
- [ ] Outline cell proliferation for growth, cell replacement and tissue repair D2.1.12
- [ ] Describe the phases of the cell cycle and what happens during interphase D2.1.13
- [ ] Outline the growth that happens in interphase, including organelles D2.1.14
- [ ] Explain how rising and falling cyclin concentrations control the cell cycle D2.1.15
- [ ] Explain how mutations in proto-oncogenes and tumour suppressor genes can lead to uncontrolled division D2.1.16
- [ ] Distinguish benign and malignant tumours, and primary and secondary tumours, and determine a mitotic index D2.1.17

Tick each one when you can do it without the book.

D2.1.1 GENERATION OF NEW CELLS BY CELL DIVISION

01 One cell becomes *two*

Cell theory says that cells only come from cells that already exist. There is no other source: every cell in an oak tree, a mushroom or you was made by a cell dividing. The cell that divides is the **parent cell**, and it ends as two **daughter cells**.

A cell cannot just keep growing instead. As it gets bigger its volume rises faster than its surface area, so each part of the membrane has more cytoplasm to supply and clear. Dividing gives two smaller cells, each with more surface for its size. Division also makes more cells: for growth, for replacing cells that wear out, and for reproduction.

Division happens in two stages, in this order. First the nucleus divides, so there is a nucleus for each new cell. Then the cytoplasm divides between them. Prokaryotes have no nucleus and divide more simply, by binary fission: the circular DNA is copied and the cell splits.

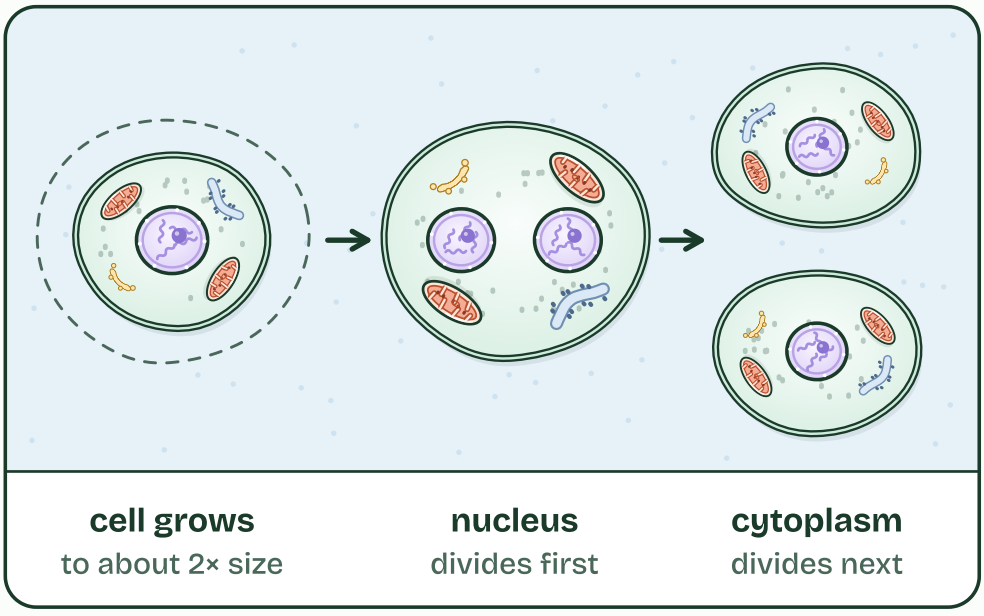
KEY POINTS

- New cells only come from existing cells, by cell division.
- A parent cell divides to give two daughter cells.
- The nucleus divides first, then the cytoplasm.

KEY TERMS

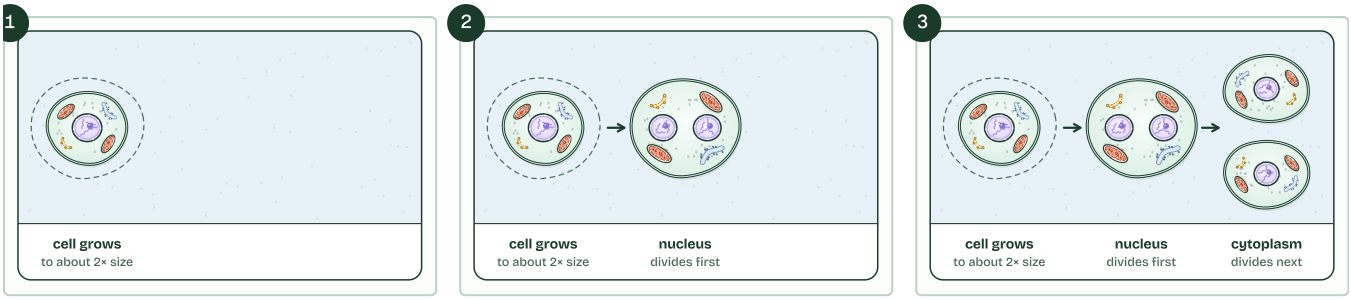
parent cell
The cell that divides, sometimes called the mother cell. It ends as two new cells.

daughter cells
One of the two cells made when a parent cell divides.



STEP BY STEP

3 STEPS



A **parent cell** grows to about twice its starting size.

Its **nucleus divides** first, so there are two.

Then the cytoplasm divides: two **daughter cells**, each with a nucleus.

TRY IT FIRST

A fertilised human egg is one cell. An adult has around 30 trillion. Roughly how many times would a cell and all its descendants need to double to reach that? (Try 2 to the power 40, then 45.)

WATCH OUT

The parent cell does not survive alongside its daughters. It becomes them: one cell in, two cells out.

PREDICT

Why does a eukaryotic cell divide its nucleus before it divides its cytoplasm?

(A) So that the cytoplasm can be shared out equally between the two daughter cells

(B) So that each daughter cell gets a nucleus and none is left without one

(C) So that the nucleus can make the proteins that split the cytoplasm in two

Decide before you look. Answer on page 39.

02 Splitting the *cytoplasm*

D2.1.2 D2.1.3 CYTOKINESIS, EQUAL AND UNEQUAL

Cytokinesis splits the cytoplasm once the nucleus has divided. Animal and plant cells do it differently, because a plant cell has a rigid wall.

In an **animal cell**, a ring of the proteins actin and myosin forms just inside the membrane around the middle of the cell. The ring contracts, like a drawstring, pulling the membrane in until it meets in the middle and the cell is pinched in two. In a **plant cell**, the wall cannot be pinched. Instead, vesicles carrying membrane and wall material line up across the middle and fuse. They make a **cell plate**, which grows outwards to the side walls and becomes the two new membranes with a new wall between them.

Cytokinesis is usually **equal**, but not always. Whatever the split, each daughter cell must get at least one mitochondrion (and, in a plant, a chloroplast), because these are only made by an existing one dividing. In human **egg cell** production the cytoplasm is divided very unequally: the egg keeps almost all of it and a tiny **polar body** is pinched off. **Yeast** divides by **budding**: a small bud grows out of the cell, takes one nucleus and pinches off.

KEY POINTS

- Animal cells: a ring of actin and myosin pinches the membrane in.
- Plant cells: vesicles fuse into a cell plate, which becomes the new membranes and wall.
- Usually equal; unequal in egg cell production (polar bodies) and yeast budding.
- Both daughter cells need at least one mitochondrion.

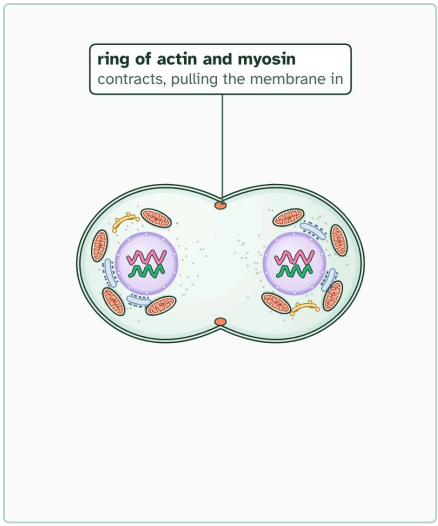
KEY TERMS

cytokinesis
The division of the cytoplasm of a parent cell between two daughter cells. It follows nuclear division.

cell plate
A flat structure of fused vesicles across the middle of a dividing plant cell. It grows out to the side walls and becomes the membranes and new wall between the daughter cells.

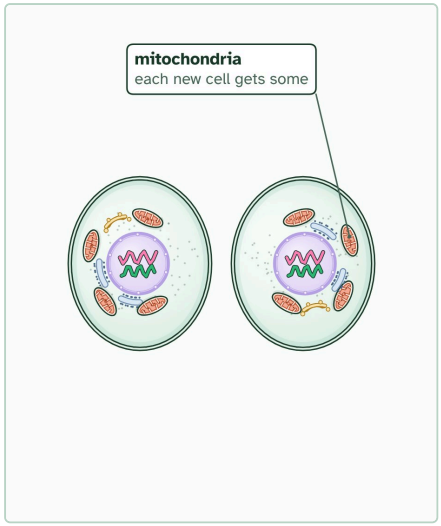
ANIMATION · SPLITTING THE CYTOPLASM
7 MOMENTS

1 AN ANIMAL CELL



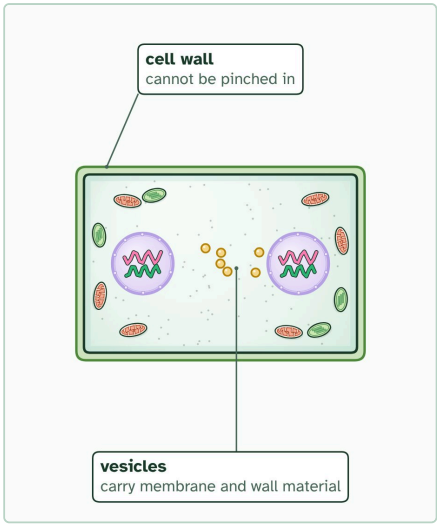
In an **animal cell**, a ring of **actin and myosin** just inside the membrane contracts and pinches the cell in two.

2 AN ANIMAL CELL



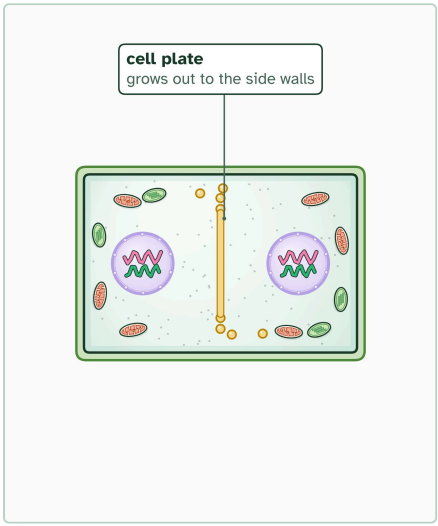
Mitochondria are only made by dividing old ones, so **each daughter cell must get at least one**.

3 A PLANT CELL



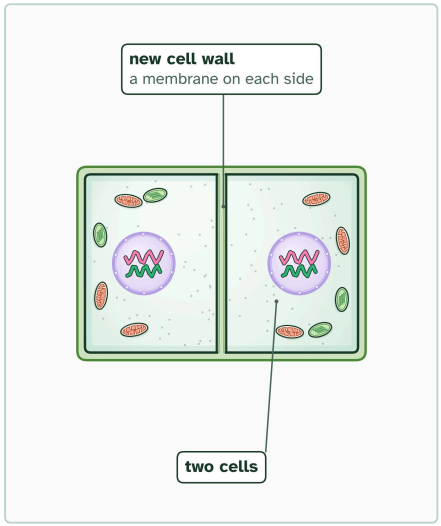
A **plant cell** has a wall, so it cannot be pinched. Vesicles carry membrane and wall material to the equator.

4 A PLANT CELL



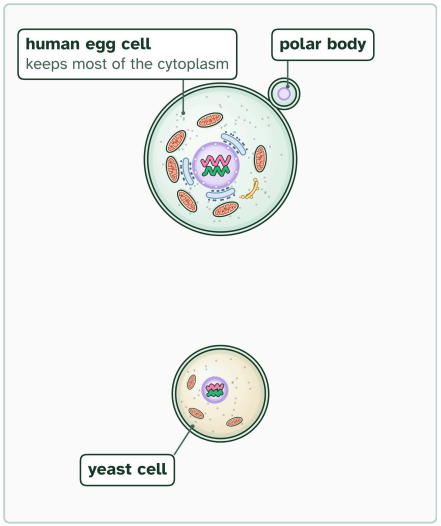
The vesicles fuse into a **cell plate**, which grows outwards until it meets the side walls.

5 A PLANT CELL



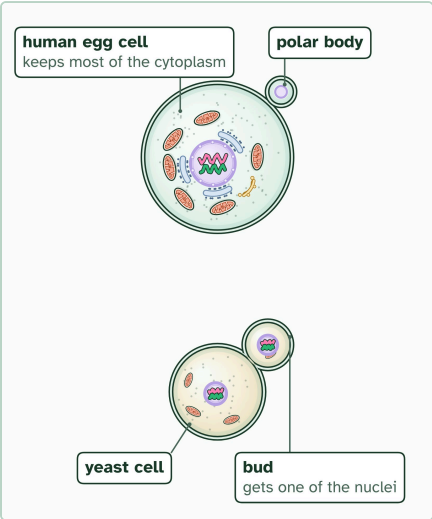
The plate becomes two membranes with **new cell wall** between them: two cells.

6 UNEQUAL DIVISION



Cytokinesis is usually equal, but not always. A human **egg cell** keeps almost all the cytoplasm and pinches off a tiny **polar body**.

7 UNEQUAL DIVISION



Yeast divides by **budding**: a small bud grows out, one nucleus moves into it, and it pinches off.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division#cytokinesis

WATCH OUT

Cytokinesis is not a phase of mitosis. Mitosis divides the nucleus; cytokinesis divides the cytoplasm, and usually starts as mitosis ends.

PREDICT

In a human egg cell's last division, why might keeping almost all the cytoplasm in one cell be an advantage?

(A) It leaves the polar body enough cytoplasm to grow into a second egg cell later

(B) The egg has the food and organelles an embryo needs before it can feed itself

(C) A larger cell has more surface for its size, so it can take in more oxygen

Decide before you look. Answer on page 39.

D2.1.4 D2.1.5 D2.1.6 MITOSIS AND MEIOSIS; REPLICATION; CONDENSING AND MOVING CHROMOSOMES

03 Copy, coil, *move*

Eukaryotes divide their nucleus in one of two ways. **Mitosis** gives two nuclei with the same chromosome number and the same genome as the parent, for growth, repair and asexual reproduction. **Meiosis** halves the chromosome number and makes every nucleus genetically different, for making gametes.

Both start the same way. Before either can happen, the DNA must be copied (D1.1). Until then each chromosome is one long DNA molecule; afterwards it is two identical molecules, the **sister chromatids**, held together at the **centromere** until anaphase.

Two more features are shared. The chromosomes **condense**: each DNA molecule winds round **histones** and then coils on itself again and again (supercoiling), so that metres of DNA become short, thick chromosomes that can be moved without tangling. And they are **moved** by **microtubules** of the spindle, pulled by motor proteins.

KEY POINTS

- Mitosis keeps the chromosome number and genome; meiosis halves the number and makes variety.
- DNA is replicated first: each chromosome becomes two sister chromatids joined at the centromere.
- Chromosomes condense by supercoiling round histones; microtubules and motor proteins move them.

KEY TERMS

mitosis
Division of the nucleus into two nuclei with the same number of chromosomes and the same genes as the parent nucleus.

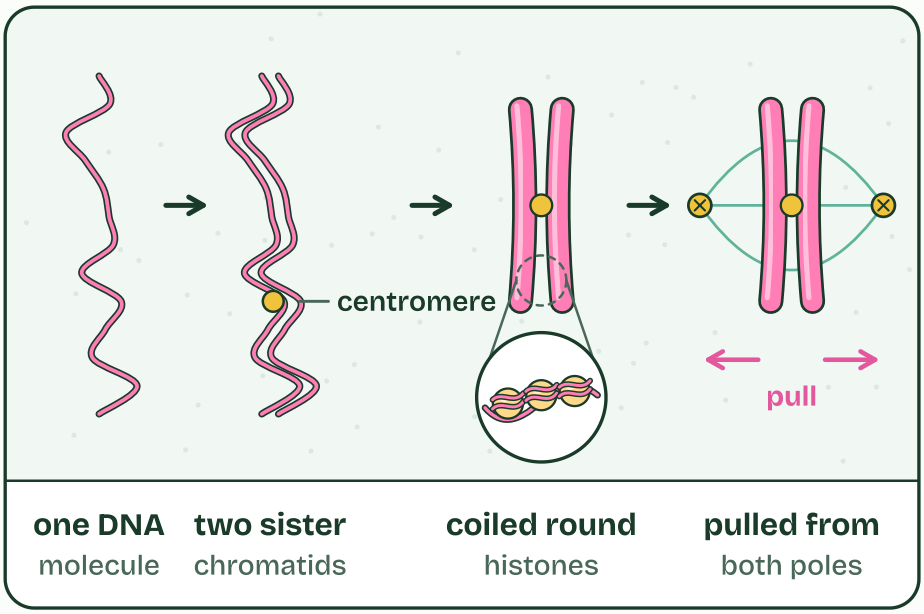
meiosis
Division of the nucleus, in two rounds, into four nuclei with half the parent's chromosome number. It produces genetically varied nuclei for gametes.

sister chromatids
One of the two identical DNA molecules of a replicated chromosome. Sister chromatids are held together at the centromere until anaphase.

centromere
The region of a chromosome where its two sister chromatids are held together, and where spindle microtubules attach.

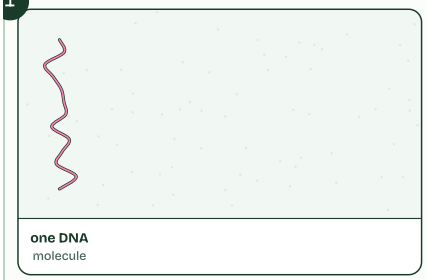
histones
Proteins that DNA winds round in eukaryotic chromosomes. They package DNA and help it supercoil when chromosomes condense.

microtubules
Protein tubes that make up the spindle. In division they attach to centromeres and, with motor proteins, pull chromosomes apart.



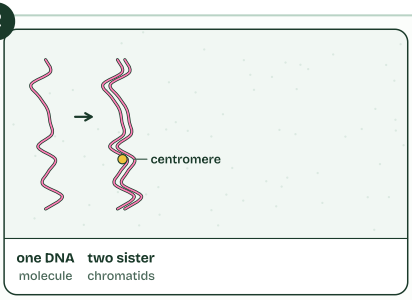
STEP BY STEP 4 STEPS

1



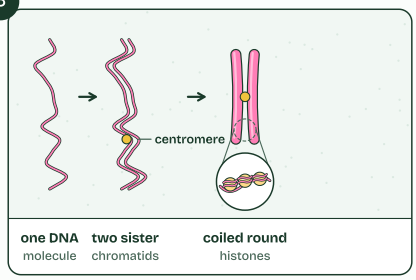
Before replication, a chromosome is **one DNA molecule**, long and thin.

2



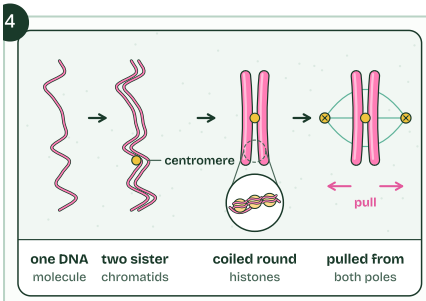
After replication it is **two sister chromatids**, joined at the centromere.

3



In prophase the DNA winds round **histones** and supercoils into a short, thick chromosome.

4



Microtubules from both poles attach at the centromere and pull.

WATCH OUT

A replicated chromosome is still counted as one chromosome. A human cell going into mitosis has 46 chromosomes, made of 92 chromatids.

PREDICT

A cell has 8 chromosomes in G1. How many DNA molecules does its nucleus hold at the start of mitosis?

(A) 8, because the number of chromosomes stays the same until anaphase splits them

(B) 16, because each of the 8 chromosomes is now 2 chromatids, each one molecule

(C) 4, because the DNA must be halved before mitosis can share it out evenly

Decide before you look. Answer on page 39.

04

D2.1.7 PHASES OF MITOSIS

Four phases, two *identical* nuclei

Mitosis is one continuous process, named in four phases. In **prophase** the chromosomes condense and become visible, the nuclear membrane breaks down, and the spindle starts to form from the two poles. In **metaphase** microtubules from both poles attach to each centromere and the chromosomes line up across the **equator**. In **anaphase** the centromeres separate and the sister chromatids are pulled to opposite poles, so each is now a chromosome in its own right. In **telophase** a nuclear membrane forms round each group, the chromosomes uncoil and the spindle breaks down.

The result is two nuclei that are **genetically identical** to each other and to the parent nucleus. That follows from the chromatids: each chromosome's two chromatids are copies of one another, and one goes to each pole. So each new nucleus gets one copy of every chromosome.

Write a sentence of four words starting P, M, A and T. The odder it is, the better it sticks.

KEY POINTS

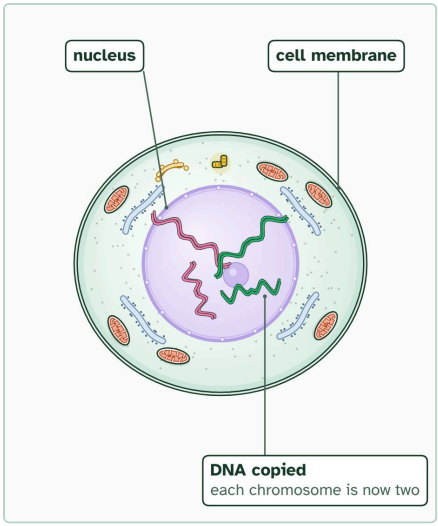
- Prophase, metaphase, anaphase, telophase, then cytokinesis.
- Sister chromatids separate in anaphase, one to each pole.
- The two nuclei are genetically identical to each other and to the parent.

KEY TERMS

equator
The plane across the middle of a dividing cell, halfway between the two poles of the spindle.

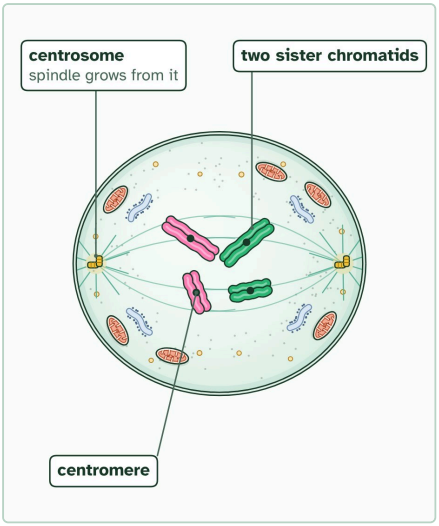
ANIMATION · MITOSIS, ONE PHASE AT A TIME
7 MOMENTS

1 INTERPHASE



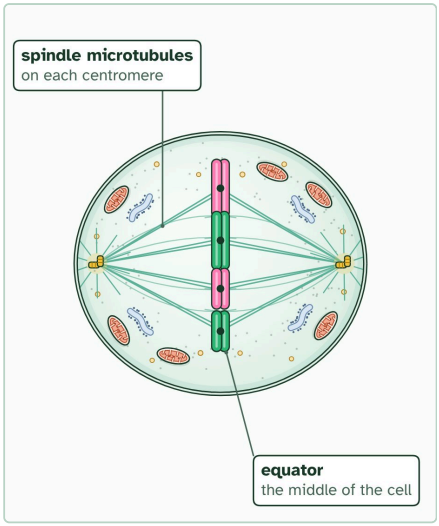
After copying, each chromosome is **two DNA molecules**, the sister chromatids, held together at the centromere.

2 PROPHASE



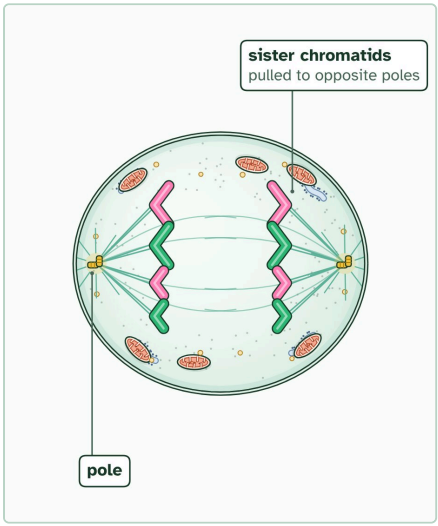
The **nuclear membrane** breaks down and the centrosomes move apart. **Spindle microtubules** grow from them.

3 METAPHASE



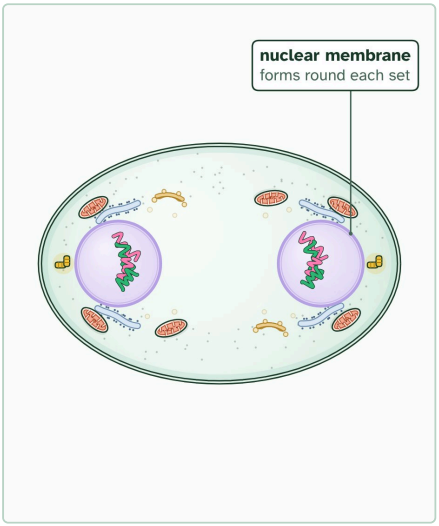
Metaphase. Microtubules from both poles attach to each centromere and line the chromosomes up on the **equator**.

4 ANAPHASE



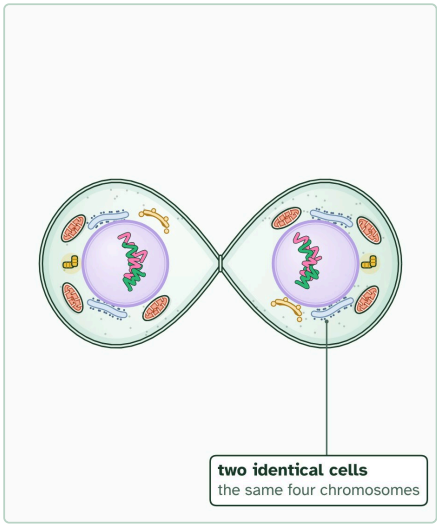
Anaphase. The centromeres split. Microtubule motors pull the **sister chromatids** to opposite poles.

5 TELOPHASE



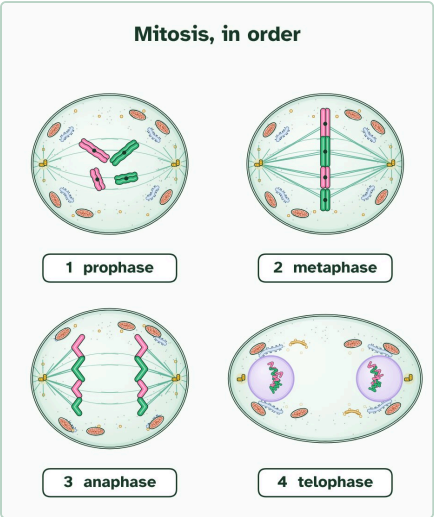
Telophase. A nuclear membrane forms round each group, the chromosomes uncoil and the spindle breaks down.

6 CYTOKINESIS



Cytokinesis. A ring of actin and myosin pinches the cell in two. Each daughter nucleus has one copy of every chromosome: they are **genetically identical**.

7 THE FOUR PHASES



Prophase, metaphase, anaphase, telophase: make up your own way to remember the order.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division#mitosis

REMEMBER IT

Make your own

P	M	A	T
P	M	A	T
Prophase	**Metaphase**	**Anaphase**	**Telophase**
condense, membrane goes	line up in the middle	chromatids pulled apart	two nuclei form

WATCH OUT

Interphase is not a phase of mitosis. It is the time between divisions, when the cell grows and copies its DNA, and most cells spend most of their time in it.

PREDICT

In a cell in metaphase, what are lined up on the equator?

(A) Single chromatids, one from each chromosome, ready to go to the poles

(B) Whole chromosomes, each still two chromatids held at the centromere

(C) Pairs of matching chromosomes lying side by side as they do in meiosis

Decide before you look. Answer on page 39.

05 Name the *phase*

D2.1.8 IDENTIFICATION OF PHASES OF MITOSIS

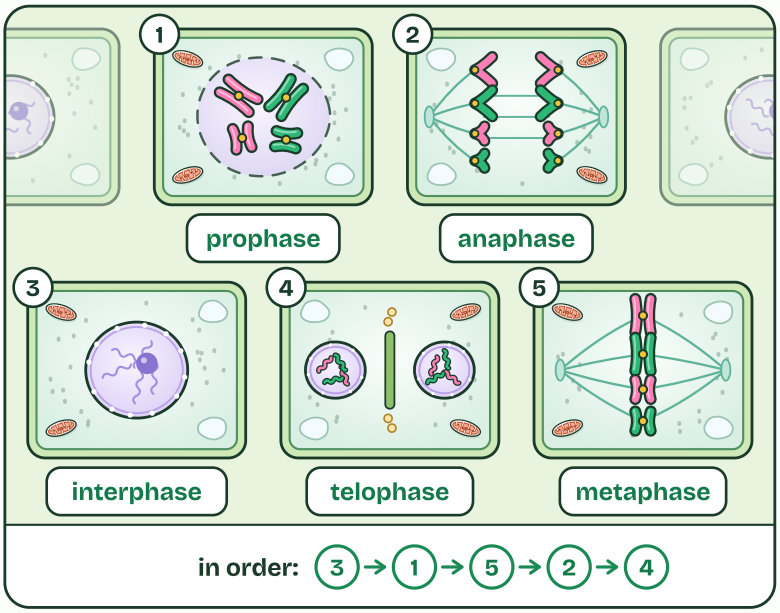
Down a microscope, a root tip squash shows hundreds of cells, each stopped at one moment. The stain colours the chromosomes, and the shape of the chromosomes tells you the phase. You need one clue for each.

Interphase: a round nucleus with a darker nucleolus and no separate chromosomes. **Prophase**: threads inside the nucleus, getting thicker; the nucleus may lose its edge. **Metaphase**: a band of chromosomes straight across the middle of the cell. **Anaphase**: two groups moving to opposite ends, often in V shapes with their arms trailing. **Telophase**: two groups at the ends, often with a new nucleus forming round each and a cell plate between them.

Micrographs are harder than diagrams: cells are seen at all angles, and a metaphase seen end on looks like a ring of chromosomes rather than a line. Count only cells you are sure of, and decide your rules before you start.

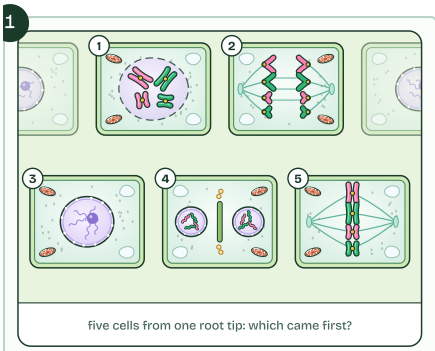
KEY POINTS

- Interphase: nucleus with a nucleolus. Prophase: threads.
- Metaphase: a line across the middle. Anaphase: two groups moving apart.
- Telophase: two groups at the ends, new nuclei, often a cell plate.



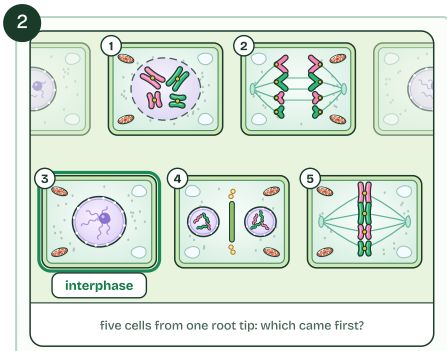
STEP BY STEP
7 STEPS

1



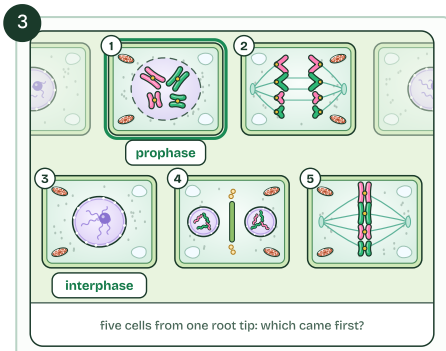
Five drawn cells from a root tip. **Name each one** before you go on.

2



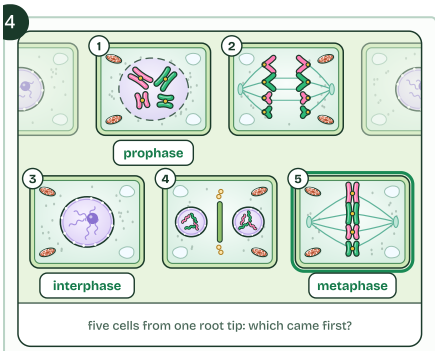
Interphase: a round nucleus and a dark nucleolus.

3



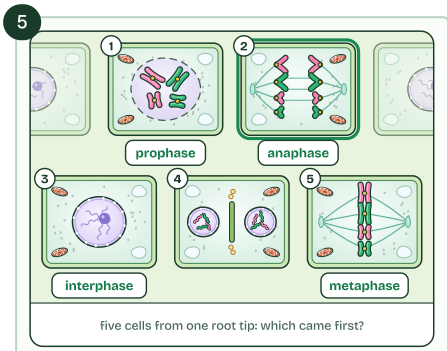
Prophase: thick threads, the nuclear membrane going.

4



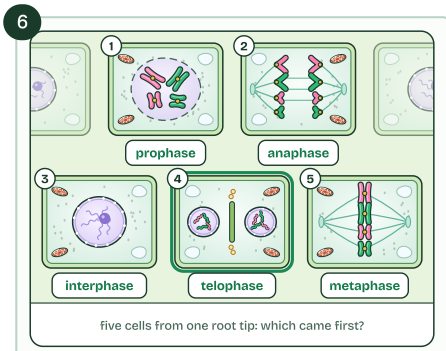
Metaphase: chromosomes in a line across the middle.

5



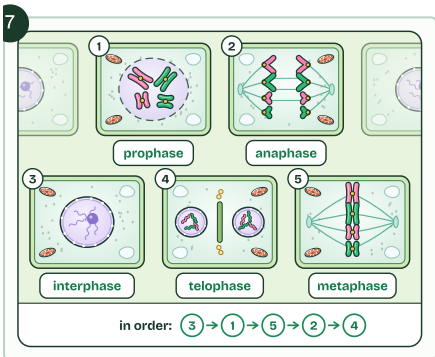
Anaphase: chromatids pulled to opposite ends.

6



Telophase: two nuclei and a new cell plate.

7



In order of the process: 3, 1, 5, 2, 4.

TRY IT

The dry lab at the end of the guide gives you fields of view to mark, one cell at a time. Name the phases by eye first, then check them.

WATCH OUT

Two separate small cells side by side are not telophase. In telophase the two nuclei are still in one cell, or at most split by a thin new wall.

PREDICT

In a root tip squash most cells are in interphase, and of the dividing cells more are in prophase than in anaphase. What does this tell you?

(A) That most cells in a root tip have stopped dividing and will never divide again

(B) That cells spend longer in interphase than mitosis, and longer in prophase than anaphase

(C) That the stain picks out cells in prophase more strongly than cells in anaphase

Decide before you look. Answer on page 39.

06

D2.1.9 MEIOSIS AS A REDUCTION DIVISION

Meiosis *halves* the number

A **diploid** cell has two sets of chromosomes, one from each parent: in humans, 23 pairs, so 2n = 46. A **haploid** cell has one set, n = 23. In a sexual life cycle two gametes fuse at fertilisation. If gametes were diploid, the chromosome number would double every generation. Meiosis prevents this by halving it.

Meiosis follows one round of replication with two divisions. In **meiosis I** the homologous chromosomes pair up and then separate, one of each pair to each pole: this is the halving, the first round of segregation. In **meiosis II** the sister chromatids of each chromosome separate, as in mitosis: the second round. One diploid nucleus becomes **four haploid nuclei**.

KEY POINTS

- Diploid (2n): two sets of chromosomes. Haploid (n): one set.
- Meiosis I separates homologous pairs; meiosis II separates sister chromatids.
- One diploid nucleus gives four haploid nuclei; fertilisation restores diploid.

KEY TERMS

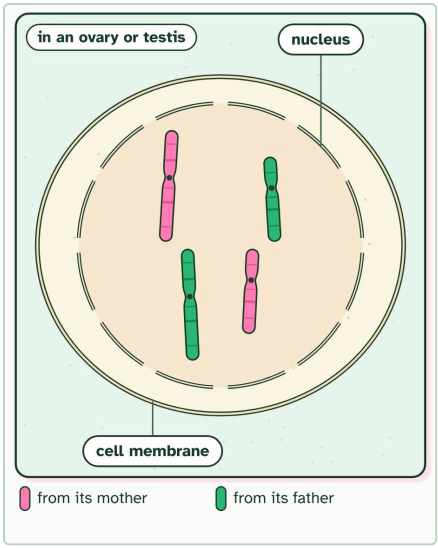
diploid
Having two sets of chromosomes, one from each parent, so each chromosome has a matching (homologous) partner. Written 2n.

haploid
Having one set of chromosomes, one of each type. Written n. Gametes are haploid.

ANIMATION · HALVING, THEN FUSING

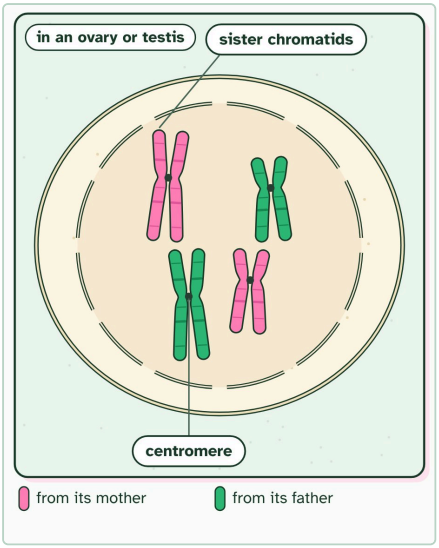
9 MOMENTS

1 DIPLOID CELL, 2N = 4



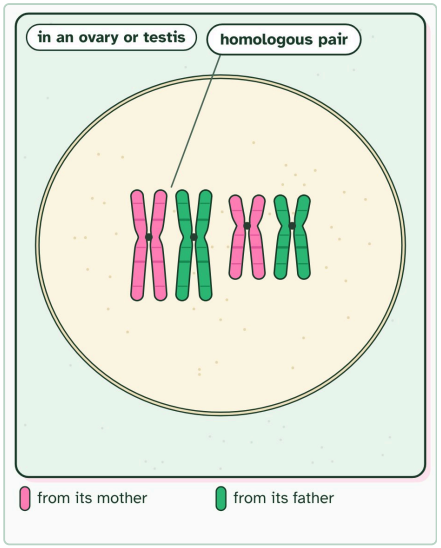
A **diploid** cell of a parent. Its chromosomes are in pairs: one of each pair came from its mother (pink), one from its father (green).

2 2N = 4, DNA COPIED



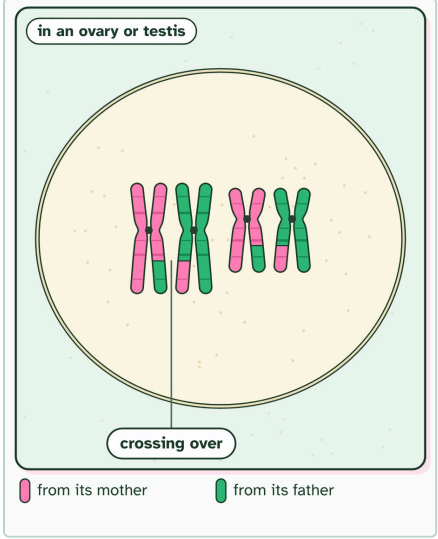
First the DNA is copied: each chromosome becomes two identical **sister chromatids**, joined at a **centromere**.

3 2N = 4, DNA COPIED



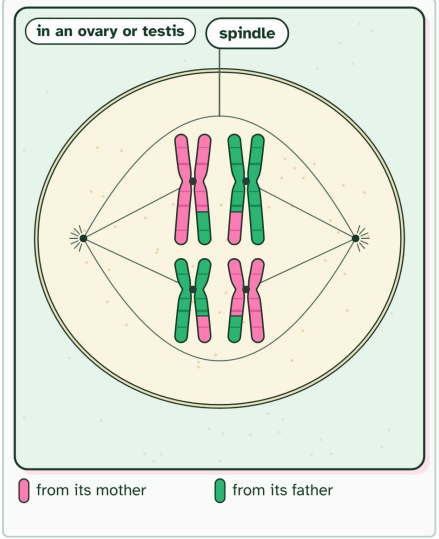
The nucleus breaks down and each chromosome lies beside its partner: a **homologous pair**, with the same genes in the same order.

4 2N = 4, DNA COPIED



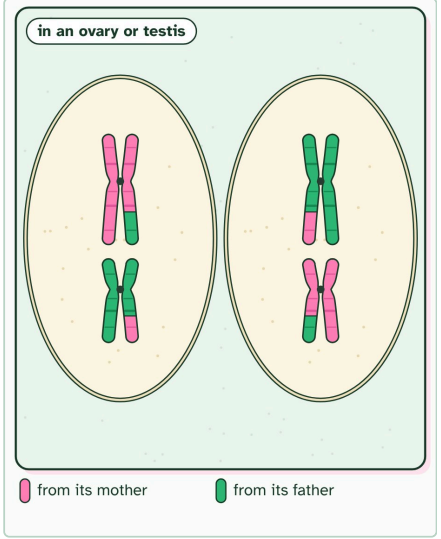
Crossing over: chromatids of a pair swap matching sections, making new mixes of the mother's and the father's alleles.

5 2N = 4, DNA COPIED



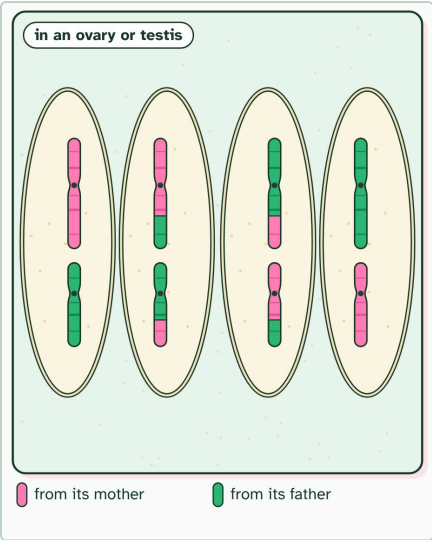
A spindle forms and the pairs line up across the middle. Which way round each pair lies is down to chance: **random orientation**.

6 2 CELLS, N = 2



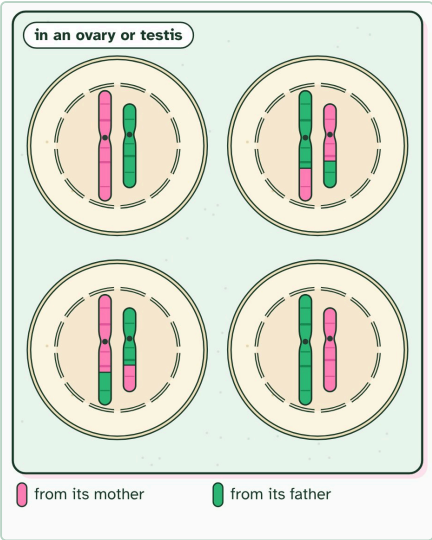
Meiosis I: one chromosome of each pair is pulled to each end, and the cell divides. Each new cell has half the number of chromosomes.

7 4 CELLS, N = 2



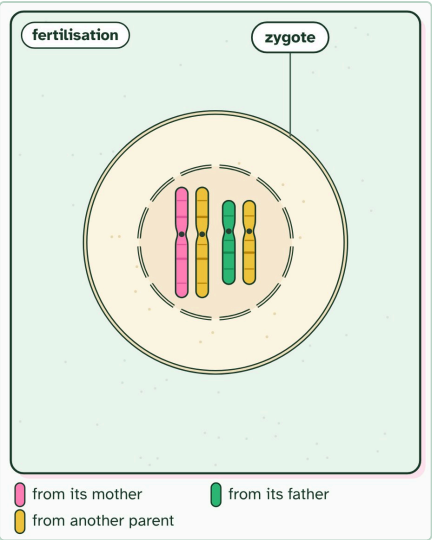
Meiosis II: in each cell the sister chromatids are pulled apart, and both cells divide again.

8 4 GAMETES, N = 2



Four **haploid** gametes, each with one chromosome of every pair, and no two alike.

9 ZYGOTE, 2N = 4



Fertilisation: the gamete fuses with one from another parent (yellow). The **zygote** is diploid again, with one of each pair from each parent.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division#meiosis

WATCH OUT

The halving happens in meiosis I, not meiosis II. After meiosis I each cell already has one chromosome of each pair, though each chromosome is still two chromatids.

PREDICT

A horse has 64 chromosomes in its body cells. How many are in a horse sperm cell, and how many in a cell after meiosis I?

(A) 32 in a sperm cell, and 64 after meiosis I, because only meiosis II halves the number

(B) 32 in a sperm cell, and 32 after meiosis I, each of them still two chromatids

(C) 16 in a sperm cell, and 32 after meiosis I, because each division halves it once

Decide before you look. Answer on page 39.

07

D2.1.10 DOWN SYNDROME AND NON-DISJUNCTION

One chromosome *too many*

Meiosis sometimes goes wrong. In **non-disjunction**, a pair of chromosomes fails to separate in meiosis I, or the two chromatids of one chromosome fail to separate in meiosis II. Both go to the same pole. Some gametes then have an extra copy of that chromosome and some have none.

If a gamete with two copies of chromosome 21 is fertilised by a normal gamete, the zygote has three: **trisomy 21**, 47 chromosomes in every cell of the body that grows from it. This causes **Down syndrome**, with a range of effects including learning difficulties, a characteristic facial appearance and a higher chance of heart problems. Most extra copies come from the egg, and the chance rises steeply with the mother's age: eggs begin meiosis before a girl is born and wait, partway through meiosis I, until ovulation.

A karyotype of a fetus can be made from cells taken in pregnancy, by **chorionic villus sampling** (a small sample of the placenta, from about 11 weeks) or **amniocentesis** (fluid from around the fetus, from about 15 weeks). Each carries a small risk of miscarriage, which parents weigh against what they would do with the result.

KEY POINTS

- Non-disjunction: chromosomes or chromatids fail to separate in meiosis.
- A gamete with two 21s plus a normal gamete gives trisomy 21: Down syndrome.
- The chance rises with the mother's age.

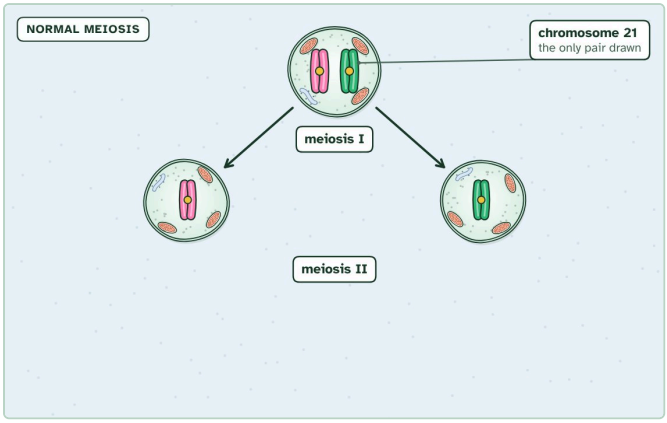
KEY TERMS

non-disjunction
The failure of homologous chromosomes (in meiosis I) or sister chromatids (in meiosis II) to separate, so that gametes get one chromosome too many or too few.

ANIMATION · ONE PAIR THAT DID NOT SEPARATE

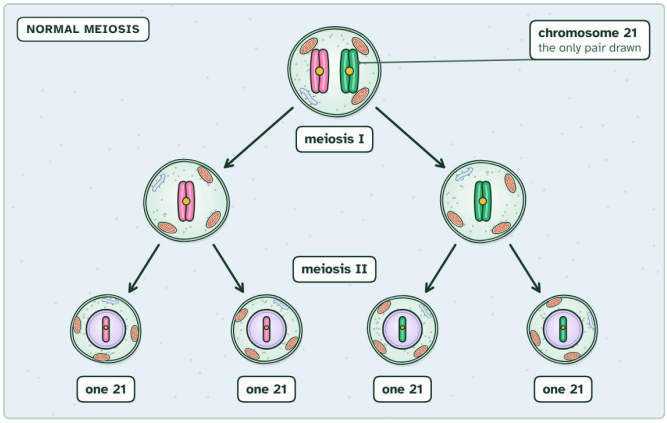
7 MOMENTS

1 NORMAL MEIOSIS



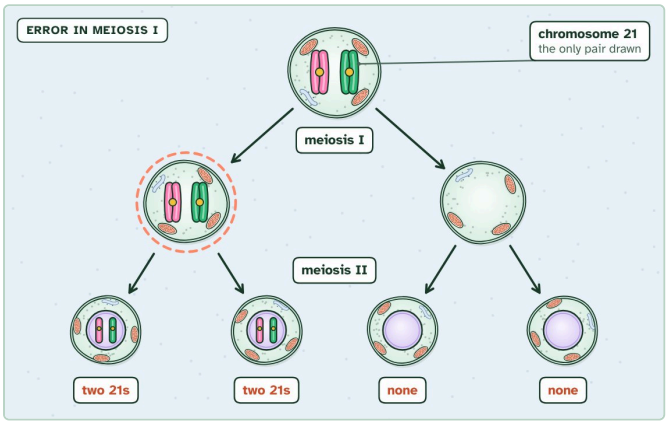
Meiosis as it should go, following one pair: **chromosome 21**. The pair separates in meiosis I and the sister chromatids in meiosis II.

2 NORMAL MEIOSIS



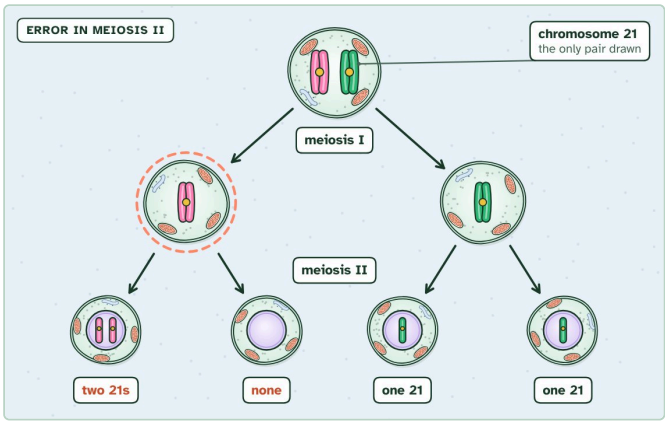
Each of the four gametes gets **exactly one** chromosome 21.

3 ERROR IN MEIOSIS I



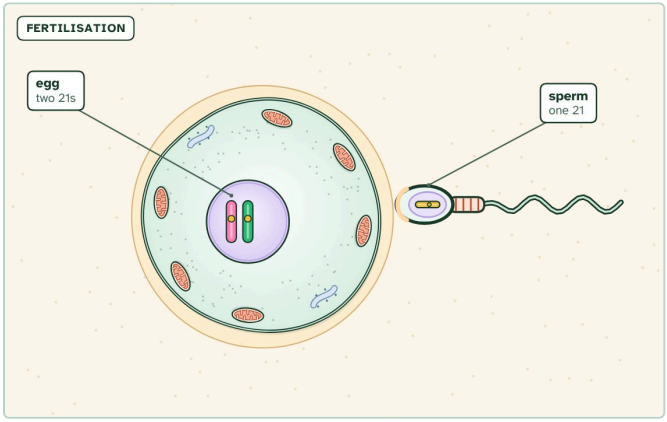
Two gametes now have **two** copies of chromosome 21, and two have **none**.

4 ERROR IN MEIOSIS II



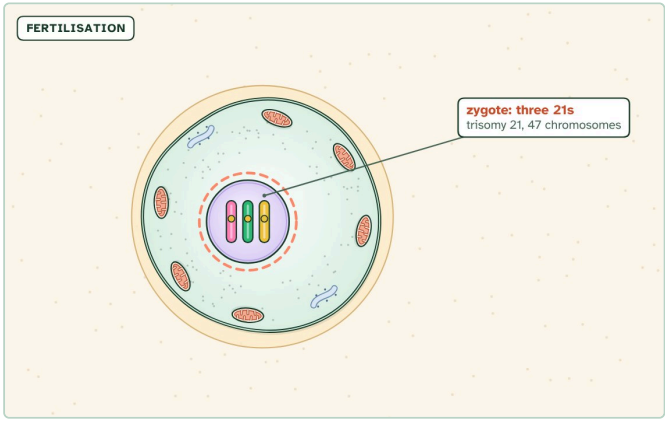
Non-disjunction can also happen in **meiosis II**, when the sister chromatids of one chromosome fail to separate.

5 FERTILISATION



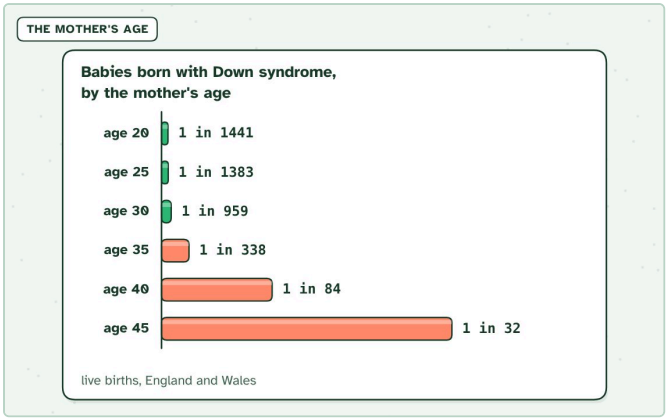
If a gamete with two 21s is fertilised by a normal gamete, the zygote has **three**: **trisomy 21**, 47 chromosomes in every cell.

6 FERTILISATION



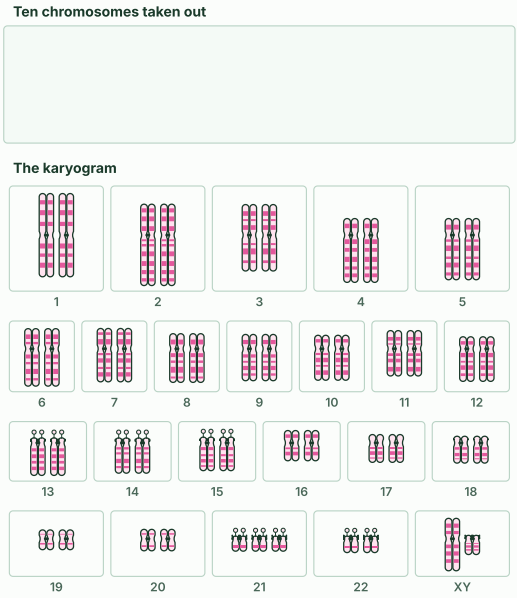
A person with trisomy 21 has **Down syndrome**.

7 THE MOTHER'S AGE



Most extra 21s come from the egg, and the chance **rises steeply with the mother's age**: eggs wait in meiosis I from before she was born.

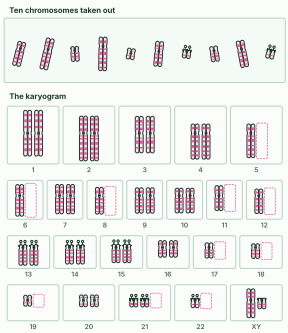
`Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division#down`



A karyogram with ten chromosomes taken out. Put each back with its pair and count. What is different about this person's cells?

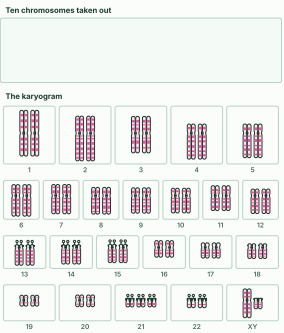
STEP BY STEP 2 STEPS

1



Ten chromosomes taken out of a karyogram. Match each to its pair by **length**, **centromere position** and **bands**.

2



Every chromosome in its place: **47** chromosomes, the sex chromosomes last.

WATCH OUT

Down syndrome is not usually inherited from a parent who has it. It is a fresh error in meiosis in one parent, almost always in the making of the egg or sperm that formed that child.

PREDICT

Non-disjunction of chromosome 21 happens in meiosis I in a father. What fraction of the sperm made from that cell would give trisomy 21 if they fertilised a normal egg?

(A) A quarter, because only one of the four sperm cells could have the extra copy

(B) A half, because two of the four sperm carry two copies and two carry none

(C) All of them, because the error in meiosis I is passed on to every sperm cell

Decide before you look. Answer on page 39.

08 Every gamete *different*

D2.1.11 MEIOSIS AS A SOURCE OF VARIATION

Meiosis makes gametes that differ from one another in two ways. The first is **random orientation**. In metaphase I each pair of homologous chromosomes (a **bivalent**) lines up on the equator with either chromosome facing either pole, and each pair does so independently of the others. With two pairs there are 4 possible combinations in the gametes; with n pairs there are 2^n. A human, with 23 pairs, can make over 8 million (2^{23}) kinds of gamete from this alone.

The second is **crossing over**. In prophase I, chromatids of the two chromosomes of a pair can break at the same point and swap ends. Each chromatid that took part now carries a mixture of the alleles of the two parents' chromosomes, a combination that may never have existed before.

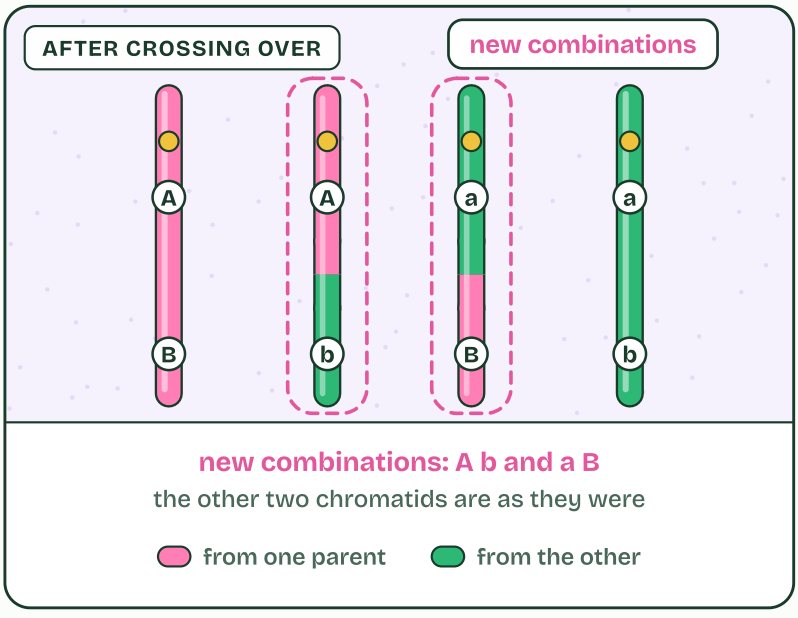
Then fertilisation joins two such gametes at random. Together these explain why siblings, apart from identical twins, are never genetically the same.

KEY POINTS

- Random orientation of bivalents in metaphase I: 2^n combinations.
- Crossing over in prophase I makes new combinations of alleles on a chromatid.
- Random fertilisation adds more variety.

KEY TERMS

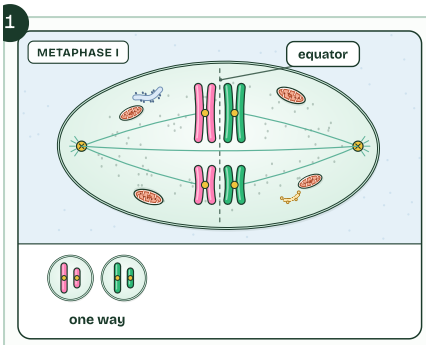
bivalent
A pair of homologous chromosomes lying side by side in meiosis I, each of two chromatids.



STEP BY STEP

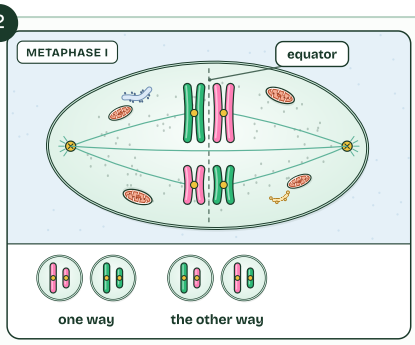
5 STEPS

1



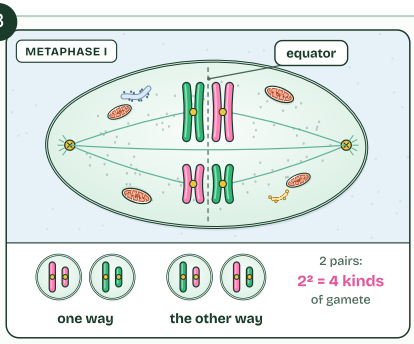
Metaphase I with two pairs: the pink chromosomes on one side.

2



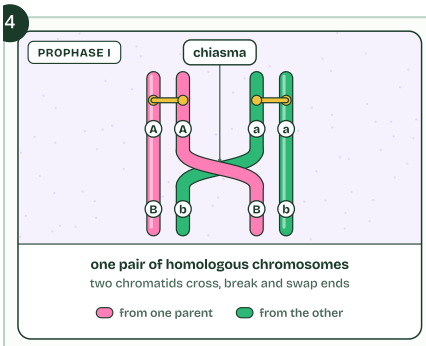
Or the long pair the other way round. Each pair lines up **independently**.

3



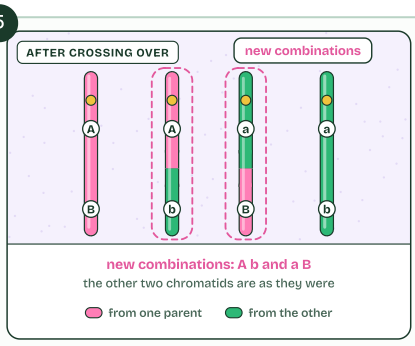
So there are four kinds of gamete: **2 to the power 2**.

4



In prophase I, chromatids of a pair can break and **swap ends**.

5



Two chromatids now carry **new combinations** of alleles.

REMEMBER IT

Two sources of variety in meiosis

S Shuffle	S Swap
Random orientation metaphase I: 2 to the n	**Crossing over** prophase I: chromatids exchange ends

WATCH OUT

Crossing over happens between chromatids of the two homologous chromosomes, not between the two sister chromatids of one chromosome, which are identical anyway.

PREDICT

A fruit fly has 4 pairs of chromosomes. Ignoring crossing over, how many kinds of gamete can random orientation give?

(A) 8, because each of the 4 pairs can line up in 2 ways, so it is 4 times 2

(B) 16, because each pair can line up 2 ways independently: 2 to the power 4

(C) 4, because each gamete gets 1 chromosome from each of the 4 pairs

Decide before you look. Answer on page 39.

09

D2.1.12 HL D2.1.13 HL D2.1.14 HL PROLIFERATION AND THE CELL CYCLE

Growth, repair and the *cycle*

Cell proliferation, cells dividing again and again, is how an organism grows, replaces cells and repairs damage. A plant grows from its **meristems**, regions at the tips of roots and shoots where cells keep dividing. An early animal embryo divides rapidly, from one cell to many hundreds. In the skin, cells in the lowest layer divide all the time to replace cells lost from the surface, and a wound makes them divide faster until it is closed.

Proliferation uses the **cell cycle**. **Interphase** is made of three stages: G1, when the cell grows; S, when the DNA is replicated; and G2, when it grows further and prepares to divide. Then come **mitosis** and **cytokinesis**.

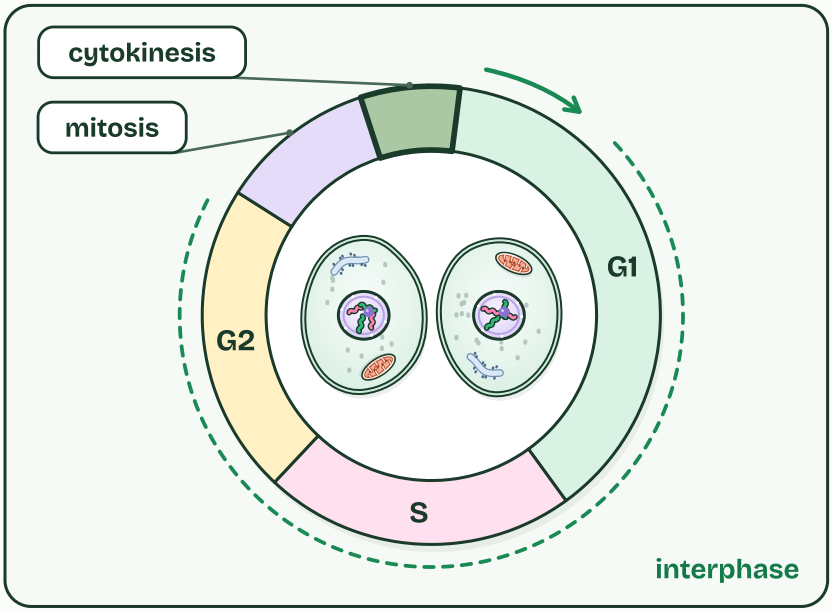
Interphase is not a resting phase. The cell is metabolically very active: making proteins, membranes and other components, copying its DNA, and increasing its numbers of mitochondria and chloroplasts, which grow and divide. A cell that stops dividing, such as most nerve cells, stays in a version of G1 often called G0.

KEY POINTS

- Proliferation: growth (meristems, embryos), replacement and repair (skin, wounds).
- The cycle: G1, S, G2 (interphase), then mitosis and cytokinesis.
- Interphase is busy: biosynthesis, DNA replication, organelles growing and dividing.

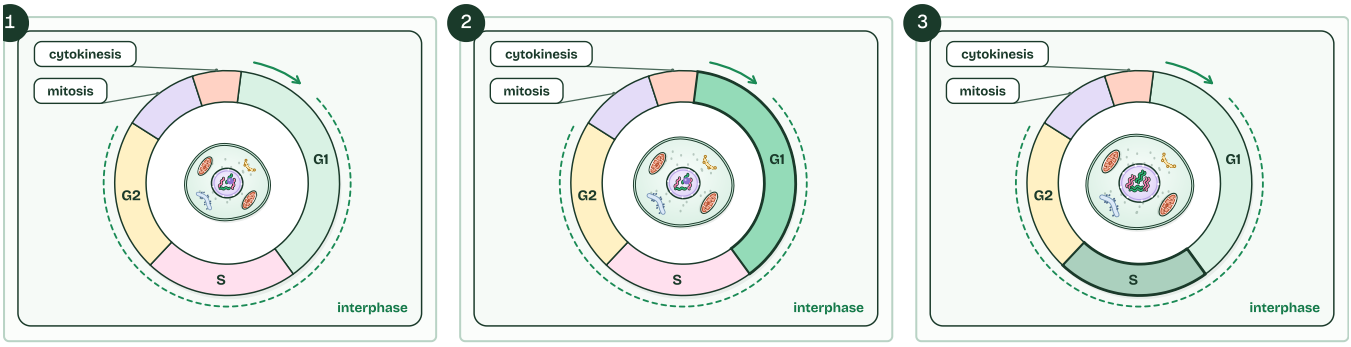
KEY TERMS

cell cycle
The sequence of events between one cell division and the next: G1, S and G2 (interphase), then mitosis and cytokinesis.



STEP BY STEP

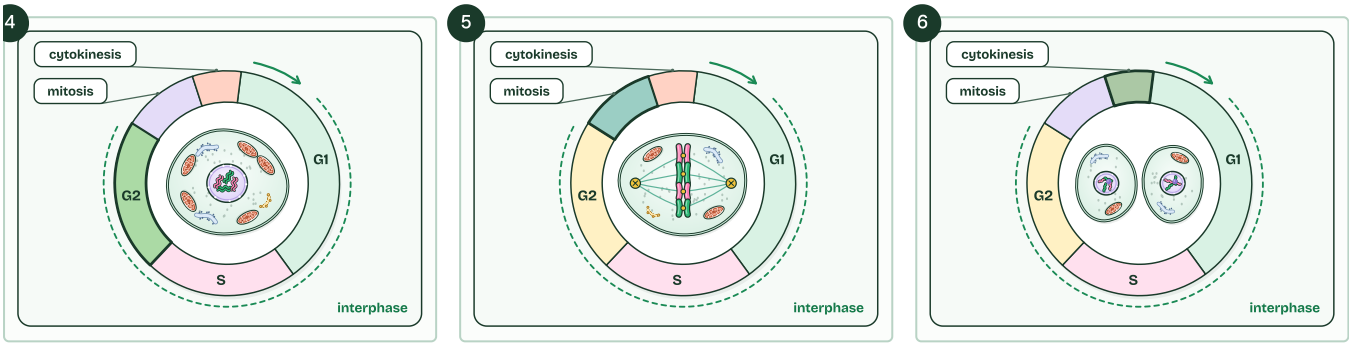
6 STEPS



The **cell cycle**: one turn is one division.

G1: the cell grows and makes proteins and organelles.

S: the DNA is replicated.



G2: more growth and preparation for division.

Mitosis: the nucleus divides.

Cytokinesis: the cytoplasm divides, giving two cells, each back in G1.

WATCH OUT

G stands for gap, between division and replication, but the gaps are when most of the cell's growth happens.

PREDICT

A cell is in G2. Compared with the same cell in G1, what does it have?

(A) The same amount of DNA, but more mitochondria and a larger volume of cytoplasm

(B) Twice the DNA, as each chromosome is now two chromatids, and usually more organelles

(C) Half the DNA, because the chromosomes have already separated to the two poles

Decide before you look. Answer on page 40.

10 Cyclins open the *gates*

D2.1.15 HL CONTROL OF THE CELL CYCLE USING CYCLINS

A cell does not move from one stage of the cycle to the next by chance. At **checkpoints**, such as the end of G1 and the end of G2, it goes on only when conditions are right. The signals that let it through are proteins called **cyclins**.

Different cyclins are made at different times in the cycle, so their concentrations rise and fall. When a particular cyclin reaches a **threshold** concentration, the cell passes the checkpoint that cyclin controls. Then that cyclin is broken down, so the cell cannot pass the same checkpoint again until the next cycle. (Cyclins work by binding and activating enzymes called cyclin-dependent kinases, which switch on the proteins for the next stage.)

The tool shows two of them: a G1 cyclin that lets the cell into S phase and an M cyclin that lets it into mitosis. Switch off the growth signal, damage the DNA, or mutate a gene, and watch what happens to the cyclins and to the number of cells.

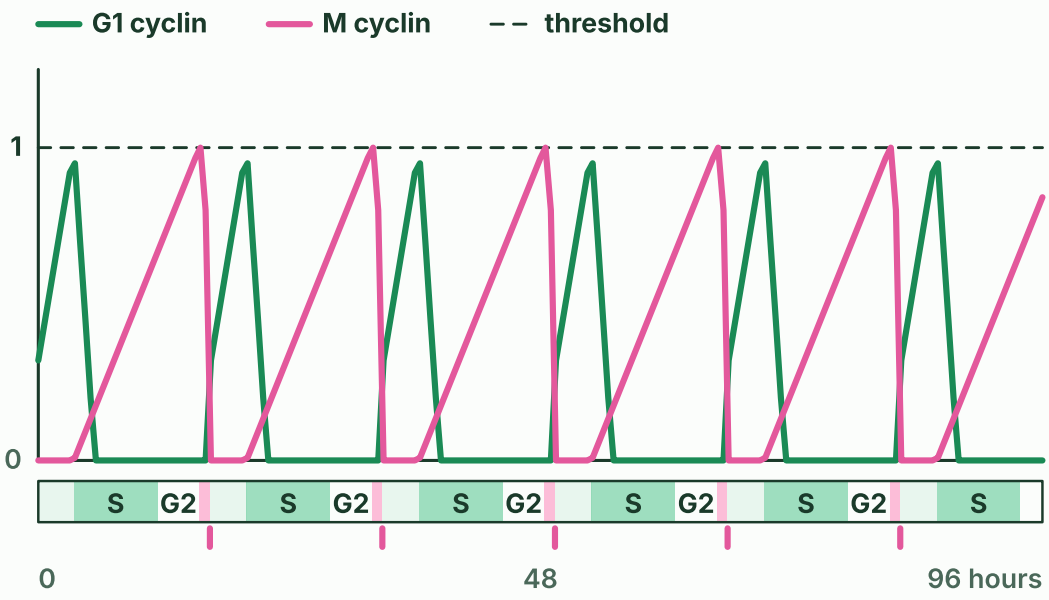
KEY POINTS

- Cyclin concentrations rise and fall through the cycle.
- A threshold concentration of a specific cyclin is needed to pass each checkpoint.
- The cyclin is then broken down.

KEY TERMS

checkpoints
A point in the cell cycle where the cell only goes on if conditions are right, such as its DNA being undamaged or fully replicated.

cyclins
Proteins whose concentration rises and falls during the cell cycle. A cell passes each checkpoint when the concentration of a particular cyclin reaches a threshold.

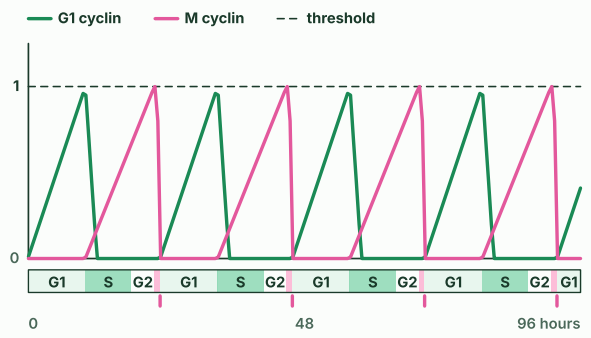


Four days of one cell and its daughters. Switch the growth signal, a mutated gene or DNA damage, and read the cyclins against the threshold. Try the four tasks.

STEP BY STEP

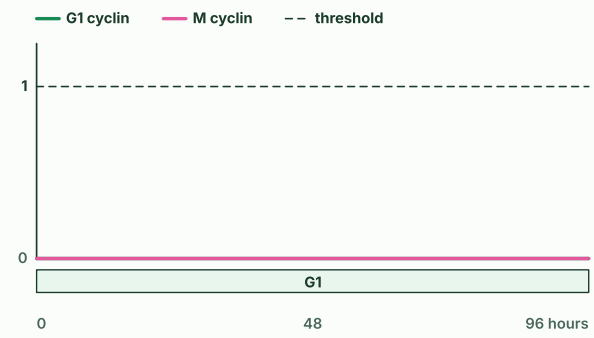
3 STEPS

1



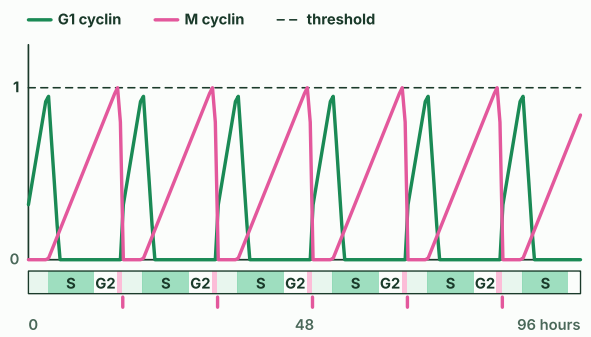
A normal cell: each cyclin rises to its **threshold**, the cell passes that **checkpoint**, and the cyclin is broken down. Four divisions in four days.

2



No growth signal: the G1 cyclin is never made, so the cell stays in **G1** and does not divide.

3



An **oncogene**: the G1 cyclin builds up fast with no signal at all, so the cell divides again and again.

WATCH OUT

A cyclin does not do the work of the next stage itself. It is a go signal: it activates the enzymes that start replication or mitosis.

PREDICT

A drug stops the M cyclin from being broken down after the cell enters mitosis. What would you expect?

(A) The cell would go through mitosis faster, then return to G1 sooner than usual

(B) The cell would stay stuck in mitosis, as the cycle can only move on once M cyclin falls

(C) The cell would skip S phase next time, because the M cyclin is still above threshold

Decide before you look. Answer on page 40.

11 When control *fails*

D2.1.16 HL D2.1.17 HL MUTATIONS IN CYCLE GENES; TUMOURS

Two kinds of gene control the cycle. **Proto-oncogenes** code for proteins that push the cell to divide when it is signalled to. A mutation can turn one into an **oncogene**, which drives division all the time, like an accelerator stuck down. **Tumour suppressor genes** code for proteins that stop the cycle, for example when DNA is damaged. A mutation that inactivates one removes the brake. Usually several such mutations, in one cell line, are needed before division becomes uncontrolled.

Uncontrolled division forms a **tumour**. A **benign** tumour grows slowly and stays where it formed, often inside a capsule; it does not cause cancer, though it can still press on organs. A **malignant** tumour divides faster, invades the tissue around it and can spread: cells break away, travel in the blood or lymph, and grow into **secondary tumours** elsewhere (metastasis). Malignant tumours are cancers. The tumour where it started is the **primary tumour**.

How fast cells divide can be measured with the **mitotic index**: the cells in mitosis as a proportion of all the cells in a field of view. A high index in a tumour sample suggests fast growth.

Benign
Slow division, low mitotic index.
Stays in place, often in a capsule.
Does not spread: not a cancer.

Malignant
Fast division, high mitotic index.
Invades neighbouring tissue.
Spreads to form secondary tumours: a cancer.

KEY POINTS

- Proto-oncogene mutated to oncogene: division stimulated. Tumour suppressor lost: division not stopped.
- Benign tumours stay put; malignant tumours invade and spread (primary to secondary).
- Mitotic index = cells in mitosis / total cells.

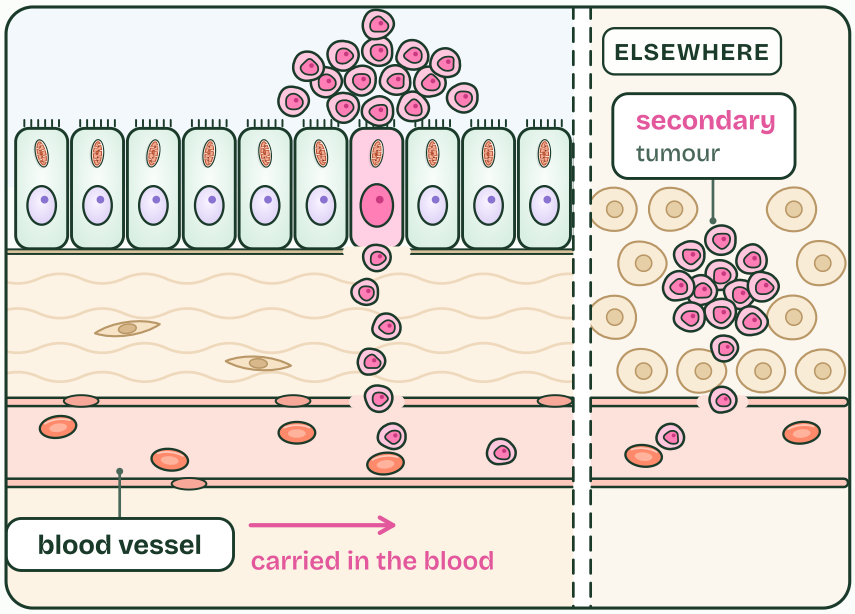
KEY TERMS

Proto-oncogenes
A gene whose product stimulates the cell cycle, for example by making a cyclin or passing on a growth signal. Mutated, it can become an oncogene.

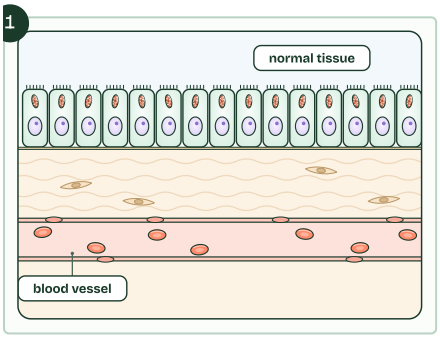
oncogene
A mutated form of a proto-oncogene that stimulates cell division all the time, even with no signal.

tumour suppressor genes
A gene whose product stops or slows the cell cycle, for example when DNA is damaged. Its loss removes a brake on division.

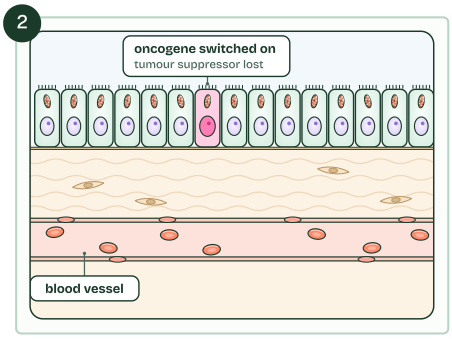
mitotic index
The number of cells in mitosis divided by the total number of cells counted, usually given as a percentage.



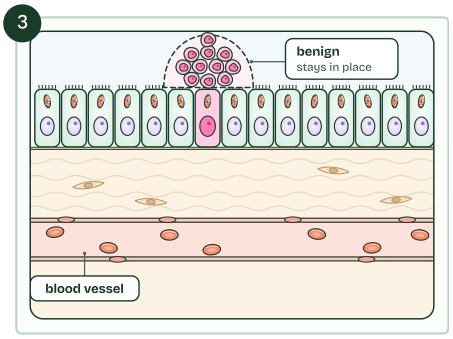
STEP BY STEP 5 STEPS



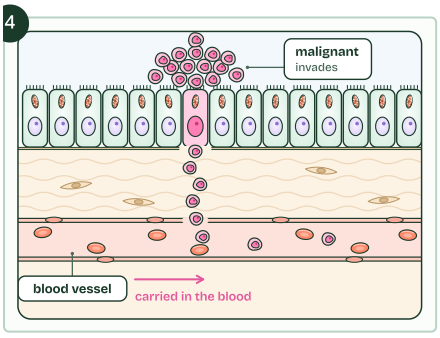
Normal tissue: cells divide only when signalled, and damaged cells are stopped.



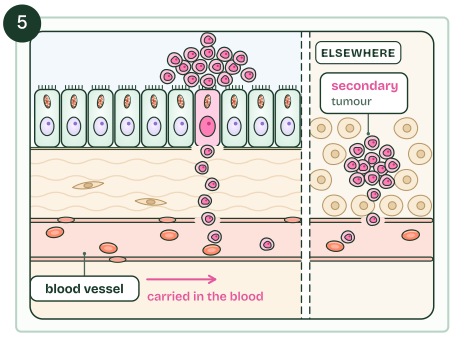
One cell gains an **oncogene** and loses a **tumour suppressor**.



Its descendants divide out of control: a **benign** tumour that stays in place.



A **malignant** tumour invades: here, into a blood vessel.



Cells carried away grow into a **secondary tumour** elsewhere.

WORK IT OUT

mitotic index = cells in mitosis ÷ total cells counted. Multiply by 100 for a percentage.

WATCH OUT

"Tumour" and "cancer" are not the same word. Every cancer forms a tumour (or, in the blood, abnormal cells), but a benign tumour is not a cancer.

PREDICT

In a field of view of 250 cells from a tumour, 30 are in mitosis. What is the mitotic index?

(A) 30 percent, as 30 of the cells in this field of view were seen dividing

(B) 12 percent, as 30 out of 250 cells is 0.12 of all the cells counted

(C) 8.3 percent, as there are 250 cells for every 30 cells that are in mitosis

Decide before you look. Answer on page 40.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

bivalent 08
A pair of homologous chromosomes lying side by side in meiosis I, each of two chromatids.

cell cycle 09
The sequence of events between one cell division and the next: G1, S and G2 (interphase), then mitosis and cytokinesis.

cell plate 02
A flat structure of fused vesicles across the middle of a dividing plant cell. It grows out to the side walls and becomes the membranes and new wall between the daughter cells.

centromere 03
The region of a chromosome where its two sister chromatids are held together, and where spindle microtubules attach.

checkpoints 10
A point in the cell cycle where the cell only goes on if conditions are right, such as its DNA being undamaged or fully replicated.

cyclins 10
Proteins whose concentration rises and falls during the cell cycle. A cell passes each checkpoint when the concentration of a particular cyclin reaches a threshold.

cytokinesis 02
The division of the cytoplasm of a parent cell between two daughter cells. It follows nuclear division.

daughter cells 01
One of the two cells made when a parent cell divides.

diploid 06
Having two sets of chromosomes, one from each parent, so each chromosome has a matching (homologous) partner. Written 2n.

equator 04
The plane across the middle of a dividing cell, halfway between the two poles of the spindle.

haploid 06
Having one set of chromosomes, one of each type. Written n. Gametes are haploid.

histones 03
Proteins that DNA winds round in eukaryotic chromosomes. They package DNA and help it supercoil when chromosomes condense.

meiosis 03
Division of the nucleus, in two rounds, into four nuclei with half the parent's chromosome number. It produces genetically varied nuclei for gametes.

microtubules 03
Protein tubes that make up the spindle. In division they attach to centromeres and, with motor proteins, pull chromosomes apart.

mitosis 03
Division of the nucleus into two nuclei with the same number of chromosomes and the same genes as the parent nucleus.

mitotic index 11
The number of cells in mitosis divided by the total number of cells counted, usually given as a percentage.

non-disjunction 07
The failure of homologous chromosomes (in meiosis I) or sister chromatids (in meiosis II) to separate, so that gametes get one chromosome too many or too few.

oncogene 11
A mutated form of a proto-oncogene that stimulates cell division all the time, even with no signal.

parent cell 01
The cell that divides, sometimes called the mother cell. It ends as two new cells.

Proto-oncogenes 11
A gene whose product stimulates the cell cycle, for example by making a cyclin or passing on a growth signal. Mutated, it can become an oncogene.

sister chromatids 03

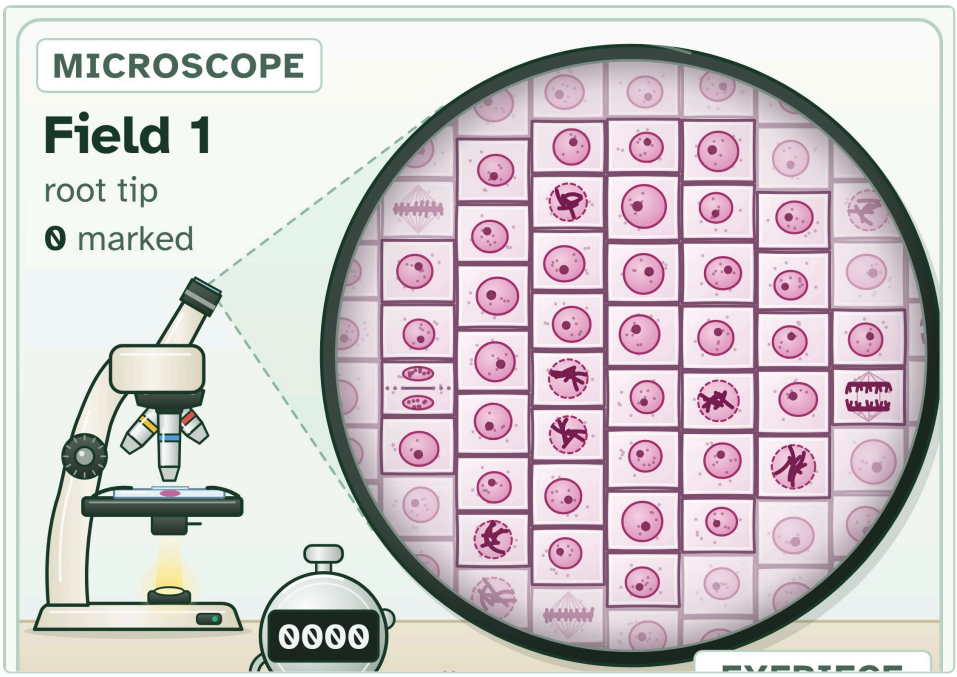
One of the two identical DNA molecules of a replicated chromosome. Sister chromatids are held together at the centromere until anaphase.

tumour suppressor genes 11

A gene whose product stops or slows the cell cycle, for example when DNA is damaged. Its loss removes a brake on division.

Dry lab: *Count the cells*

Fields of view down a microscope, from a root tip, from further back along the root, from normal tissue and from two tumours. Mark every cell that is dividing by its phase, work out the mitotic index, and find out where cells divide fastest.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-d2-1-cell-and-nuclear-division#lab`

Your question

How does the mitotic index differ between the tip of a root and the region behind it, and between normal tissue, a benign tumour and a malignant tumour? Make a prediction for each before you count.

What you can change

The sample and the field of view. Each field is a new set of cells from the same sample, so counting several fields of one sample is how you repeat. Mark it for me fills a field in for you once you can name the phases by eye.

What to record

For each field: the sample, the number of whole cells, the number in each phase of mitosis and the mitotic index. At least three fields for each sample, then the mean. The fields are drawn and their rates invented to show the method.

Find out

- **Name them by eye.** In the first root tip field, mark every dividing cell by its phase yourself, then Count this field and see which marks were right.
- **Tip or further back?** Count at least three fields from the root tip and three from 1 cm behind it. Where are cells dividing, and why there?
- **Which phase is longest?** Add up the cells in each phase across all your root tip fields. Which phase holds the most cells, and what does that say about how long each phase lasts?
- **Tumours (HL).** Count three fields each of normal epithelium, a benign tumour and a malignant tumour. Rank them by mean mitotic index.
- **Back to cells.** Use your results to explain how a root grows: where its cells divide, and what happens to them after.

Record

- For each field: the sample, the number of whole cells, the cells in each phase and the mitotic index to one decimal place.
- A mean mitotic index for each sample, and the range. The graph shows each field as a point and the mean as a bar.
- Say how confident you are in each difference: do the ranges overlap? How many more fields would make it clearer?
- Download the CSV to keep your table. A real squash has cells cut by the edge of the field and cells on top of each other: say how you would decide which to count.

Your question How does the mitotic index differ between the tip of a root and the region behind it, and between normal tissue, a benign tumour and a malignant tumour? Make a prediction for each before you count.**What you can change**The sample and the field of view. Each field is a new set of cells from the same sample, so counting several fields of one sample is how you repeat. Mark it for me fills a field in for you once you can name the phases by eye.**What to record**For each field: the sample, the number of whole cells, the number in each phase of mitosis and the mitotic index. At least three fields for each sample, then the mean. The fields are drawn and their rates invented to show the method.

Back to cells

Your root tip fields were full of dividing cells and the fields 1 cm back had almost none. Use your results to explain how a root grows.

QUESTIONS ON THE LAB

QUESTION 1

The root tip fields have a mitotic index of around 15 percent and the fields 1 cm back have almost none. What explains the difference?

(A) Cells further back divide just as often, but too fast for any to be caught in mitosis

(B) The tip holds the meristem, where cells divide; further back, cells grow longer instead

(C) The stain only reaches the tip of the root, so cells further back cannot be seen dividing

Answer on page 40.

QUESTION 2

Across all your root tip fields, prophase holds the most dividing cells and anaphase the fewest. What can you conclude?

(A) That some cells skip anaphase and go straight from metaphase to telophase

(B) That prophase lasts longest and anaphase is the shortest phase of mitosis

(C) That cells in anaphase are harder to stain and so are missed in the count

Answer on page 40.

QUESTION 3

One student counts 9 dividing cells out of 50 in one field and reports the root tip's index as 18 percent. Why is this not yet a good estimate?

(A) Because the index must be found from the cells in mitosis divided by those in interphase

(B) Because one small field gives a noisy figure; several fields and a mean are needed

(C) Because 50 cells is too many to count without losing track of which were counted

Answer on page 40.

Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on D2.1 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=D2.1&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 Why does a eukaryotic cell divide its nucleus before it divides its cytoplasm?

B **So that each daughter cell gets a nucleus and none is left without one**

So that each daughter cell gets a nucleus. If the cytoplasm divided first, one cell would have the nucleus and the other none. A cell with no nucleus cannot make new proteins for long, and cannot divide again.

02 In a human egg cell's last division, why might keeping almost all the cytoplasm in one cell be an advantage?

B **The egg has the food and organelles an embryo needs before it can feed itself**

The egg keeps the stored food, mitochondria and other organelles that the early embryo will run on until it implants. The polar bodies carry away the spare chromosomes with very little cytoplasm and break down.

03 A cell has 8 chromosomes in G1. How many DNA molecules does its nucleus hold at the start of mitosis?

B **16, because each of the 8 chromosomes is now 2 chromatids, each one molecule**

16. Replication in S phase doubles the DNA: still 8 chromosomes, but each is two chromatids, and each chromatid is one DNA molecule.

04 In a cell in metaphase, what are lined up on the equator?

B **Whole chromosomes, each still two chromatids held at the centromere**

Whole chromosomes, each of two chromatids, lined up one by one. The chromatids only separate in anaphase. Matching chromosomes pairing up happens in meiosis, not mitosis.

05 In a root tip squash most cells are in interphase, and of the dividing cells more are in prophase than in anaphase. What does this tell you?

B **That cells spend longer in interphase than mitosis, and longer in prophase than anaphase**

The share of cells in a phase reflects how long the phase lasts. A cell spends most of its cycle in interphase, and anaphase is the quickest phase, so few cells are caught in it.

06 A horse has 64 chromosomes in its body cells. How many are in a horse sperm cell, and how many in a cell after meiosis I?

B **32 in a sperm cell, and 32 after meiosis I, each of them still two chromatids**

32 and 32. Meiosis I separates the pairs, so each cell has 32 chromosomes, each two chromatids. Meiosis II separates the chromatids, leaving 32 chromosomes of one chromatid each.

07 Non-disjunction of chromosome 21 happens in meiosis I in a father. What fraction of the sperm made from that cell would give trisomy 21 if they fertilised a normal egg?

B **A half, because two of the four sperm carry two copies and two carry none**

A half. Both 21s go to one cell in meiosis I, so both of its sperm get two copies of 21 and the other two sperm get none. A sperm with none would give a zygote with only one 21, which does not survive.

08 A fruit fly has 4 pairs of chromosomes. Ignoring crossing over, how many kinds of gamete can random orientation give?

B **16, because each pair can line up 2 ways independently: 2 to the power 4**

16. Each pair has 2 orientations and each is independent of the others, so the combinations multiply: $2 \times 2 \times 2 \times 2 = 2^4 = 16$.

09 A cell is in G2. Compared with the same cell in G1, what does it have?

B **Twice the DNA, as each chromosome is now two chromatids, and usually more organelles**

Twice the DNA, because S phase comes between G1 and G2, and usually more organelles and a larger size, because it has kept growing.

10 A drug stops the M cyclin from being broken down after the cell enters mitosis. What would you expect?

B **The cell would stay stuck in mitosis, as the cycle can only move on once M cyclin falls**

It would get stuck in mitosis. The fall in M cyclin is what lets the chromatids separate and the cell finish dividing. Experiments with cyclin that cannot be broken down show exactly this.

11 In a field of view of 250 cells from a tumour, 30 are in mitosis. What is the mitotic index?

B **12 percent, as 30 out of 250 cells is 0.12 of all the cells counted**

12 percent: 30 ÷ 250 = 0.12. The index divides by all the cells counted, dividing or not.

QUESTIONS ON THE DRY LAB

Q1 The root tip fields have a mitotic index of around 15 percent and the fields 1 cm back have almost none. What explains the difference?

B **The tip holds the meristem, where cells divide; further back, cells grow longer instead**

Cell division in a root happens in the meristem just behind the tip. The cells it makes are left behind as the tip grows on, and there they elongate and specialise rather than divide, which is why the cells further back are longer.

Q2 Across all your root tip fields, prophase holds the most dividing cells and anaphase the fewest. What can you conclude?

B **That prophase lasts longest and anaphase is the shortest phase of mitosis**

In a sample of cells caught at random moments, the share in each phase is proportional to how long that phase lasts. Prophase is the longest phase and anaphase the shortest. If the whole cycle takes 24 hours, a phase holding 2 percent of cells lasts about half an hour.

Q3 One student counts 9 dividing cells out of 50 in one field and reports the root tip's index as 18 percent. Why is this not yet a good estimate?

B **Because one small field gives a noisy figure; several fields and a mean are needed**

One field of 50 cells can easily give 12 percent or 22 percent by chance. Counting several fields (or several hundred cells) and taking the mean, with the range, gives a figure you can compare between samples.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.