Meiosis, Genetics & Inheritance

IB HL Study Guide

Contents

Topics Covered in This Guide

- **D2.1 Meiosis** — chromosome behaviour in meiosis I and II, crossing over at chiasmata, independent assortment, genetic variation
- **D2.2 Inheritance** — Mendel's laws, monohybrid and dihybrid crosses, sex-linkage, codominance (ABO), incomplete dominance
- **D2.3 Gene Pools & Speciation** — allele frequency, Hardy-Weinberg principle (qualitative), allopatric and sympatric speciation
- **MCQ Practice** — styled like real IB Paper 1 questions
- **Exam Alerts** — the exact traps that cost marks in D2 questions

Aligned to IB Biology 2025 syllabus — D2.1 Meiosis — D2.2 Inheritance — D2.3 Speciation

Jump to section: Meiosis · Inheritance Patterns · Gene Pools & Speciation · MCQ Practice · Exam Strategy

Section 1: Meiosis (D2.1)

Overview

Meiosis is a specialised form of cell division that produces four genetically unique haploid cells from one diploid parent cell. It occurs in the gonads (testes and ovaries in animals) and is the basis of sexual reproduction.

$$2n \xrightarrow{\text{meiosis}} 4 \times n$$

Meiosis consists of **two successive divisions** — Meiosis I and Meiosis II — each with its own prophase, metaphase, anaphase, and telophase.

MEMORISE THIS

Meiosis at a Glance

Division	What Separates	Starting Ploidy	Ending Ploidy
Meiosis I (reductional)	Homologous chromosomes	$2n$	n (but chromosomes still double-stranded)
Meiosis II (equational)	Sister chromatids	n	n (single-stranded chromosomes)

After meiosis I, the chromosome number is halved. After meiosis II, the chromatids are separated — the outcome mirrors a mitotic division of a haploid cell.

DNA Replication Before Meiosis

Before meiosis begins, the cell undergoes a normal **S phase** of interphase — DNA is replicated so that each chromosome now consists of two identical **sister chromatids** joined at the **centromere**. This replication is essential; it provides the material for crossing over.

> ⚠ **EXAM ALERT**
>
> **Exam Alert:** DNA replication occurs **once** before meiosis begins, not before each division. There is **no S phase** between meiosis I and meiosis II. A common exam trap asks which event separates the two phases — the answer is that there is only a brief interkinesis, with no DNA replication.

Meiosis I — Reductional Division

The key distinction of meiosis I is that **homologous chromosomes** (not sister chromatids) are separated.

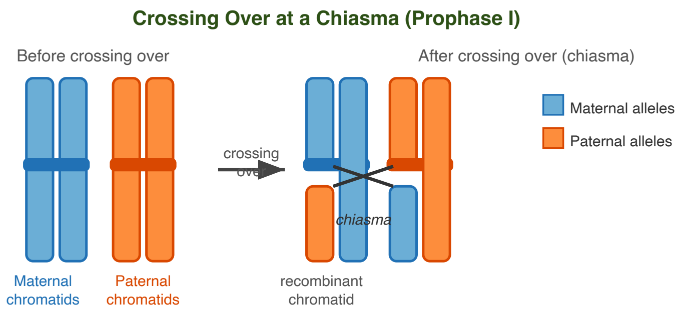
Prophase I

This is the longest and most complex phase of meiosis. Several critical events occur:

1. **Chromosomes condense** and become visible under a light microscope.
2. **Homologous chromosomes pair up** — each pair of homologues comes together in a process called **synapsis**, forming a **bivalent** (a tetrad of four chromatids: two from each homologue).
3. **Crossing over** occurs — non-sister chromatids of homologous chromosomes exchange corresponding segments of DNA at points called **chiasmata** (singular: chiasma).
4. The nuclear envelope breaks down.
5. Spindle fibres form and begin attaching to centromeres.

> **MEMORISE THIS**
>
> **Crossing Over — Key Terms**

Term	Definition
Bivalent	A pair of synapsed homologous chromosomes (4 chromatids total)
Chiasma (pl. chiasmata)	The physical point where crossing over has occurred between non-sister chromatids
Crossing over	The exchange of corresponding DNA segments between non-sister chromatids of homologous chromosomes
Non-sister chromatids	A chromatid from one homologue paired with a chromatid from the other homologue



Crossing over between non-sister chromatids during Prophase I creates recombinant chromatids with new allele combinations.

Metaphase I

- Bivalents (pairs of homologous chromosomes) align along the **metaphase plate** (cell equator).
- Spindle fibres from opposite poles attach to the centromeres of each homologue in a bivalent.
- The **orientation of each bivalent is random** — this is the physical basis of **independent assortment**.

Anaphase I

- Homologous chromosomes are pulled to **opposite poles** by spindle fibres.
- **Sister chromatids remain joined** at their centromeres — they do not separate yet.
- Each pole now has a haploid set of chromosomes, but each chromosome is still double-stranded (two chromatids).

Telophase I and Cytokinesis

- Nuclear envelopes may reform around each haploid set.
- Cytokinesis divides the cell into two haploid cells.
- The cells enter a brief **interkinesis** — there is no DNA replication.

Meiosis II — Equational Division

Meiosis II is essentially a mitotic division of the two haploid cells produced by meiosis I.

Phase	Key Events
Prophase II	Chromosomes recondense; spindle fibres reform; nuclear envelope breaks down
Metaphase II	Individual chromosomes (each with two chromatids) align at the equator
Anaphase II	**Sister chromatids separate** — pulled to opposite poles
Telophase II	Nuclear envelopes reform; cytokinesis produces four haploid cells

The final result: **four haploid cells**, each genetically unique.

Sources of Genetic Variation in Meiosis

Meiosis generates genetic variation through three mechanisms:

MEMORISE THIS

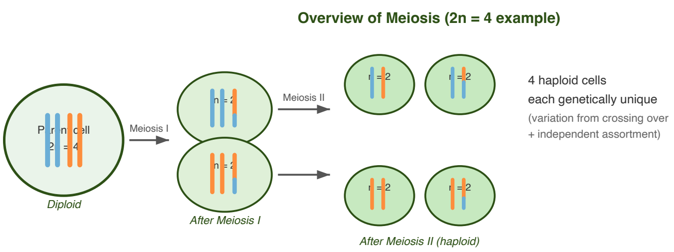
Three Sources of Variation

1. **Crossing over (Prophase I)** — segments of DNA are exchanged between homologous chromosomes, creating new combinations of alleles (recombinant chromosomes). Multiple chiasmata can form per bivalent.
2. **Independent assortment (Metaphase I)** — the orientation of each bivalent at the metaphase plate is random and independent of all other bivalents. For an organism with n chromosome pairs, there are 2^n possible chromosome combinations in the gametes. For humans ($n = 23$): $2^{23} = 8{,}388{,}608$ possible combinations from independent assortment alone.
3. **Random fertilisation** — any gamete from one parent can fuse with any gamete from the other parent, multiplying the variation further.

IB TIP

Significance for IB: When an exam question asks about the "significance of meiosis", the expected answer centres on the generation of genetic variation (through crossing over and independent assortment) and the maintenance of chromosome number across generations (halving chromosome number in gametes so fertilisation restores the diploid number).

Meiosis Stages — Full Summary Diagram



Meiosis overview: one diploid parent cell produces four genetically unique haploid daughter cells.

Section 2: Inheritance Patterns (D2.2)

Key Terminology

Before working through genetic crosses, master the vocabulary — IB mark schemes are precise about these terms.

MEMORISE THIS

Essential Genetics Vocabulary

Term	Definition
Gene	A heritable unit of information; a specific sequence of DNA that codes for a polypeptide or functional RNA
Allele	A variant form of a gene, occupying the same locus on homologous chromosomes
Locus	The specific position of a gene on a chromosome
Genotype	The alleles present in an organism (e.g., Aa, BB)
Phenotype	The observable/measurable characteristics of an organism
Homozygous	Both alleles at a locus are the same (e.g., AA or aa)
Heterozygous	The two alleles at a locus differ (e.g., Aa)
Dominant	An allele whose effect is expressed in both heterozygous and homozygous conditions
Recessive	An allele whose effect is only expressed in the homozygous condition
Codominance	Both alleles are fully expressed in the heterozygote — both phenotypes are visible simultaneously
Incomplete dominance	The heterozygote shows an intermediate phenotype between the two homozygotes
Carrier	A heterozygous individual who carries a recessive allele but does not express the associated phenotype

Mendel's Laws

Law of Segregation (Monohybrid Inheritance)

Each individual carries two alleles for each gene. During gamete formation, the two alleles segregate so that each gamete carries only one allele.

This is the basis of monohybrid crosses. Alleles are written as letters: dominant allele as upper case (A), recessive allele as lower case (a).

Law of Independent Assortment (Dihybrid Inheritance)

The alleles of two different genes assort into gametes independently of one another, provided the genes are on different (non-homologous) chromosomes.

This is the basis of dihybrid crosses. Note that genes on the same chromosome (linked genes) do **not** independently assort — this is a key HL concept.

Monohybrid Cross — Worked Example

WORKED EXAMPLE

Example: Pea seed colour (yellow Y dominant over green y)

Cross: heterozygous yellow (Yy) × heterozygous yellow (Yy)

Step 1 — Parental genotypes:

$P : Yy \times Yy$

Step 2 — Gametes produced by each parent:

Parent 1 gametes: Y or y

Parent 2 gametes: Y or y

Step 3 — Punnett square:

	Y	y
Y	YY	Yy
y	Yy	yy

Step 4 — Genotype ratio: $YY : Yy : yy = 1 : 2 : 1$

Step 5 — Phenotype ratio: yellow : green = 3 : 1

(Both YY and Yy produce yellow phenotype; only yy produces green phenotype.)

Testcross

A **testcross** crosses an individual of unknown genotype with a **homozygous recessive** individual (aa). The ratio of offspring phenotypes reveals the unknown genotype.

Unknown Genotype	Cross	Offspring Ratio
Homozygous dominant (AA)	$AA \times aa$	All dominant phenotype (all Aa)
Heterozygous (Aa)	$Aa \times aa$	1 dominant : 1 recessive ($Aa : aa$)

EXAM ALERT

Exam Alert — Testcross Language: IB mark schemes require you to state the **testcross organism** is homozygous recessive, not just "recessive". The distinction matters because the term "recessive" alone could imply heterozygous. Always write: "crossed with a homozygous recessive individual."

Dihybrid Cross — Worked Example

WORKED EXAMPLE

Example: Pea seed colour (Y/y) and seed shape (R round dominant over r wrinkled)

Cross: double heterozygote × double heterozygote ($YyRr \times YyRr$)

Gametes for each parent (using FOIL or a 4×4 Punnett square):

Each $YyRr$ parent produces four gamete types: YR, Yr, yR, yr in equal proportions.

Expected phenotype ratio from $YyRr \times YyRr$:

9 yellow round : 3 yellow wrinkled : 3 green round : 1 green wrinkled

This **9:3:3:1 ratio** is the hallmark of a dihybrid cross with two independently assorting genes, each showing simple dominance.

Punnett square (4×4):

	YR	Yr	yR	yr
YR	$YYRR$	$YYRr$	$YyRR$	$YyRr$
Yr	$YYRr$	$YYrr$	$YyRr$	$Yyrr$
yR	$YyRR$	$YyRr$	$yyRR$	$yyRr$
yr	$YyRr$	$Yyrr$	$yyRr$	$yyrr$

Count the phenotypes: 9 with at least one Y and one R (yellow round), 3 with Y but rr (yellow wrinkled), 3 with yy but at least one R (green round), 1 with yy and rr (green wrinkled).

Codominance — ABO Blood Groups

ABO blood groups are controlled by the I gene with three alleles: I^A, I^B, and i.

- I^A and I^B are **codominant** to each other — both alleles are fully expressed
- i is **recessive** to both I^A and I^B

MEMORISE THIS

ABO Blood Group Genotypes and Phenotypes

Phenotype (Blood Type)	Possible Genotypes
A	I^AI^A or I^Ai
B	I^BI^B or I^Bi
AB	I^AI^B (codominance — both A and B antigens present)
O	ii (homozygous recessive — no A or B antigens)

WORKED EXAMPLE

ABO Cross Example

A mother has blood type A (genotype I^Ai) and a father has blood type B (genotype I^Bi). What blood types are possible in their children?

Punnett square:

	I^A	i
I^B	I^AI^B (AB)	I^Bi (B)
i	I^Ai (A)	ii (O)

Possible offspring blood types: A, B, AB, and O — all four types are possible (each with probability 1/4).

Incomplete Dominance

In incomplete dominance, the heterozygote shows a phenotype **intermediate** between the two homozygous phenotypes. Neither allele is dominant or recessive.

Example: Snapdragon flower colour

- R^1R^1 = red flowers
- R^2R^2 = white flowers
- R^1R^2 = pink flowers (intermediate)

EXAM ALERT

Exam Alert — Codominance vs Incomplete Dominance:

- **Codominance:** Both allele products are fully expressed — you can detect both simultaneously (e.g., type AB blood has both A and B antigens; a roan cow has both red and white hairs)
- **Incomplete dominance:** The heterozygote shows a blend/intermediate phenotype not seen in either homozygote (e.g., pink snapdragons from red × white cross)

These are frequently confused on Paper 1. The key question is: "Can you detect both original phenotypes in the heterozygote?" If yes → codominance. If no, and you see a blend → incomplete dominance.

Sex-Linked Inheritance (X-linked Traits)

In humans, the sex chromosomes are X (larger, gene-rich) and Y (smaller, fewer genes). Genes located on the X chromosome but **not** on the Y chromosome are called **X-linked** (or sex-linked).

Because males have only one X chromosome (hemizygous), they express X-linked recessive traits whenever the allele is present on their single X chromosome — there is no second X to "mask" a recessive allele.

MEMORISE THIS

Notation for X-linked genes:

- X^H = dominant allele (e.g., normal blood clotting)
- X^h = recessive allele (e.g., haemophilia)
- $X^H X^H$ = homozygous dominant female (normal)
- $X^H X^h$ = heterozygous carrier female (normal phenotype, carries recessive allele)
- $X^h X^h$ = affected female (recessive phenotype)
- $X^H Y$ = normal male
- $X^h Y$ = affected male (hemizygous — only one X allele)

WORKED EXAMPLE

X-linked Haemophilia Cross

A carrier female ($X^H X^h$) × normal male ($X^H Y$)

Gametes: Female produces X^H and X^h; Male produces X^H and Y

Punnett square:

	X^H	X^h
X^H	$X^H X^H$ (normal female)	$X^H X^h$ (carrier female)
Y	$X^H Y$ (normal male)	$X^h Y$ (haemophiliac male)

Phenotype ratio: 1 normal female : 1 carrier female : 1 normal male : 1 haemophiliac male

Key point: 1/2 of all sons will be affected; 0 daughters will be affected (but 1/2 will be carriers). Haemophilia is more common in males because males only need one copy of the recessive allele.

IB TIP

IB Exam Language for Sex-linkage: When asked to explain why X-linked recessive conditions are more common in males, the expected answer is: males are **hemizygous** for X-linked genes — they have only one copy of the X chromosome and therefore express any allele on it, whether dominant or recessive. Do not simply write "boys only have one X chromosome" without explaining the hemizygous consequence.

Pedigree Analysis

IB often presents a pedigree chart (family tree diagram) and asks you to determine the mode of inheritance.

MEMORISE THIS

Pedigree Clues — Mode of Inheritance

Observation	Likely Conclusion
Trait skips generations	Recessive
All affected individuals have at least one affected parent	Dominant
More affected males than females	X-linked recessive
Affected father has all affected daughters, no affected sons	X-linked dominant
Unaffected parents have affected child	Recessive (both parents are carriers)
Male-to-male transmission present	Autosomal (NOT X-linked — Y is required for male-to-male)

Section 3: Gene Pools & Speciation (D2.3) HL

Gene Pools and Allele Frequency

A **gene pool** is the total set of all alleles of all genes present in a population at a given time.

Allele frequency is the proportion of a particular allele among all alleles of that gene in the population.

Allele frequency of $A = \frac{\text{number of } A \text{ alleles}}{\text{total number of alleles for that gene in population}}$

Example: In a population of 100 diploid individuals, if 60 carry the A allele out of 200 total alleles: allele frequency of $A = \frac{60}{200} = 0.30$

Hardy-Weinberg Principle (Qualitative)

The Hardy-Weinberg principle states that **allele and genotype frequencies in a population remain constant from generation to generation** in the absence of evolutionary influences.

MEMORISE THIS

Hardy-Weinberg Equilibrium Conditions (MARGE)

A population is in Hardy-Weinberg equilibrium only if **all** of the following conditions are met:

1. **M**ating is random (no sexual selection)
2. **A**llele frequencies are not altered by mutation
3. **R**andom genetic drift is negligible (population is very large)
4. **G**ene flow does not occur (no migration in or out)
5. **E**volution is not occurring (no natural selection)

Real populations virtually never meet all five conditions, so Hardy-Weinberg equilibrium is a theoretical baseline.

IB TIP

IB Requirement for D2.3: The IB 2025 syllabus requires a **qualitative** understanding of Hardy-Weinberg — you should know what the principle states and what conditions are required, but you are not required to perform calculations using the Hardy-Weinberg equations ($p + q = 1$; $p^2 + 2pq + q^2 = 1$) at SL. HL students should be aware of the equations and what each term represents, but the primary exam demand is explaining the conditions and significance.

Speciation

Speciation is the evolutionary process by which new species arise. A **species** is a group of organisms that share common characteristics and can interbreed to produce fertile offspring.

Reproductive isolation is the key mechanism — once populations can no longer exchange genes, they diverge.

Allopatric Speciation

Allopatric speciation occurs when a population is divided by a **geographical barrier** (mountain range, ocean, river), creating two isolated sub-populations.

Process:

1. Original population is split by a geographic barrier.
2. Gene flow between populations ceases.
3. Each sub-population is subject to different selection pressures, mutations, and genetic drift.
4. Over time, allele frequencies diverge.
5. Populations accumulate enough genetic differences that, if brought back together, they can no longer interbreed → reproductive isolation is complete → two species.

Example: Darwin's finches on the Galápagos Islands — ancestral finches colonised different islands; geographical isolation led to divergence in beak morphology and feeding behaviour.

Sympatric Speciation

Sympatric speciation occurs within the **same geographical area** — no physical barrier separates the populations. It is less common in animals but well-documented in plants and insects.

Mechanisms include:

- **Polyploidy** — a sudden multiplication of chromosome sets (common in plants). An allopolyploid organism (with chromosome sets from two different species) cannot reproduce with either parent species → instant speciation.
- **Ecological specialisation** — subpopulations exploit different resources in the same area, reducing gene flow between them (e.g., insects specialising on different host plants).

Example: Many crop plants (wheat, cotton) arose through allopolyploidy.

Feature	Allopatric Speciation	Sympatric Speciation
Geographic barrier	Required	Not required
Gene flow interrupted by	Physical separation	Reproductive/ecological isolation
Common in	Animals and plants	Primarily plants (polyploidy); some insects
Speed	Gradual (thousands of generations)	Can be rapid (polyploidy can be near-instantaneous)

⚠ **EXAM ALERT**

Exam Alert — Speciation Definitions: IB mark schemes award marks for precision. “Allopatric” = geographic isolation. “Sympatric” = same area, no geographic barrier. Simply writing “isolation” without the qualifier will lose marks. Always specify the type of isolation.

Section 4: MCQ Practice (IB Paper 1 Style)

Question 1. Which of the following events occurs during prophase I of meiosis but NOT during prophase of mitosis?

A. Chromosomes condense and become visible.

B. The nuclear envelope breaks down.

C. Homologous chromosomes pair and crossing over occurs.

D. Spindle fibres begin to form.

▶ Reveal answer

Question 2. In a population of rabbits, the allele for brown coat (B) is dominant over the allele for white coat (b). Two brown rabbits are crossed and produce 3 brown offspring and 1 white offspring. What are the genotypes of the parent rabbits?

A. $BB \times BB$

B. $BB \times Bb$

C. $Bb \times Bb$

D. $Bb \times bb$

▶ Reveal answer

Question 3. A woman with type AB blood and a man with type O blood have children. Which of the following blood types is POSSIBLE for their children?

A. Type O

B. Type AB

C. Type A

D. Neither A nor B can be produced

▶ Reveal answer

Question 4. Haemophilia is an X-linked recessive condition. A non-haemophiliac woman whose father had haemophilia marries a non-haemophiliac man. What is the probability that their first son will have haemophilia?

A. 0 (impossible)

B. 1/4

C. 1/2

D. 1 (certain)

▶ Reveal answer

Question 5. Which of the following is NOT a condition required for a population to be in Hardy-Weinberg equilibrium?

A. No migration into or out of the population

B. Random mating within the population

C. Large population size

D. High rate of mutation at the gene locus in question

▶ Reveal answer

Question 6. A new species of plant arose when a hybrid formed between two different species underwent chromosome doubling (polyploidy). This is an example of which type of speciation?

A. Allopatric speciation due to geographic isolation

B. Allopatric speciation due to reproductive isolation

C. Sympatric speciation

D. Adaptive radiation

▶ Reveal answer

Section 5: Exam Strategy

Top Mistakes on D2 Questions

1. **Confusing what separates in meiosis I vs meiosis II.** In meiosis I: homologous chromosomes separate. In meiosis II: sister chromatids separate. A diagram question showing double-stranded chromosomes moving apart = meiosis I. Single-stranded = meiosis II or mitosis.

2. **Forgetting to show all gamete types in a dihybrid cross.** For $AaBb$ parents, there are four gamete types (AB, Ab, aB, ab). Students often write only two gametes. In a 4×4 Punnett square, you must list all four.

3. **Writing "dominant" instead of "codominant" for ABO blood groups.** I^A is not dominant over I^B — they are codominant. Saying "I^A is dominant and I^B is recessive" is factually incorrect.

4. **Confusing incomplete dominance with codominance.** Use the test: can you detect *both* original phenotypes in the heterozygote? If yes (e.g., roan cattle have both red and white hairs) → codominance. If the heterozygote is a blend (e.g., pink snapdragons) → incomplete dominance.

5. **Failing to use notation correctly for X-linked alleles.** Always write X-linked alleles as superscripts on X: X^H and X^h, not simply H or h. The IB mark scheme requires the X to appear in the genotype.

6. **Confusing allopatric and sympatric speciation.** "Allopatric" = geo (geographic) separation. "Sympatric" = same place, reproductive/ecological isolation.

IB TIP

Genetic Cross Method for IB Exams:

Always show your working in four explicit steps:

1. State parental genotypes
2. State gametes for each parent
3. Complete the Punnett square
4. State genotype ratio then phenotype ratio

The IB mark scheme awards marks at each step. Even if your final ratio is wrong due to a counting error, you can earn marks for correctly stating gametes and setting up the Punnett square.

MEMORISE THIS

Fast-Recall Checklist — D2 Key Facts

- Meiosis I separates **homologous chromosomes** ($2n \to n$); Meiosis II separates **sister chromatids** ($n \to n$)
- Crossing over: exchange of DNA between non-sister chromatids of homologous chromosomes at **chiasmata** in **prophase I**
- Independent assortment: random orientation of bivalents at **metaphase I**
- Monohybrid Aa × Aa → 3:1 phenotype ratio
- Dihybrid AaBb × AaBb → 9:3:3:1 phenotype ratio
- ABO: I^A and I^B codominant; i recessive to both
- X-linked recessive: males more commonly affected (hemizygous)
- Testcross: unknown genotype × homozygous recessive
- Hardy-Weinberg: stable allele frequencies require no mutation, random mating, large population, no migration, no selection
- Allopatric speciation: geographic barrier; Sympatric speciation: same area (polyploidy/ecological)

PDF version available at Download PDF