

ESAT

Biology

Cell division and sex determination

Free lesson notes

Covers	B3.1, B3.2, B3.3 and B3.4
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

A human grows from a single fertilised egg into trillions of cells, repairs cuts, and produces eggs and sperm for the next generation. All of this depends on cells dividing, and there are two very different kinds of cell division. **Mitosis** makes two genetically identical cells for growth and repair; **meiosis** makes four genetically different cells with half the chromosomes, the gametes used in sexual reproduction. This lesson covers the cell cycle, mitosis and what goes wrong in cancer (B3.1), meiosis (B3.2), the comparison of asexual and sexual reproduction (B3.3), and how sex is determined by the X and Y chromosomes, with genetic diagrams and ratios (B3.4).

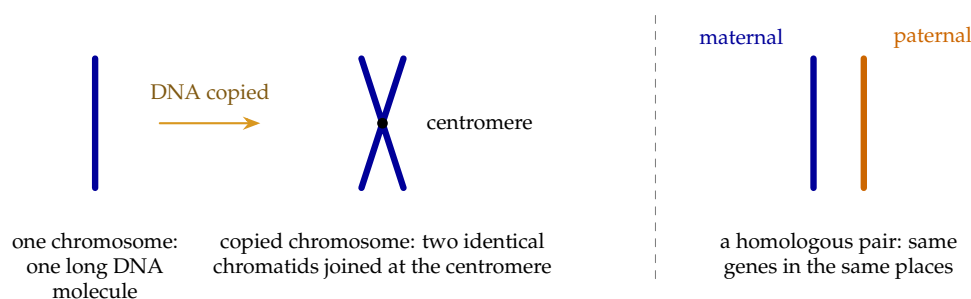
Chromosome and cell-counting numbers are very common in ESAT questions, so we practise them throughout. Cover each worked example and try it first. There is no calculator in the real ESAT, so the numbers are friendly. Finish with the self-check, then the practice set.

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1 Chromosomes: what is being shared out (B3.1, B3.2)

The nucleus of a cell contains the DNA, the instructions for building and running the organism. The DNA is packaged into structures called **chromosomes**. A chromosome is one very long DNA molecule (wound up tightly) carrying many **genes**.

A human body cell has **46 chromosomes**, which come as **23 pairs**. One chromosome of each pair came from the mother, the other from the father. The two chromosomes in a pair are called a **homologous pair**: they are the same size and carry the same genes in the same places (though perhaps different versions of them). A cell with two sets of chromosomes is **diploid** ($2n$; for humans, $2n = 46$). A cell with a single set is **haploid** (n ; for humans, $n = 23$): the gametes (sperm and egg cells) are haploid.



Before a cell divides, it copies all its DNA. Each chromosome becomes two identical copies, called **chromatids**, held together at the **centromere**, giving the familiar X shape. When the cell divides, the two chromatids are separated, and each is then called a chromosome in its own right.

Key ideas

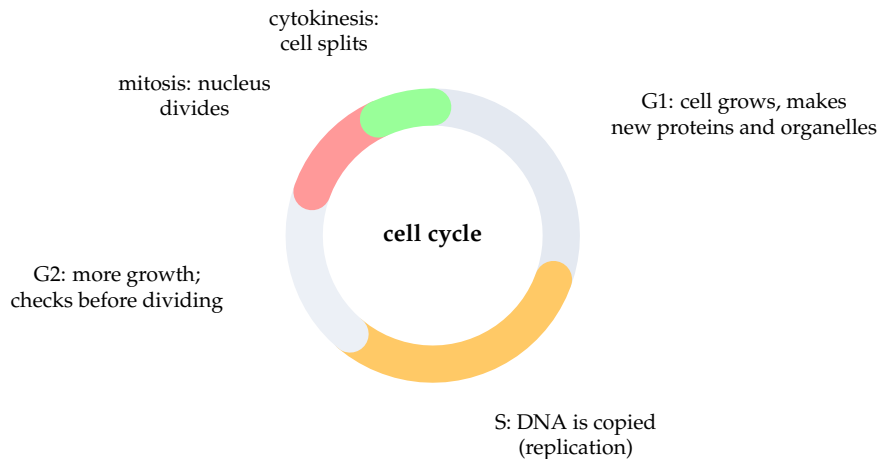
- Human body (somatic) cells: $2n = 46$ (diploid, 23 pairs). Human gametes: $n = 23$ (haploid).
- A chromosome is a long DNA molecule carrying genes. After copying, each chromosome has two identical chromatids.

Common mistakes

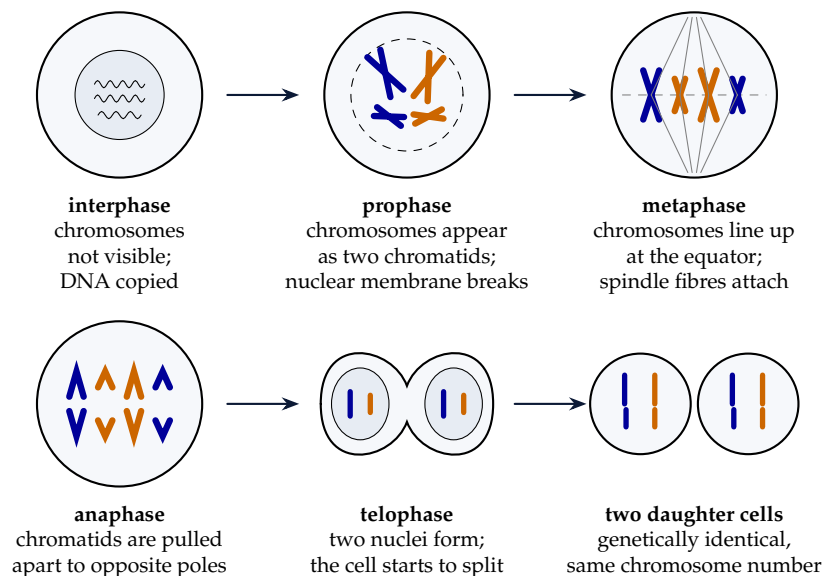
- Mixing up *chromosomes* (46 in a body cell) and *pairs of chromosomes* (23).
- Calling the two chromosomes of a homologous pair "identical". They carry the same genes but may carry different versions (alleles) of them. The two chromatids of one copied chromosome are the identical ones.
- Thinking gametes have 23 pairs: they have 23 chromosomes, one from each pair.

2 The cell cycle and mitosis (B3.1)

Cells that divide go round a repeating sequence called the **cell cycle**. Most of it is **interphase**, when the cell is not dividing but is busy getting ready: it grows, makes new proteins, increases the number of organelles such as mitochondria and ribosomes, and copies its DNA (**DNA replication**). Then comes **mitosis**, when the nucleus divides, followed by **cytokinesis**, when the cytoplasm and membrane divide to make two cells.

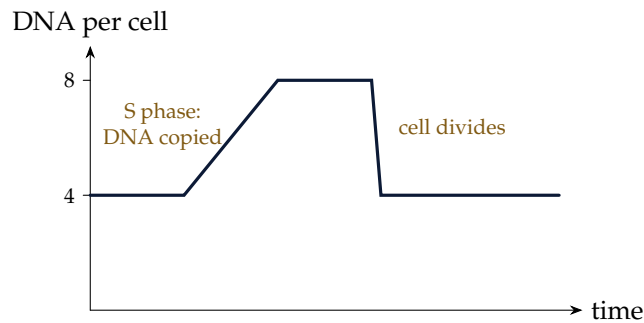


Mitosis gives two cells that are genetically identical to the parent cell. The sequence (shown here for a cell with four chromosomes, two long and two short, with blue and orange colours for the two parents' chromosomes):



1. **Prophase:** the chromosomes (already copied) condense and become visible as X shapes; the nuclear membrane breaks down.
2. **Metaphase:** the chromosomes line up across the middle of the cell; fibres of the spindle attach to the centromeres.
3. **Anaphase:** the spindle fibres shorten and pull the two chromatids of each chromosome apart to opposite ends.
4. **Telophase** and cytokinesis: a new nuclear membrane forms around each set, and the cell splits in two.

The two daughter cells each have the same number of chromosomes as the parent ($46 \rightarrow 46$) and carry exactly the same genetic information. We can follow the amount of DNA in the cell: it doubles during replication, and halves again when the cell divides.



Uses of mitosis. Growth (more cells), repair (replacing damaged cells), and asexual reproduction (making new organisms genetically identical to the parent). Because the cell copies its DNA accurately, all the cells made by mitosis from one zygote carry the same DNA.

Worked example: doubling

A single cell divides by mitosis every 30 min. How many cells are there after 3 h (assuming no cell dies)?
3 hours = 6 divisions of 30 minutes. The number doubles each time: $2^6 = 64$ cells.

Common mistakes

- Saying the chromosomes “copy during mitosis”. The DNA is copied in interphase, before mitosis starts.
- Saying the cells made by mitosis are “similar”. They are genetically *identical* (barring mutation).
- In anaphase, saying whole chromosomes (pairs) are pulled apart. In mitosis it is the two chromatids of each chromosome that separate.
- Confusing the number of cells and the number of chromosomes per cell: after mitosis there are two cells, each with 46.

3 Cell counting, mitotic index and cancer (B3.1)

Mitotic index. In a tissue like the tip of a growing root, we can count the cells seen under the microscope and note how many are in mitosis. The **mitotic index** is

$$\text{mitotic index} = \frac{\text{number of cells in mitosis}}{\text{total number of cells}} \times 100\%.$$

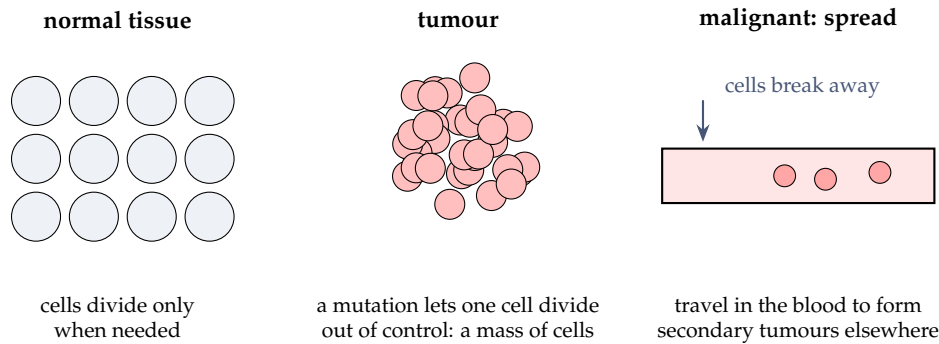
It indicates how fast the tissue is growing. Because the time spent in a stage is proportional to the fraction of cells seen in it, we can also estimate durations: if 4% of cells are in metaphase and the whole cell cycle takes 25 h, then metaphase lasts about $0.04 \times 25 = 1$ h.

Worked example: mitotic index

A student counts 200 cells in a root tip and finds that 30 are in mitosis. The cell cycle takes 20 h. Find the mitotic index, and estimate how long mitosis lasts.

$$\text{Mitotic index} = \frac{30}{200} \times 100 = 15\%. \text{ Duration of mitosis} \approx 0.15 \times 20 = 3 \text{ h.}$$

Cancer. Normally, the cell cycle is tightly controlled by genes: cells divide only when new cells are needed. A **mutation** (a change in the DNA) in one of these controlling genes can make a cell divide again and again, out of control. The result is a mass of abnormal cells called a **tumour**. A **benign** tumour stays in one place and is usually not dangerous. In a **malignant** tumour (cancer), cells break away, are carried in the blood to other parts of the body and form **secondary tumours**.



Things that increase the risk of mutations, and so of cancer, include ultraviolet light (skin cancer), ionising radiation, chemicals in tobacco smoke (lung cancer), and some viruses; some people also inherit gene versions that make cancer more likely. Cancer cells have a high mitotic index. Treatments such as chemotherapy and radiotherapy target dividing cells, which is why they also affect normal fast-dividing cells (such as hair follicles).

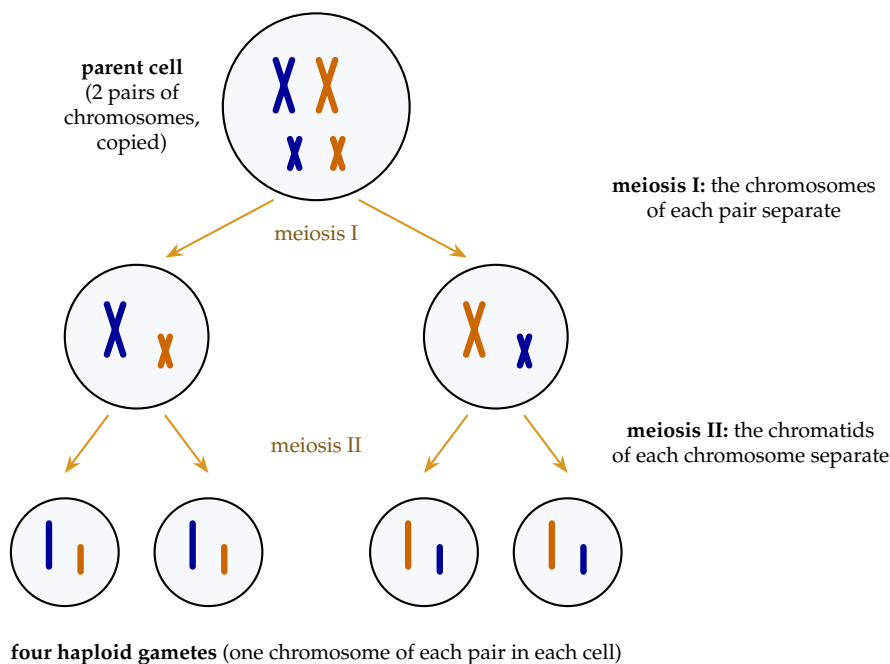
Common mistakes

- Saying cancer cells divide "faster because they are bigger". The fault is loss of *control* over the cell cycle.
- Saying all tumours are cancer. Benign tumours do not spread.
- Using the wrong denominator for the mitotic index: divide by the *total* number of cells counted, not by the number in interphase.

4 Meiosis and gametes (B3.2)

If gametes were made by mitosis they would have 46 chromosomes, and fertilisation would give a zygote with 92, then 184, and so on. Instead gametes are made by a different division, **meiosis**, which **halves** the chromosome number. Meiosis happens only in the reproductive organs (the ovaries and testes in humans).

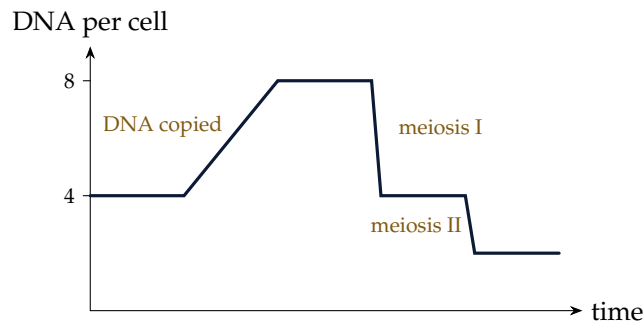
Meiosis starts with a diploid cell that has copied its DNA, and involves *two* divisions:



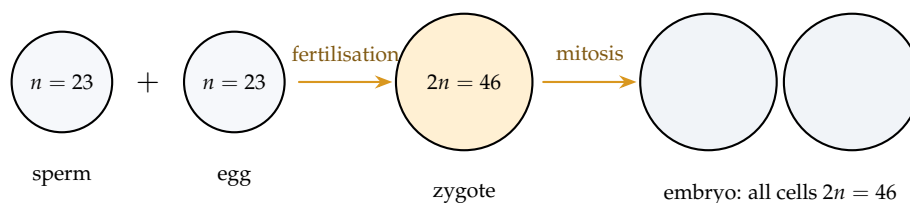
- **Meiosis I:** the chromosomes of each homologous pair are pulled apart, so each new cell gets one chromosome of every pair (the number has halved).
- **Meiosis II:** the two chromatids of each chromosome are separated (as in mitosis).

The result is **four haploid cells** that are **genetically different**. The differences arise because the maternal and paternal

chromosomes of each pair are shared out at random: in the picture, a gamete may carry the blue long chromosome with the orange short one, or with the blue short one. With n pairs there are 2^n possible combinations; for humans, 2^{23} is more than eight million. (Real meiosis also swaps pieces of DNA between homologous chromosomes, which creates yet more variation.)



The graph shows the DNA per cell falling in two steps, to a quarter of its peak. **Fertilisation** then joins two gametes, restoring the diploid number, and the zygote divides by mitosis to form the embryo:



Each fertilisation involves a random sperm and a random egg, which adds more variation again.

Worked example: chromosome numbers

A crop plant has $2n = 24$. How many chromosomes are in (a) a pollen grain nucleus, (b) a zygote, (c) a root cell, (d) each daughter cell after meiosis?

(a) gametes are haploid: $24/2 = 12$. (b) fertilisation restores the diploid number: $12 + 12 = 24$. (c) a body cell: 24. (d) after meiosis the cells are haploid: 12.

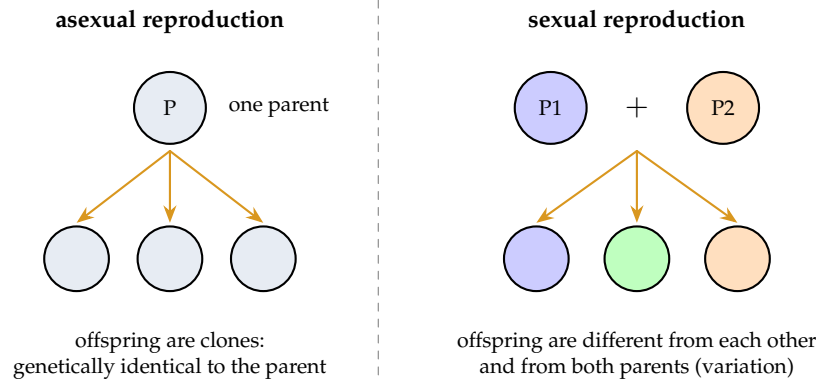
Common mistakes

- Saying meiosis makes two cells. It makes four (two divisions).
- Thinking the four cells are identical. They are different from each other and from the parent.
- Saying meiosis happens in all cells: only in the cells that make gametes.
- Mixing up the stage where the chromosome number halves (meiosis I, when homologous chromosomes separate) with the stage where chromatids separate (meiosis II).

5 Asexual and sexual reproduction (B3.3)

Asexual reproduction involves only one parent. There are no gametes and no fertilisation: the offspring are made by mitosis and are **genetically identical** to the parent (clones). Bacteria divide by binary fission, strawberry plants send out runners, and gardeners take cuttings.

Sexual reproduction involves the fusion (fertilisation) of two haploid gametes from two parents, formed by meiosis. The offspring inherit a mixture of the genes of both parents and are genetically different from each other and from either parent: there is **variation**.



	asexual	sexual
parents	one	two
cell division	mitosis	meiosis, then fertilisation
offspring	identical clones	show variation
advantages	fast; only one parent; no need to find a mate; good if the environment stays the same	variation: some offspring may survive a change or a new disease; allows evolution
disadvantages	no variation, so a disease or a change can wipe out all of them	slower; needs two parents and energy to find a mate

Common mistakes

- Saying asexual offspring are “similar”. They are identical (clones).
- Saying sexual reproduction is better in every case. It is better when the environment changes; asexual reproduction is quick and efficient in a stable environment.
- Forgetting that variation comes from *both* meiosis and random fertilisation.

6 Sex determination and genetic diagrams (B3.4)

Of the 23 pairs of human chromosomes, 22 pairs are the same in males and females (these are called **autosomes**). The 23rd pair is the **sex chromosomes**. Females have two X chromosomes (XX). Males have one X and one smaller Y chromosome (XY). The Y chromosome carries a gene that makes the embryo develop as male.

When gametes form by meiosis the pair separates. Every egg gets an X. Half of the sperm get an X and half get a Y. The sex of a child is therefore decided by the **father's sperm**: an X sperm fertilises the egg to make a girl (XX), a Y sperm makes a boy (XY). We show this in a **genetic diagram** (Punnett square): the gametes of one parent along the top, the other down the side, and the possible children in the boxes.

		eggs from the mother (XX)		
		X	X	
sperm from the father (XY)	X	XX	XX	genotypes: 2 XX : 2 XY = 1 female : 1 male probability of a girl = $\frac{1}{2}$
	Y	XY	XY	

The four boxes are equally likely, so the probability of a girl is $\frac{2}{4} = \frac{1}{2}$ and of a boy $\frac{1}{2}$, a ratio of 1 : 1. A ratio is a prediction of the average over many births, not a guarantee for one family. Each fertilisation is independent: the sex of earlier children has no effect on the next one.

Writing out a genetic diagram. Parents' phenotypes → parents' genotypes → gametes → offspring genotypes (in the square) → offspring phenotypes and the ratio. Here: mother (female, XX) × father (male, XY); gametes X, X and X, Y; children XX, XX, XY, XY; 1 female : 1 male.

Worked example: probabilities for a family

A couple has three children. What is the probability that all three are girls? What is the probability that exactly two are girls?

Each child is a girl with probability $\frac{1}{2}$, independently. All three girls: $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$. Exactly two girls: the arrangements are GGB, GBG, BGG, each with probability $\frac{1}{8}$, so $3 \times \frac{1}{8} = \frac{3}{8}$.

Worked example: the next child

A couple already has four daughters. What is the probability that the fifth child is a girl? Still $\frac{1}{2}$. The previous births do not change the proportion of X and Y sperm, so there is no "due" son.

Common mistakes

- Believing that having had four girls makes a boy more likely. Each birth is independent.
- Saying the mother decides the sex. Her eggs all carry X; the father's sperm (X or Y) decides.
- Writing the gametes in the genetic diagram as the full genotype (XX, XY) instead of one chromosome from each pair (X; X or Y).
- Forgetting that Punnett squares give probabilities (and expected ratios), not exact results.

7 Mitosis versus meiosis: putting it together

	mitosis	meiosis
where	most body cells	reproductive organs only
divisions	one	two
cells produced	2	4
chromosome number	stays the same ($46 \rightarrow 46$)	halves ($46 \rightarrow 23$)
daughter cells are	genetically identical	genetically different
used for	growth, repair, asexual reproduction	making gametes

Exam technique. (1) For chromosome-number questions write the number at each step ($2n$ or n). (2) For counting questions (cells after x divisions) use powers of 2. (3) For genetic ratios, always write the gametes first. (4) For graphs of DNA per cell: a gradual rise is replication; one sudden drop is mitosis (or the first division of meiosis); a second drop (to half again) is meiosis II. (5) Look for the key discriminating words: "identical" → mitosis, "four", "haploid" or "different" → meiosis.

Spec coverage (B3.1 to B3.4). The cell cycle, mitosis and cancer (B3.1); meiosis and haploid gametes (B3.2); asexual versus sexual reproduction (B3.3); XX and XY sex determination, genetic diagrams and ratios (B3.4).

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. A human skin cell has how many chromosomes? How many does a sperm cell have?
2. In which stage of mitosis are the chromatids pulled apart?
3. A single cell divides by mitosis five times. How many cells are there?
4. Of 500 root tip cells counted, 40 are in mitosis. Find the mitotic index.
5. Give two differences between mitosis and meiosis.
6. Why are the offspring of sexual reproduction varied?
7. A couple have two sons. What is the probability that their third child is a daughter?
8. Which parent determines the sex of a child, and why?

Answers to the self-check

1. 46; 23.
2. Anaphase.
3. $2^5 = 32$.
4. $40/500 \times 100 = 8\%$.
5. Mitosis makes 2 identical diploid cells in one division (growth, repair); meiosis makes 4 different haploid cells in two divisions (gametes).
6. Meiosis shares out maternal and paternal chromosomes randomly, and fertilisation joins a random sperm with a random egg.
7. $\frac{1}{2}$ (independent).
8. The father: his sperm carry X or Y, while all eggs carry X.

Next step

Heurisco's *ESAT Biology: Cell Division and Sex Determination Practice Set* has twenty original exam-style questions on this lesson, with diagrams of mitosis, DNA graphs and genetic probability, in order of difficulty, with a full worked solution and a note on the trap in each.