

Inheritance

A2

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What you need to know

By the end of this topic you should be able to:

1. **Explain haploid (n) and diploid ($2n$).**
2. **Explain what homologous pairs of chromosomes are.**
3. **Explain why gametes are made by a reduction division** (meiosis).
4. **Describe what the chromosomes, nuclear envelope, cell surface membrane and spindle do in each stage of meiosis**, including the division of the cytoplasm (cytokinesis), in plant and animal cells: prophase I, metaphase I, anaphase I, telophase I, prophase II, metaphase II, anaphase II and telophase II. You don't need the sub-stages of prophase I.
5. **Identify the stages of meiosis** in photomicrographs and diagrams.
6. **Explain how crossing over and random orientation (independent assortment)** of homologous pairs and of sister chromatids make genetically different gametes.
7. **Explain how random fertilisation** makes genetically different individuals.
8. **Explain the terms** gene, locus, allele, dominant, recessive, codominant, linkage, test cross, F1, F2, phenotype, genotype, homozygous and heterozygous.
9. **Use and draw genetic diagrams and Punnett squares** for monohybrid and dihybrid crosses (dominance, codominance, multiple alleles, sex linkage), dihybrid crosses with autosomal linkage and epistasis (ratios worked out, not learned), and test crosses.
10. **Use the chi-squared (χ^2) test** to decide whether observed and expected results differ significantly. The formula is given.
11. **Explain how gene $\rightarrow$ protein $\rightarrow$ phenotype** for the *TYR* gene (tyrosinase, albinism), *HBB* (haemoglobin, sickle cell anaemia), *F8* (factor VIII, haemophilia) and *HTT* (huntingtin, Huntington's disease).
12. **Explain how gibberellin makes stems grow longer**, including the dominant allele *Le* (a working enzyme in gibberellin synthesis) and the recessive allele *le* (a non-working enzyme).
13. **Describe structural and regulatory genes, and repressible and inducible enzymes.**
14. **Explain how the *lac* operon controls protein production** in a prokaryote (cAMP is not needed).
15. **State that transcription factors are proteins** that bind to DNA and increase or decrease transcription in eukaryotes.
16. **Explain how gibberellin switches genes on** by causing DELLA repressor proteins to be broken down.

Understand it

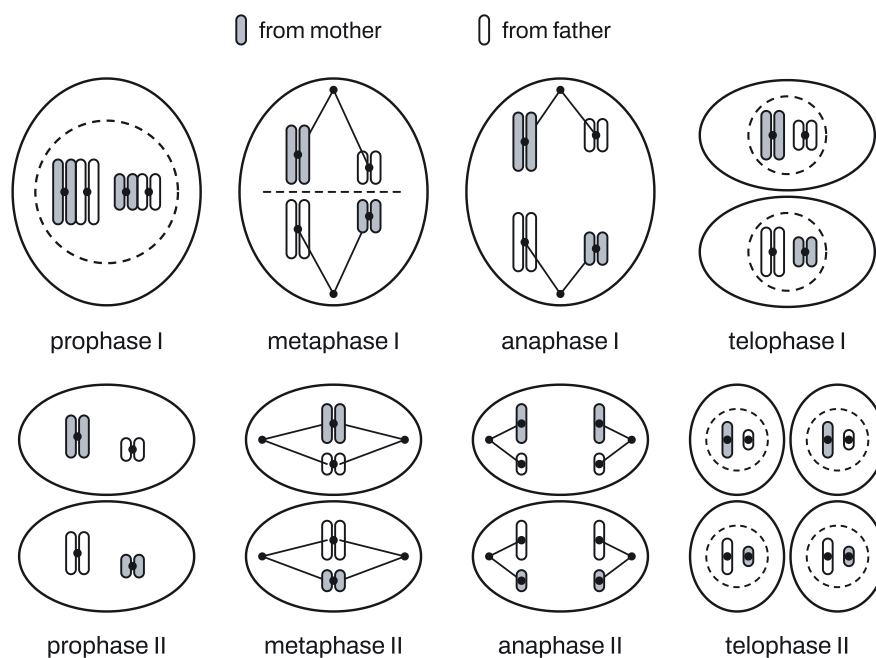
Chromosome sets

A **diploid** ($2n$) cell has two sets of chromosomes, one set from each parent: human body cells have $2n = 46$. A **haploid** (n) cell, such as a gamete, has one set ($n = 23$). The two chromosomes of a **homologous pair** are one from the mother and one from the father. They are the same size, have the centromere in the same place, and carry the **same genes at the same loci**, but may carry **different alleles** of those genes.

If gametes were diploid, fertilisation would double the chromosome number every generation. Meiosis halves it ($2n \rightarrow n$), so fertilisation ($n + n$) restores $2n$ and the number stays constant. It also mixes alleles, so the gametes differ.

Meiosis

Before meiosis the DNA replicates, so each chromosome is two **sister chromatids** joined at the centromere. A cell with $2n = 24$ starts meiosis with $24 \times 2 = 48$ chromatids. There are two divisions: **meiosis I** separates homologous chromosomes (this is the **reduction division**: the cells become haploid), and **meiosis II** separates sister chromatids, as in mitosis.



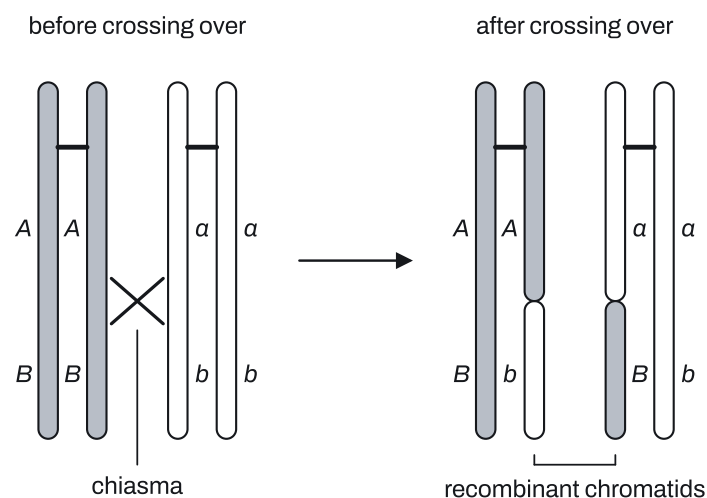
Stage	What happens
Prophase I	Chromosomes condense. Homologues pair up to form bivalents ; non-sister chromatids cross over at chiasmata . The nuclear envelope breaks down; the spindle forms (from centrioles in animal cells; plant cells have none).
Metaphase I	Bivalents line up in pairs on the equator, each pair facing either way (random orientation). Spindle fibres attach to centromeres.

Stage	What happens
Anaphase I	Spindle fibres shorten: homologous chromosomes move to opposite poles. Centromeres do not divide.
Telophase I	Nuclear envelopes may re-form; the cytoplasm divides (cytokinesis : the cell surface membrane pinches in, or a new cell wall forms in plants). Two haploid cells.
Prophase II	Chromosomes condense again, the nuclear envelope breaks down, a new spindle forms.
Metaphase II	Chromosomes line up singly on the equator.
Anaphase II	Centromeres divide; sister chromatids are pulled to opposite poles, centromeres first.
Telophase II	Nuclear envelopes re-form and the cytoplasm divides (cytokinesis): four haploid cells .

Identifying a stage: pairs on the equator → metaphase I; single chromosomes on it → metaphase II; one cell, two groups moving apart → anaphase I; two cells, four groups → anaphase II; four nuclei or cells → telophase II.

Why gametes differ

- **Crossing over** (prophase I): non-sister chromatids of a homologous pair break at the same point and swap sections at a chiasma. Chromatids get **new combinations of alleles**.
- **Random orientation** (metaphase I): each homologous pair lines up independently of the others, so a gamete can get any mix of maternal and paternal chromosomes: 2^n combinations (2^{23} , over 8 million, in humans). After crossing over, sister chromatids are no longer identical, so their random orientation at metaphase II adds more variety.
- **Random fertilisation**: any male gamete can fuse with any female gamete, so each offspring gets a new combination.



Genes and alleles

A **gene** is a length of DNA with a base sequence that codes for a polypeptide. Its position on a chromosome is its **locus**. **Alleles** are different forms of a gene. The **genotype** is the alleles an organism has; the **phenotype** is its features, from its genotype and its environment. **Homozygous** means two identical alleles (AA or aa); **heterozygous**, two different (Aa).

- **Dominant:** the allele shows in the phenotype of a heterozygote. **Recessive:** it shows only when homozygous.
- **Codominant:** both alleles show in a heterozygote, e.g. $Hb^A Hb^S$ makes both kinds of haemoglobin.
- **Multiple alleles:** a gene with more than two alleles (each person still has only two).
- **Sex linkage:** the gene is on the X chromosome. Males (XY) have one copy, so a recessive allele always shows; write alleles as superscripts, X^H , and give Y no allele.
- **Autosomal linkage:** two genes on the same (non-sex) chromosome are inherited together unless crossing over separates them.
- **Epistasis:** one gene affects whether another gene is expressed, e.g. gene 1's enzyme makes a pigment precursor and gene 2's enzyme makes the precursor into a colour.
- **F1** are the offspring of the first cross (of two homozygous parents), and **F2** the offspring of crossing F1 with F1.
- **Test cross:** cross an organism with the dominant phenotype with a **homozygous recessive** one. Every gamete of the tester carries recessive alleles, so the offspring show exactly which alleles the unknown parent's gametes carried.

From gene to phenotype

A mutation changes a gene's base sequence, so the protein's primary structure changes, which can change its 3D shape and stop it working.

Gene	Protein	Allele	Effect
<i>TYR</i>	tyrosinase, the enzyme that turns tyrosine into DOPA and dopaquinone on the way to melanin	recessive	no melanin: albinism, very pale skin and hair, pale or pink iris, poor vision, sensitive to light
<i>HBB</i>	β -globin of haemoglobin; one base substitution puts valine in place of glutamic acid	codominant	HbS is less soluble at low oxygen, forms long fibres, red cells sickle, block capillaries (pain) and carry less oxygen: sickle cell anaemia
<i>F8</i>	factor VIII, a blood clotting factor	recessive, on the X chromosome	clotting cascade fails, fibrinogen is not turned into fibrin: bleeding lasts much longer (haemophilia); mostly males

Gene	Protein	Allele	Effect
<i>HTT</i>	huntingtin	dominant	too many CAG repeats give a long glutamine chain; the protein misfolds and clumps in brain neurones, which die: loss of movement control, mood and thinking (Huntington's disease), usually from middle age

Gibberellin and stem length

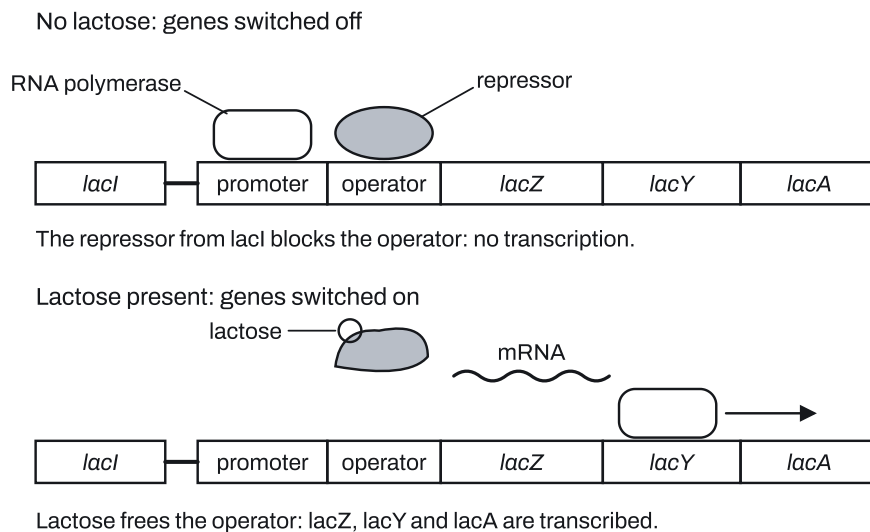
In peas, the gene *Le/le* codes for the enzyme that converts inactive gibberellin GA_{20} to active **GA_1** . *Le* (dominant) gives a working enzyme. *le* has a single base substitution, so one amino acid near the active site changes and the enzyme does not work. *le le* plants make little GA_1 , their internodes stay short, and they are dwarf. One *Le* allele is enough to be tall.

GA_1 makes stems grow through **DELLA proteins**. Normally DELLA proteins bind a transcription factor and stop it working. Gibberellin binds a receptor; the receptor–gibberellin complex causes the DELLA proteins to be broken down. The transcription factor is released, binds the promoter of growth genes, and RNA polymerase transcribes them. Their proteins loosen cell walls, and cells take in water and elongate.

Controlling genes

- **Structural genes** code for proteins that do a job in the cell (enzymes, transport or structural proteins). **Regulatory genes** code for proteins that control other genes, such as repressors and transcription factors.
- **Transcription factors** are proteins that bind DNA (often the promoter) and increase or decrease the rate of transcription in eukaryotes.
- An **inducible enzyme** is made only when its substrate is present (the *lac* enzymes). A **repressible enzyme** is made until its product switches its genes off (the *trp* operon).

An **operon** is a group of structural genes with one promoter and one operator, transcribed together as one mRNA. In *E. coli* the ***lac* operon** has a promoter, an operator and three structural genes: ***lacZ*** (β -galactosidase, which hydrolyses lactose to glucose and galactose), ***lacY*** (lactose permease, which takes lactose into the cell) and ***lacA*** (transacetylase). The regulatory gene ***lacI***, with its own promoter, always makes the **repressor**.



- **No lactose:** the repressor binds the operator. RNA polymerase cannot bind the promoter (or cannot move), so the genes are not transcribed and no energy or amino acids are wasted.
- **Lactose present:** lactose (as allolactose) binds the repressor and changes its shape, so it leaves the operator. RNA polymerase binds the promoter and transcribes all three genes; the enzymes are made and lactose is taken in and broken down. When lactose runs out, the repressor binds again.

Key facts and formulas

Only the chi-squared formula is in the syllabus formula list ("Given"); critical values come in a table in the question.

Formula	Status
$\chi^2 = \sum \frac{(O - E)^2}{E}$	Given
Critical value of χ^2 at $p = 0.05$ (from the table in the question)	Given
Degrees of freedom = number of classes – 1	Learn it
Expected number = total $\times$ that class's fraction of the ratio	Learn it
χ^2 below the critical value: difference not significant, due to chance	Learn it
Haploid = n , diploid = $2n$; chromatids at the start of meiosis = $2 \times 2n$	Learn it
Combinations of chromosomes from random orientation = 2^n	Learn it
$Aa \times Aa$: genotypes 1 : 2 : 1; phenotypes 3 : 1 (dominance) or 1 : 2 : 1 (codominance)	Learn it
$Aa \times aa$ (test cross): 1 : 1	Learn it
$AaBb \times AaBb$, unlinked: 9 : 3 : 3 : 1; test cross $AaBb \times aabb$: 1 : 1 : 1 : 1	Learn it
$X^H X^h \times X^H Y$: all daughters unaffected, half of sons affected	Learn it

How to do it

In the Paper 4 questions we have tagged for this topic (73 questions, 2021–2025, including 10 repeated across paper variants), the types came up this often. 39 of the 73 mix several types, so the counts add up to more than 73.

Question type	Questions
Gene → protein → phenotype for a genetic disease	19
Define genetic terms	12
Monohybrid genetic diagram	11
Gibberellin, <i>Le/le</i> and DELLA	11
Sex-linked cross	9
Deduce inheritance from a pedigree or data	9
Test cross	8
Stages of meiosis	8
How meiosis and fertilisation cause variation	8
Haploid, diploid, homologues and reduction division	8
<i>lac</i> operon, inducible and repressible enzymes	7
Structural and regulatory genes, transcription factors	6
Dihybrid cross, unlinked genes	5
Epistasis cross	5
Chi-squared test	5
Linkage from unexpected ratios	3

Every genetic diagram gets these marks separately, so lay it out the same way each time:

1. **Key:** the symbols and what each means (use the ones given).
2. **Parental phenotypes and genotypes.**
3. **Gametes:** each different gamete once, circled or listed.
4. **Offspring genotypes**, from a Punnett square, with gametes along the top and side.
5. **Offspring phenotypes linked to each genotype**, then the **ratio** with each number labelled.

1. Gene → protein → phenotype for a genetic disease (19 questions)

1. Name the **gene** and say it is mutated (a changed base sequence); give the type of allele (recessive, codominant, X-linked recessive, dominant).
2. Name the **protein** and say it is non-functional, absent or abnormal; give the biochemical step from the table above.

3. Give the **phenotype**: the physiological effects.

For a 6-mark "two examples" essay, give about three points for each disease. **Unfamiliar diseases**: mutation → changed primary structure → changed shape (active site) → no working protein → its substrate builds up or its product is missing → symptoms.

2. Define genetic terms (12 questions)

Use the definitions in "Genes and alleles", one precise sentence each. Codominant: **both** alleles are expressed in the heterozygote; "neither is dominant" alone is not enough.

3. Monohybrid genetic diagram (11 questions)

Lay it out as above. For two carriers of a recessive disease: $Hh \times Hh$ gives HH, Hh, Hh, hh : 3 unaffected : 1 affected, so each child has a $\frac{1}{4}$ chance. **Outlining the F1/F2 method** in words: cross a homozygous dominant with a homozygous recessive; all F1 are heterozygous; cross F1 with F1 (or self-pollinate); F2 is 25% AA , 50% Aa , 25% aa .

- **Codominance**: use a gene letter with superscripts, e.g. $C^R C^W$; the heterozygote has its own phenotype, so the F2 ratio is 1 : 2 : 1.
- **Multiple alleles**: work out the order of dominance from the stem, e.g. I^A and I^B codominant, both dominant to I^O . "Breeds true" means homozygous.
- **Explain observed numbers**: 44 and 13 is close to 3 : 1, so both parents were heterozygous.

4. Gibberellin, Le/le and DELLA (11 questions)

Dwarfism: le → single base substitution → changed amino acid → non-functional enzyme → GA_{20} not converted to GA_1 → short internodes. **Stem growth**: gibberellin binds a receptor → DELLA broken down → transcription factor freed → binds promoter → RNA polymerase transcribes growth genes → cell walls loosen, cells take in water and elongate. Say what binds to what, and that genes are **transcribed**; in crosses, Le is simply dominant.

- **Germinating seeds**: the same pathway in the aleurone layer switches on the gene for amylase, which hydrolyses starch in the endosperm.

5. Sex-linked cross (9 questions)

1. Write genotypes as $X^H X^h$ and $X^H Y$.
 2. Gametes: X^H, X^h from the mother; X^H, Y from the father.
 3. Give each offspring its **sex and phenotype** ("carrier female", "affected male").
- **Why more males**: a male has one X; there is no second allele to mask a recessive one.
 - **An affected father never passes an X-linked allele to his sons**: they get his Y. All his daughters get it.

- **X-linked dominant:** an affected heterozygous mother and unaffected father give 1 : 1 : 1 : 1 affected female : unaffected female : affected male : unaffected male.
- **Other systems** (birds: female ZW, male ZZ): follow the stem's symbols.

6. Deduce inheritance from a pedigree or data (9 questions)

State a conclusion, then **name the individuals or numbers** that prove it:

- two unaffected parents with an affected child → **recessive**;
- two affected parents with an unaffected child → **dominant**;
- an affected daughter of an unaffected father → **not X-linked recessive**;
- only males affected, and every son of an affected father → **Y-linked**;
- similar numbers of affected males and females → probably **autosomal**;
- a heterozygote with a phenotype of its own → **codominant**; a table of crosses lets you rank multiple alleles.

7. Test cross (8 questions)

1. Cross the unknown with a **homozygous recessive** (name its phenotype, e.g. "long-haired and white").
2. Any offspring with the recessive phenotype → the unknown is **heterozygous**; all offspring dominant → **homozygous dominant**. For two genes, judge each gene separately.
3. Use many offspring, so a 1 : 1 ratio shows up.

8. Stages of meiosis (8 questions)

Use "Identifying a stage" and the stage table. Always write **I** or **II**. When describing a picture, count cells and groups of chromosomes, and say what the spindle fibres, centromeres and nuclear envelope are doing. Reduction happens in **meiosis I** (homologues separate in anaphase I).

- Homologous pairs are present from prophase I to anaphase I; cells are haploid from telophase I on (every stage of meiosis II).
- Dividing the cytoplasm after each telophase is **cytokinesis**.

9. How meiosis and fertilisation cause variation (8 questions)

Name the three causes with **when** and **what**: crossing over between **non-sister chromatids** at chiasmata in prophase I (new allele combinations); random orientation of **homologous pairs** at metaphase I and of chromatids at metaphase II; random fusion of gametes. To fill in alleles after crossing over, swap everything beyond the chiasma between the two non-sister chromatids, as in the crossing-over diagram.

10. Haploid, diploid, homologues and reduction division (8 questions)

- Chromatid counts: gametes with 12 chromosomes → mother cell $2n = 24$ → 48 chromatids at the start of meiosis.
- **Why the zygote is diploid with homologous pairs:** two haploid gametes fuse, and each chromosome from the father matches one from the mother.
- **Unfamiliar life cycles:** gametes made by mitosis in a haploid organism; meiosis happens only in a diploid cell. A recessive allele always shows in a haploid organism.

11. *lac* operon, inducible and repressible enzymes (7 questions)

For a β -galactosidase curve after lactose is added: lactose enters → binds repressor → repressor changes shape and leaves the operator → RNA polymerase binds the promoter → *lacZ*, *lacY* and *lacA* transcribed → enzymes made, activity rises → levels off at a maximum. **Inducible** because the enzymes are made only when lactose is present.

- **Repressor mutation:** a repressor that cannot bind means genes are always on; one that cannot bind lactose means they are never on.
- **Repressible (*trp*):** tryptophan binds the repressor and activates it, so it binds the operator and synthesis stops when there is enough.
- **Glucose present:** lactose is kept out, so the *lac* genes stay off.

12. Structural and regulatory genes, transcription factors (6 questions)

Use the definitions in "Controlling genes". For a **mutated transcription factor:** changed base sequence → changed primary and tertiary structure → it cannot bind the promoter → genes it switched on are transcribed less, and genes it repressed are transcribed more.

13. Dihybrid cross, unlinked genes (5 questions)

AaBb makes four gametes, *AB*, *Ab*, *aB*, *ab*, in equal numbers. A 4×4 Punnett square gives 9 *A_B_* : 3 *A_bb* : 3 *aaB_* : 1 *aabb*. The double-dominant phenotype has four genotypes: *AABB*, *AABb*, *AaBB*, *AaBb*. Link phenotypes to genotypes with a key.

14. Epistasis cross (5 questions)

1. From the stem, write the rule for each genotype (e.g. "*ww* has no pigment whatever the other gene").
2. Draw the full 4×4 square and give **every box** a phenotype using the rule.
3. Count the boxes for the ratio (e.g. 15 : 1 when either dominant allele gives the feature) and name the interaction **epistasis**. Explain it through the proteins: which enzyme is missing, and which step stops.

15. Chi-squared test (5 questions)

1. **Null hypothesis**: no significant difference between observed and expected.
2. **Expected** numbers from the total and the ratio.
3. Work $\frac{(O-E)^2}{E}$ for each class to the stated precision, then **sum**.
4. Degrees of freedom = classes – 1; read the critical value at $p = 0.05$.
5. Conclude: below it → not significant, differences due to chance, accept the null hypothesis; above it → significant, reject it.

Reasons results differ from the ratio: small samples, random fertilisation, linkage, epistasis, or a genotype that dies.

16. Linkage from unexpected ratios (3 questions)

A dihybrid test cross expected to give 1 : 1 : 1 : 1 gives two **large** classes (the parental combinations) and two **small** classes (recombinants): the genes are **linked** on one chromosome, and the few recombinants come from **crossing over** in prophase I. The further apart the loci, the more crossing over, so the more recombinants.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
 - **A1** accuracy mark: for a correct answer; it needs the M mark before it.
 - **B1** mark for a correct result on its own, with no method needed.
-

Example 1

In a species of beetle, a recessive allele on the X chromosome, X^g , gives green wing cases; X^B gives blue. Males are XY.

A heterozygous blue female is crossed with a green male. Draw a genetic diagram to show the expected offspring and state their phenotypic ratio. **[4]**

Parents: blue female $X^B X^g$ × green male $X^g Y$.

Gametes: X^B , X^g and X^g , Y . **B1**

	X^g	Y
X^B	$X^B X^g$ blue female	$X^B Y$ blue male
X^g	$X^g X^g$ green female	$X^g Y$ green male

B1 offspring genotypes, **B1** each linked to sex and phenotype.

Ratio: 1 blue female : 1 green female : 1 blue male : 1 green male. **B1**

Example 2

In a flowering plant, gene W/w controls whether pigment is made: ww plants make none and have white flowers. In plants with at least one W , gene P/p controls colour: P gives purple, pp gives red. The genes are on different chromosomes.

(a) Two plants with genotype $WwPp$ are crossed. Use a Punnett square to find the expected ratio of offspring phenotypes. **[4]**

(b) The cross gave 84 purple, 34 red and 42 white plants. Use the chi-squared test to decide whether these results fit the expected ratio. The critical value at $p = 0.05$ for 2 degrees of freedom is 5.991. **[4]**

(a) Gametes of each parent: WP , Wp , wP , wp . **B1**

	WP	Wp	wP	wp
WP	$WWPP$ purple	$WWPp$ purple	$WwPP$ purple	$WwPp$ purple
Wp	$WWPp$ purple	$WWpp$ red	$WwPp$ purple	$Wwpp$ red
wP	$WwPP$ purple	$WwPp$ purple	$wwPP$ white	$wwPp$ white
wp	$WwPp$ purple	$Wwpp$ red	$wwPp$ white	$wwpp$ white

B1 the 16 genotypes, **B1** phenotypes linked to them. Ratio **9 purple : 3 red : 4 white** (epistasis: ww hides gene P). **B1**

(b) Total = 160. Expected: purple $\frac{9}{16} \times 160 = 90$, red 30, white 40. **B1**

	O	E	$\frac{(O-E)^2}{E}$
purple	84	90	0.400
red	34	30	0.533
white	42	40	0.100

$$\chi^2 = 1.03. \mathbf{M1A1}$$

Degrees of freedom = $3 - 1 = 2$. $1.03 < 5.991$, so the difference is not significant: it is due to chance, and the results fit **9 : 3 : 4**. **A1**

Example 3

In a moth, allele *D* (dark body) is dominant to *d* (pale), and *L* (long antennae) is dominant to *l* (short). A moth heterozygous at both loci, whose parents were *DDLL* and *ddll*, was test crossed. The offspring were 188 dark long, 176 pale short, 22 dark short and 14 pale long.

(a) State the ratio expected if the genes were on different chromosomes. [1]

(b) Explain the results. [4]

(a) 1 : 1 : 1 : 1 (100 of each). **B1**

(b) The genes are **linked**: both loci are on the same chromosome. **B1** The moth got *D* and *L* on one chromosome and *d* and *l* on its homologue, so most gametes are *DL* or *dl*, giving the two large classes (dark long, pale short). **B1** The small classes (dark short, pale long) are recombinants, **B1** made when **crossing over** between non-sister chromatids in prophase I separated *D* from *L*; this is rare because the loci are close together. **B1**

Common mistakes

- **"Gene" when you mean "allele"**. *A* and *a* are alleles of one gene. Examiners see this every year.
- **Missing parts of the genetic diagram**. Each part (gametes, genotypes, phenotypes linked to genotypes, ratio) is a separate mark. Phenotypes written in a list, not matched to genotypes, lose the linking mark.
- **Treating sickle cell anaemia as sex-linked**, or haemophilia as autosomal. *HBB* is on an autosome; *F8* is on the X.
- **Mixing up chromatids and chromosomes**. Whole chromosomes move in anaphase I, single chromatids in anaphase II.
- **Crossing over "between sister chromatids" or "in metaphase"**. It is between **non-sister** chromatids of a homologous pair, in **prophase I**.
- **Saying gibberellin breaks DELLA down itself**. Gibberellin binds a receptor, and that leads to DELLA being destroyed.
- **Saying "the gene for amylase is made" or "the gene is activated" without "transcribed"**. Genes are transcribed; proteins are made.
- **Incomplete *lac* operon structure**. Name the promoter, operator and **all three** structural genes.
- **Chi-squared slips**: rounding each value differently, forgetting to add them, or using the number of classes as the degrees of freedom.
- **Blaming mutations** for unexpected ratios; linkage and epistasis are the usual answers.

How to get the marks

- **"Construct a genetic diagram"**: key, parents, gametes, offspring genotypes, phenotypes linked to them, ratio. Use the symbols in the question, and superscripts on X for sex linkage.

- **"State the ratio"**: label every number with its phenotype, e.g. "9 purple : 3 red : 4 white".
- **"Describe" a stage of meiosis**: name it (with I or II), then give what the chromosomes, spindle and nuclear envelope are doing.
- **"Explain" a pattern with "Use evidence"**: a conclusion, then named individuals or numbers from the figure.
- **Chi-squared**: show E and each $\frac{(O-E)^2}{E}$; compare χ^2 with the critical value, then conclude in words ("not significant, due to chance").
- **"Suggest"**: apply the ideas to the unfamiliar example; any correct, sensible reason earns credit.

Quick check

1. An animal has $2n = 18$. How many chromatids are in one of its cells at the start of meiosis, how many chromosomes does each gamete have, and how many chromosome combinations can random orientation give?
2. In a snail, shell colour has three alleles: C^B (brown) is dominant to C^P (pink), which is dominant to C^Y (yellow). Find the phenotype ratio from $C^B C^Y \times C^P C^Y$.
3. A mutation stops the *lac* repressor from binding the operator. What happens to β -galactosidase production with and without lactose?
4. A dwarf *le le* pea plant is sprayed with GA_1 . Explain whether it will grow taller.
5. A monohybrid cross expected to give 3 : 1 gave 70 and 30 offspring. Calculate χ^2 and state the conclusion (critical value 3.841, 1 degree of freedom).

Answers

1. $2 \times 18 = 36$ chromatids; $n = 9$ chromosomes; $2^9 = 512$ combinations.
2. Offspring: $C^B C^P$, $C^B C^Y$ (brown), $C^P C^Y$ (pink), $C^Y C^Y$ (yellow): **2 brown : 1 pink : 1 yellow**.
3. The operator is never blocked, so RNA polymerase transcribes the genes all the time: β -galactosidase is made **both with and without** lactose.
4. Yes. *le* codes for a non-working enzyme, so the plant cannot make GA_1 from GA_{20} ; supplying GA_1 bypasses the missing step, DELLA proteins are broken down and the stem elongates.
5. $E = 75$ and 25. $\chi^2 = \frac{25}{75} + \frac{25}{25} = 1.33$. $1.33 < 3.841$, so the difference is not significant; the results fit 3 : 1.

Past questions to try

- [9700/42/O/N/24 Q4](#): monohybrid and dihybrid diagrams, with variation.
- [9700/43/M/J/23 Q5](#): a sex-linked cross, chi-squared and crossing over.
- [9700/42/O/N/23 Q5](#): chi-squared and linkage in a dihybrid test cross.
- [9700/42/F/M/21 Q7](#): meiosis stages and crossing over with named alleles.