Unit 1

Answers: Cell Biology

Quick checks

1 b S stands for synthesis, the making of new DNA. In G_1 the cell grows before copying; in G_2 it checks the copies and prepares to divide; by prophase each chromosome is already double.

2 b Each sister chromatid has a kinetochore on its side of the centromere, and the fibers from its pole hold it there. The telomeres are the ends, and the secondary constriction (with the nucleolus organizer) has nothing to do with the spindle.

3 c At anaphase each centromere splits, so the 46 double chromosomes become 92 single ones, 46 heading to each pole. Until then each chromosome, though double, counts as one; after cytokinesis each cell has 46 again.

4 b A bivalent (bi, two) is the two homologous chromosomes of a pair, paired up in synapsis. Since each is double, a bivalent has four chromatids, which is why it is also called a tetrad. One chromosome with two chromatids is just a copied chromosome.

5 b In anaphase I whole homologous chromosomes go to opposite poles, so each new cell made in telophase I gets n. In anaphase II only the sister chromatids separate, as in mitosis: each cell keeps its n chromosomes. That is why meiosis I is called the reduction division.

6 b If the gametes had 2n chromosomes, the zygote would have 2n + 2n = 4n, its children 8n, and so on. Meiosis halves the number in the gametes, so fertilization restores 2n.

1 a. **b** The DNA was copied in S phase (2C → 4C), but each chromosome is now double, with two chromatids on one centromere, so the number of chromosomes hasn't changed.

1 b. **a** Both disappear during prophase (the envelope at its very end). They reappear in telophase.

1 c. **c** Sister chromatids part when the centromeres split: at anaphase of mitosis and anaphase II of meiosis. At anaphase I whole homologous chromosomes separate, each still with both its chromatids.

1 d. **b** The homologs pair in zygotene, held by the synaptonemal complex. In leptotene they are still apart; crossing over follows in pachytene.

1 e. **b** Pieces are swapped between a chromatid of the maternal homolog and a chromatid of the paternal homolog. Swapping between sister chromatids, which are identical, would change nothing.

1 f. **b** Meiosis I separates the homologs, so each cell gets one of each pair, n = 12; the centromeres haven't split, so each chromosome still has two chromatids. They part in meiosis II.

1 g. **b** A plant cell's wall stops it pinching in, so it builds a cell plate from Golgi vesicles across its middle, from the center out to the wall.

1 h. **d** Mitosis copies the chromosomes exactly, so it makes identical cells. The other three, in meiosis and fertilization, make new combinations of genes.

1 i. **b** $n = 4$ pairs, so $2^4 = 16$ kinds. 256 is 16×16, the combinations when two flies' gametes meet.

1 j. **c** They come from one parent by mitosis alone, so they all have its genes: a clone. A hybrid is the offspring of a cross between two different parents.

2 a. In mitosis each chromosome is copied and then the sister chromatids are shared, one to each daughter cell. So each daughter cell gets **exactly the same number** (and kind) of chromosomes as the mother cell: a 2n cell gives two 2n cells. The number stays equal, hence equational.

2 b. Meiosis **halves** the chromosome number: a diploid (2n) meiocyte gives four haploid (n) cells. The halving happens in meiosis I, when the homologous chromosomes of each pair separate to opposite poles. It reduces the number, hence reduction division.

2 c. In meiosis II, as in mitosis, single chromosomes line up on the equator with one sister chromatid facing each pole, the centromeres split at anaphase, and the **sister chromatids** go to opposite poles. The chromosome number doesn't change (n stays n), so it is an equational division, like mitosis. The difference is only that the cell is haploid and there was no DNA copying before it.

2 d. Though no chromosomes can be seen and the nucleus looks inactive, the cell is very busy: it **grows** and makes proteins and organelles (G_1), **copies all its DNA** (S), and makes the proteins for division and checks its DNA (G_2). It is the preparation without which the cell couldn't divide.

2 e. Fertilization joins two gametes. If gametes had the full 2n, the zygote would have 4n, the next generation 8n, and so on. Meiosis **halves** the number in the gametes, so fertilization restores the normal 2n, keeping the **chromosome number constant** from generation to generation. Meiosis also makes the variation that sexual reproduction is valued for.

2 f. A clone is made by asexual reproduction, in which the offspring are formed from the parent's cells by **mitosis** only. Mitosis gives each daughter cell an exact copy of the mother cell's chromosomes, and there is no meiosis or fertilization to mix genes. So all members have the same genes as the parent and each other (apart from rare mutations).

2 g. Each child grows from a different egg and sperm, and every gamete is different because of **crossing over** and **independent assortment** in meiosis; which sperm meets which egg is also chance (**random fertilization**). So each child gets a different combination of the parents' genes. Identical twins come from **one zygote** that split in two, so they share the same genes.

2 h. The root tip has a **meristem**, where cells divide rapidly to grow the root, so many cells are caught in every stage of mitosis. Onion roots are easy to grow in water in a few days, and onion cells have a small number (16) of large chromosomes that are easy to see when stained.

3 a.

Mitosis	Meiosis
In somatic (body) cells.	In meiocytes of the testes, ovaries, anthers and ovules.
One division.	Two divisions (meiosis I and II).
Two daughter cells.	Four daughter cells.
Daughter cells diploid (2n): equational.	Daughter cells haploid (n): reductional.
Daughter cells identical to each other and the mother cell.	Daughter cells genetically different.
No synapsis, crossing over or chiasmata.	Synapsis, crossing over and chiasmata in prophase I.
For growth, repair and asexual reproduction.	For making gametes, and variation.

3 b.

Meiosis I	Meiosis II
Reduction division: 2n → n.	Equational division: n → n.
Prophase I long, with five sub-stages; synapsis and crossing over.	Prophase II short and simple; no pairing.
Pairs of homologs line up at metaphase I.	Single chromosomes line up at metaphase II.
Homologous chromosomes separate at anaphase I; centromeres don't split.	Sister chromatids separate at anaphase II; centromeres split.
Preceded by interphase with DNA copying.	Preceded by interkinesis, with no DNA copying.
One cell gives two.	Two cells give four.

3 c.

Karyokinesis	Cytokinesis
Division of the nucleus.	Division of the cytoplasm.
Comes first.	Follows karyokinesis (from late anaphase or telophase).
Has stages: prophase, metaphase, anaphase, telophase.	Has no named stages.
Shares the chromosomes between two nuclei.	Shares the cytoplasm and organelles between two cells.
Similar in plant and animal cells.	By a furrow in animal cells, a cell plate in plant cells.

3 d.

Animal cell	Plant cell
By a cleavage furrow.	By a cell plate.
A ring of actin and myosin pinches the membrane in.	Golgi vesicles with wall material join across the middle.
Proceeds from the outside in (centripetal).	Proceeds from the center out (centrifugal).
No new wall is made.	The cell plate becomes the middle lamella, and new walls form on either side.

3 e.

Homologous chromosomes	Sister chromatids
The two chromosomes of a pair, one from each parent.	The two copies of one chromosome, made by DNA copying in S phase.
Similar (same length, centromere and genes) but not identical: they may carry different forms of the genes.	Identical (until crossing over changes them in meiosis).
Separate chromosomes, each with its own centromere.	Joined at one centromere.
Separate at anaphase I of meiosis.	Separate at anaphase of mitosis and anaphase II of meiosis.

3 f.

Asexual reproduction	Sexual reproduction
One parent.	Usually two parents.
No gametes or fertilization.	Gametes made by meiosis fuse at fertilization.
Involves mitosis only.	Involves meiosis, fertilization and mitosis.
Offspring are clones, identical to the parent.	Offspring show variation.
Fast; many offspring.	Slower; fewer offspring.

4 a. The **cell cycle** is the sequence of events in a dividing cell from one division to the next. It has two phases:

1. **Interphase**, the long period between divisions: **G_1** (the cell grows, makes proteins and organelles, and does its normal work), **S** (the DNA is copied, so each chromosome becomes two sister chromatids; DNA 2C → 4C), and **G_2** (the cell grows more, makes the proteins for division, and checks its DNA).
2. **M phase**: **karyokinesis** (mitosis: prophase, metaphase, anaphase, telophase) and **cytokinesis**.

Cells that stop dividing leave the cycle from G_1 into **G_0**. In a typical human cell the cycle takes about 24 hours, of which the M phase takes about one.

4 b.

1. **Prophase:** chromatin condenses into visible chromosomes, each of two sister chromatids joined at the centromere; the nucleolus disappears; in animal cells the centrosomes move to the poles with asters round them; the spindle forms; at the end the nuclear envelope breaks up.
2. **Metaphase:** spindle fibers attach to the kinetochores on each centromere, from both poles; the chromosomes line up on the equator (metaphase plate); they are at their shortest and thickest.
3. **Anaphase:** the centromeres split; the sister chromatids (now daughter chromosomes) are pulled to opposite poles, centromeres first; the cell lengthens.
4. **Telophase:** the chromosomes reach the poles and uncoil; a nuclear envelope and nucleolus re-form round each group; the spindle disappears.
5. **Cytokinesis:** a cleavage furrow (animal cells) or cell plate (plant cells) divides the cytoplasm, giving two identical diploid cells.

Diagrams: as in the widget Mitosis, step by step, labeling the chromosomes (chromatids, centromere), spindle fibers, poles (centrosomes), equator, nuclear envelope and nucleolus.

4 c.

1. **Leptotene:** chromatin condenses into long, thin threads with bead-like chromomeres; each is already double, but the chromatids can't be seen separately.
2. **Zygotene:** homologous chromosomes pair gene by gene (**synapsis**), held by the synaptonemal complex; each pair is a **bivalent**.
3. **Pachytene:** the bivalents shorten and thicken; four chromatids are seen (a **tetrad**); **crossing over** takes place between non-sister chromatids, exchanging pieces.
4. **Diplotene:** the synaptonemal complex dissolves and the homologs begin to separate, staying joined at the **chiasmata**, where crossing over happened.
5. **Diakinesis:** the chromosomes are most condensed; the chiasmata move towards the ends (terminalization); the nucleolus and nuclear envelope disappear and the spindle forms.

4 d. Meiosis I is preceded by an **interphase** in which the DNA is copied.

1. **Prophase I:** chromosomes condense; homologs pair (synapsis) to form bivalents; non-sister chromatids cross over; chiasmata are seen; the nucleolus and nuclear envelope disappear and the spindle forms (leptotene, zygotene, pachytene, diplotene, diakinesis).
2. **Metaphase I:** the bivalents line up on the equator in pairs, the two homologs of each pair facing opposite poles, each pair oriented by chance.
3. **Anaphase I:** the homologs of each pair separate and move to opposite poles; the centromeres do not split, so each chromosome still has two chromatids. The chromosome number is halved here.
4. **Telophase I:** the chromosomes reach the poles, nuclear envelopes may re-form, and cytokinesis gives two haploid cells, each with n chromosomes of two chromatids.

Diagrams: as in the widget Meiosis, step by step, stages 2 to 5.

4 e. In each of the two cells from meiosis I: **prophase II** (chromosomes condense, nuclear envelope breaks up, spindle forms), **metaphase II** (chromosomes line up singly on the equator, sister chromatids facing opposite poles), **anaphase II** (centromeres split; sister chromatids move to opposite poles), **telophase II** (nuclei re-form, chromosomes uncoil) and **cytokinesis**, giving four haploid cells in all, each with n single chromosomes.
It works like mitosis, but: the cells are **haploid**, not diploid; it is **not preceded by DNA copying** (only interkinesis); and because of crossing over, the two sister chromatids that separate are **not identical**.

4 f.

1. **Growth** of a multicellular organism from a zygote, by increasing the number of cells.
2. **Repair and replacement** of worn-out, damaged and lost cells (skin, blood, wounds).
3. **Asexual reproduction** in single-celled eukaryotes and by vegetative parts of plants.
4. **Genetic stability:** every body cell gets the same chromosomes.
5. **Restoring cell size** and the nucleus–cytoplasm balance as cells grow.
6. **Regeneration** of lost parts in some animals (a planarian, a starfish).

When mitosis isn't controlled, cells divide without stopping and form tumors: cancer.

4 g.

1. It makes the **gametes** (and plant spores), so it is essential for sexual reproduction.
2. It **halves the chromosome number** in the gametes, so fertilization restores 2n and the number stays **constant** generation after generation.
3. It produces **genetic variation** by crossing over and independent assortment, so every gamete differs; variation helps a species survive change and is the raw material of evolution.
4. Damaged DNA can be repaired while the homologs are paired.

Errors in meiosis (non-disjunction) give gametes with an extra or a missing chromosome, causing disorders such as Down syndrome.

4 h.

1. **Crossing over** (pachytene of prophase I): non-sister chromatids of homologous chromosomes exchange pieces, so the chromosomes in the gametes carry new combinations of the parents' genes.
2. **Independent assortment** (metaphase I): each pair of homologs lines up by chance, independently of the others, so each gamete gets a random mixture of maternal and paternal chromosomes: 2^n kinds, more than 8 million (2^{23}) in humans.
3. **Random fertilization:** any sperm can fertilize any egg, so one couple could have about 2^{46} (some 70 trillion) different combinations, even before crossing over.

So each offspring is a new combination, different from its parents and from its brothers and sisters.

4 i. A **clone** is a group of organisms (or cells) descended from a single parent by asexual reproduction, all with the **same genes** as the parent and each other. In nature clones form because asexual reproduction uses only **mitosis**, which copies the chromosomes exactly. Examples: the cells of an *Amoeba* or yeast colony; potatoes from tubers, sugarcane from stem pieces, bananas from suckers, *Bryophyllum* plantlets, bamboo from rhizomes; a budding *Hydra*; identical twins.

Advantages: only one parent is needed; reproduction is fast; a good variety is kept exactly.

Disadvantages: there is no variation, so a new disease can wipe out the whole clone (as late blight did to the Lumper potato in Ireland); the offspring can't adapt to change.

4 j. **Non-disjunction** is the failure of a pair of homologous chromosomes to separate at anaphase I (or of sister chromatids at anaphase II) during meiosis. One gamete then gets **both** chromosomes of the pair ($n + 1$) and another gets **none** ($n - 1$). If an egg (or sperm) with two copies of **chromosome 21** is fertilized by a normal gamete, the zygote has **three copies** of chromosome 21 (trisomy 21), 47 chromosomes in all, and the child has **Down syndrome**. The risk rises with the mother's age.

4 k. Find the small, square meristem cells near the tip under high power.

- **Prophase:** the nucleus is still round but filled with visible, coiled threads; the nucleolus may be fading.
- **Metaphase:** no nucleus; the chromosomes form a dark line (or a band seen from the side) across the middle of the cell.
- **Anaphase:** two groups of V- or J-shaped chromosomes moving apart towards the two ends of the cell.
- **Telophase:** two dense groups at the two ends of the cell, nuclei re-forming, often a cell plate forming between them.

Interphase cells (most of them) have a round nucleus with fine chromatin and a nucleolus.

4 l. All the plants of one variety grown from tubers are a **clone**, with the same genes. If that variety has no resistance to the disease, **no plant** has it, so the disease can destroy every field at once, as late blight did in Ireland in the 1840s. There is no variation for some plants to survive and carry on.
Farmers could grow **several different varieties** side by side, so that a disease that kills one doesn't kill all, and plant clean, disease-free seed tubers. Breeders can **cross** varieties (sexual reproduction, which makes new combinations of genes by meiosis and fertilization), grow the seedlings, pick those that resist the disease, and then multiply the best as new clones from tubers. So sexual reproduction makes the variation, and asexual reproduction keeps the useful result.

5 a. Number of divisions = 4 h ÷ 30 min = 240 min ÷ 30 min = 8.
Number of cells = 2^8 = **256**.

5 b.

Stage	Chromosomes	Chromatids
a. G_1	20	20
b. Metaphase of mitosis	20	40
c. Anaphase of mitosis	40	40
d. Metaphase I (10 bivalents)	20	40
e. After meiosis I	10	20
f. After meiosis II	10	10

5 c. Cells dividing = 28 + 6 + 4 + 10 = 48.
Mitotic index = 48 ÷ 400 × 100% = **12%**.
Interphase: 352 ÷ 400 × 20 h = **17.6 h**.
Prophase: 28 ÷ 400 × 20 h = 1.4 h = **84 minutes**.
(Anaphase, the shortest: 4 ÷ 400 × 20 h = 0.2 h = 12 minutes.)

5 d. Sperm: 25 × 4 = **100 sperm**. Eggs: 25 × 1 = **25 eggs** (the rest are polar bodies).
Each meiosis gives 4 sperm, so 100 sperm need 100 ÷ 4 = **25 meioses** (25 primary spermatocytes).

5 e. n = 12 pairs, so **12 bivalents**.
Kinds of pollen = 2^{12} = **4,096**.

5 f. 2C = 12 pg, so 1C = 6 pg.
a. G_2 (4C): **24 pg**. b. After mitosis (2C): **12 pg**. c. After meiosis I (2C): **12 pg**. d. Gamete (1C): **6 pg**.

5 g. Kinds of sperm = 2^{23} = **8,388,608**.
Combinations = $2^{23} \times 2^{23} = 2^{46}$ = 70,368,744,177,664 ≈ $\mathbf{7.0 \times 10^{13}}$ (about 70 trillion).

5 h. 2^9 = 512 and 2^{10} = 1,024, so after **10 rounds** there are 1,024 cells, more than 1,000.
Each cell has **46 chromosomes**, the same as the zygote: mitosis is equational.