

GENE INTERACTIONS & GENETIC CROSSES

Semi-Dominance • Co-dominance • Test & Back Cross • Multiple Alleles • Epistasis

Modified Dihybrid (Epistatic) Ratios — Quick Reference

9 : 3 : 4	Recessive epistasis Mouse coat colour (C/c masks A/a)
12 : 3 : 1	Dominant epistasis Summer squash fruit colour (W/w masks Y/y)
9 : 7	Duplicate recessive (complementary genes) Flower colour in sweet pea (C_P_ = purple; else white)
15 : 1	Duplicate dominant epistasis Seed capsule shape in shepherd's purse
9 : 6 : 1	Polymeric gene interaction Fruit shape in summer squash (disc : sphere : long)
13 : 3	Inhibitory (dominant) epistasis Feather colour in Leghorn fowl (I masks colour gene C)

Comprehensive Illustrated Study Notes

Genetics & Biology | Extensions and Exceptions to Simple Mendelian Inheritance, with Worked Punnett-Square Examples

Prepared for academic study & examination revision

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1. Introduction

Mendel's laws describe the simplest case of inheritance: one gene, two alleles, complete dominance. Real genetic systems, however, show several important extensions and refinements of these basic rules. This set of notes focuses in depth on five such concepts: **semi-dominance** (incomplete dominance), **co-dominance**, the **test cross and back cross** (the experimental tools used to determine unknown genotypes), **multiple alleles**, and **epistasis** (interaction between different genes). Each is illustrated with a fully worked Punnett-square example.

2. Test Cross and Back Cross

An organism showing a dominant phenotype may be either **homozygous** or **heterozygous** for that gene — the phenotype alone cannot distinguish the two. Test crosses and back crosses are breeding tools designed to reveal the hidden genotype.

2.1 Test Cross

A **test cross** crosses an individual of unknown genotype (showing the dominant phenotype) with a **homozygous recessive** individual. Because the recessive tester contributes only recessive alleles, the phenotypes of the offspring directly reveal which gametes the unknown parent produced — and therefore its genotype.

Monohybrid Test Cross: Tt (unknown, tall) $\times$ tt (recessive tester)

Purpose: find out if a tall plant is TT or Tt

	t	t
T	Tt Tall	Tt Tall
t	tt Dwarf	tt Dwarf

If offspring are ALL tall $\rightarrow$ unknown parent is TT (homozygous)

If offspring are 1 Tall : 1 Dwarf $\rightarrow$ unknown parent is Tt (heterozygous)

Figure 1. A monohybrid test cross ($Tt \times tt$). A 1:1 ratio in the offspring proves the tested parent is heterozygous.

The same logic extends to two genes at once. In a **dihybrid test cross**, an individual of unknown genotype is crossed with a double-recessive tester. If the unknown parent is heterozygous for both genes and the genes assort independently, the offspring appear in an unmistakable **1 : 1 : 1 : 1** ratio.

Dihybrid Test Cross: RrYy (unknown) × rryy (double recessive tester)

The tester (rryy) contributes only ry gametes, so offspring directly reveal the gametes made by the unknown parent

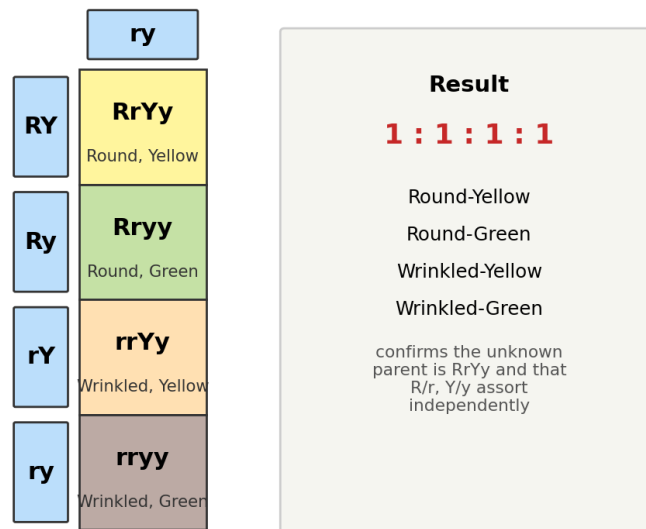


Figure 2. A dihybrid test cross (RrYy × rryy) produces four equally frequent classes, confirming both the genotype of the unknown parent and independent assortment of the two genes.

2.2 Back Cross

A **back cross** is, more broadly, any cross of an F1 hybrid with one of its own parental genotypes — either the dominant (true-breeding) parent or the recessive parent. Back crosses are used in plant and animal breeding to reinforce a desired parental trait in later generations (e.g. recovering a particular variety after an experimental cross).

Back Cross: F1 (Tt) Crossed Back to Either Parent

Back cross to DOMINANT parent

F1 (Tt) × P (TT)

	T	T
T	TT Tall	TT Tall
t	Tt Tall	Tt Tall

Result: ALL offspring tall
(1 TT : 1 Tt — no dwarf plants appear)

Back cross to RECESSIVE parent (= Test Cross)

F1 (Tt) × P (tt)

	t	t
T	Tt Tall	Tt Tall
t	tt Dwarf	tt Dwarf

Result: 1 Tall : 1 Dwarf
(recessive genotype is revealed in the offspring)

A test cross is simply a special case of a back cross — one made specifically to the recessive parent

Figure 3. Back-crossing F1 (Tt) to the dominant parent (TT) yields no visible segregation (all tall); back-crossing to the recessive parent (tt) reproduces the test-cross result (1:1).

A **test cross** is a special case of a back cross — specifically, a back cross made to the **recessive** parent, chosen deliberately because it is the only back cross that can reveal a hidden heterozygous genotype.

Feature	Test Cross	Back Cross (general)
Crossed with	Always the homozygous recessive individual	Either parent (dominant or recessive)
Main purpose	Determine an unknown genotype	Recover/reinforce a parental genotype in breeding
Typical result	1:1 ratio (if heterozygous) or all-dominant (if homozygous)	Depends on which parent is used

3. Semi-Dominance (Incomplete Dominance)

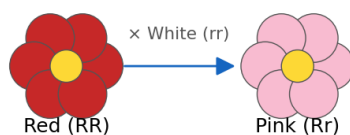
In **semi-dominance**, neither allele of a gene pair is completely dominant over the other. The heterozygote therefore displays a phenotype that is **intermediate** — a blend — between the two homozygous parental phenotypes, rather than resembling one parent exactly.

3.1 Key Features

- The F1 hybrid shows a new, intermediate phenotype not seen in either parent.
- The phenotypic ratio in F2 is identical to the genotypic ratio: **1 : 2 : 1**.
- This is unlike complete dominance, where the F2 phenotypic ratio (3:1) differs from the genotypic ratio (1:2:1), because the heterozygote there looks identical to the homozygous dominant.

Semi-Dominance (Incomplete Dominance) in *Mirabilis jalapa* (4 o'clock plant)

Neither allele fully dominates — the heterozygote shows a blended, intermediate phenotype



F1 self-cross: Rr × Rr

	R	r
R	RR Red	Rr Pink
r	Rr Pink	rr White

Other examples of semi-dominance:

- Andalusian fowl: black × white → blue-grey
- Human hair texture: curly × straight → wavy
- Snapdragon flower colour (red × white → pink)

Key feature

Phenotypic ratio = Genotypic ratio

1 Red : 2 Pink : 1 White
(= 1 RR : 2 Rr : 1 rr)

Figure 4. Semi-dominant inheritance of flower colour in *Mirabilis jalapa*: red (RR) × white (rr) gives an intermediate pink (Rr) F1, and F1 self-cross reproduces 1 Red : 2 Pink : 1 White in F2.

4. Co-dominance

In **co-dominance**, unlike semi-dominance, **both** alleles of a heterozygote are fully and separately expressed at the same time — neither masks nor blends with the other. The heterozygous phenotype shows both parental traits **side by side**, simultaneously.

4.1 The MN Blood Group System

The human MN blood group is controlled by two co-dominant alleles, L^M and L^N , which determine antigens present on red blood cells.

Co-dominance: The Human MN Blood Group System

Both alleles L^M and L^N are expressed fully and simultaneously — there is no blending or masking

Cross: $L^M L^N \times L^M L^N$

	L^M	L^N
L^M	$L^M L^M$ Type M	$L^M L^N$ Type MN
L^N	$L^M L^N$ Type MN	$L^N L^N$ Type N

Genotypic ratio = Phenotypic ratio = 1 $L^M L^M$ (M) : 2 $L^M L^N$ (MN) : 1 $L^N L^N$ (N)

Unlike semi-dominance, the MN heterozygote is a distinct THIRD phenotype (both antigens present on red cells) — not a blend of M and N

Figure 5. L^M and L^N are co-dominant: heterozygotes ($L^M L^N$) express both M and N antigens simultaneously as a distinct "type MN" — not a blended type.

4.2 Multiple Alleles Combined with Co-dominance: ABO Blood Groups

The human ABO blood group system beautifully illustrates **both** multiple alleles and co-dominance acting together in a single gene.

Multiple Alleles + Co-dominance: ABO Blood Group Cross

Parents: Group A ($I^A i$) × Group B ($I^B i$)

	I^B	i
I^A	$I^A I^B$ AB	$I^A i$ A
i	$I^B i$ B	ii O

Offspring phenotype ratio = 1 A : 1 B : 1 AB : 1 O

I^A and I^B are co-dominant with each other; both are dominant over i

This shows how multiple alleles (I^A , I^B , i) and co-dominance can act together in one gene

Figure 6. Cross between a Group A parent ($I^A i$) and a Group B parent ($I^B i$) produces all four ABO phenotypes in equal proportion.

4.3 Semi-Dominance vs Co-dominance — Key Distinction

Feature	Semi-dominance	Co-dominance
Heterozygote phenotype	Blended / intermediate (e.g. pink)	Both traits fully visible together (e.g. roan, MN)
Example	Mirabilis flower colour (red × white → pink)	MN blood group; ABO blood group; roan cattle
F2 phenotypic ratio	1 : 2 : 1 (= genotypic ratio)	1 : 2 : 1 (= genotypic ratio, but middle class is a combined phenotype, not a blend)

5. Multiple Alleles

A gene showing **multiple allelism** exists in more than two allelic forms within a population, even though any single diploid individual can carry only two of them (one on each homologous chromosome). Multiple-allele systems often also show dominance hierarchies or co-dominance relationships among the alleles.

5.1 ABO Blood Group Alleles — Quick Reference

Genotype(s)	Blood Group (Phenotype)
$I^A I^A$ or $I^A i$	A
$I^B I^B$ or $I^B i$	B
$I^A I^B$	AB (co-dominant)
ii	O

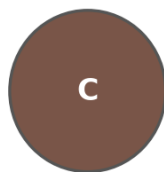
5.2 A Dominance-Hierarchy Example: Rabbit Coat Colour

Not all multiple-allele systems are co-dominant — many show a strict order of dominance. Coat colour in rabbits is controlled by a single gene (C) with **four** known alleles, forming a dominance hierarchy: full colour is dominant over chinchilla, which is dominant over himalayan, which is dominant over albino.

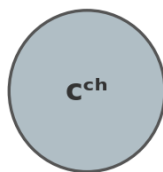
Multiple Alleles: Coat Colour Series in Rabbits

A single gene (C) has FOUR alleles in the population; each rabbit carries only two

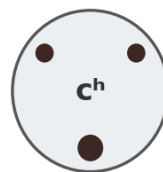
Dominance hierarchy: $C > c^{ch} > c^h > c$



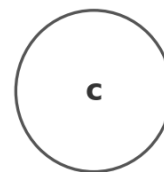
Full colour
(grey/agouti)



Chinchilla
(silver-grey)



Himalayan
(white, dark points)



Albino
(pure white, pink eyes)

Example genotype outcomes:

$Cc^h \rightarrow$ full colour | $c^{ch}c \rightarrow$ chinchilla | $c^hc \rightarrow$ himalayan | $cc \rightarrow$ albino

Figure 7. The C-gene allelic series in rabbits and its dominance hierarchy ($C > c^{ch} > c^h > c$).

6. Epistasis

Epistasis is an interaction **between two different genes**, in which the alleles of one gene mask, modify, or suppress the phenotypic expression of alleles at a completely different gene locus. This is fundamentally different from ordinary dominance, which is an interaction between two alleles of the **same** gene.

Epistasis modifies the classic dihybrid 9:3:3:1 ratio into other characteristic ratios, because two or more of the four dihybrid phenotypic classes end up looking identical to each other.

6.1 Recessive Epistasis (9 : 3 : 4)

Here, being homozygous recessive at one gene ("epistatic gene") completely masks the phenotype of the other ("hypostatic") gene. Example: mouse coat colour, where gene C/c controls whether any pigment is made at all, and gene A/a (expressed only when C is present) determines agouti vs black pigment pattern.

Recessive Epistasis (9 : 3 : 4) — Coat Colour in Mice

Gene C/c (pigment / albino) is epistatic to gene A/a (agouti / black) — "cc" masks the A gene entirely

Cross: AaCc (agouti) × AaCc (agouti)

	AC	Ac	aC	ac
AC	AACC Agouti	AACc Agouti	AaCC Agouti	AaCc Agouti
Ac	AACc Agouti	AAcc Albino	AaCc Agouti	Aacc Albino
aC	AaCC Agouti	AaCc Agouti	aaCC Black	aaCc Black
ac	AaCc Agouti	Aacc Albino	aaCc Black	aacc Albino

Agouti (9)
 Black (3)
 Albino (4)

Phenotypic ratio 9 Agouti : 3 Black : 4 Albino

Figure 8. In mice, cc individuals are albino regardless of their A/a genotype, converting the usual 9:3:3:1 ratio into 9 Agouti : 3 Black : 4 Albino.

6.2 Dominant Epistasis (12 : 3 : 1)

Here, a single **dominant** allele at one gene is enough to mask the other gene's expression. Example: fruit colour in summer squash, where a dominant inhibitor allele W produces white fruit regardless of the Y/y genotype; only ww plants show yellow or green colour.

Dominant Epistasis (12 : 3 : 1) — Fruit Colour in Summer Squash

Gene W/w (white pigment inhibitor) is epistatic to gene Y/y (yellow/green pigment) — a single dominant "W" masks colour entirely

Cross: WwYy (white) × WwYy (white)

	WY	Wy	wY	wy
WY	WWYY White	WWYy White	WwYY White	WwYy White
Wy	WWYy White	WWyy White	WwYy White	Wwyy White
wY	WwYY White	WwYy White	wwYY Yellow	wwYy Yellow
wy	WwYy White	Wwyy White	wwYy Yellow	wwyy Green

White (12)
 Yellow (3)
 Green (1)

Phenotypic ratio 12 White : 3 Yellow : 1 Green

Figure 9. Any genotype carrying at least one dominant W allele is white, giving 12 White : 3 Yellow : 1 Green instead of 9:3:3:1.

6.3 Other Epistatic Ratios

Several other characteristic modified ratios arise from different types of gene interaction, summarised below.

Modified Dihybrid (Epistatic) Ratios — Quick Reference

9 : 3 : 4	Recessive epistasis Mouse coat colour (C/c masks A/a)
12 : 3 : 1	Dominant epistasis Summer squash fruit colour (W/w masks Y/y)
9 : 7	Duplicate recessive (complementary genes) Flower colour in sweet pea (C_P_ = purple; else white)
15 : 1	Duplicate dominant epistasis Seed capsule shape in shepherd's purse
9 : 6 : 1	Polymeric gene interaction Fruit shape in summer squash (disc : sphere : long)
13 : 3	Inhibitory (dominant) epistasis Feather colour in Leghorn fowl (I masks colour gene C)

Figure 10. The complete family of modified dihybrid (epistatic) ratios and a representative example for each.

Ratio	Type	Mechanism (brief)
9 : 3 : 4	Recessive epistasis	Homozygous recessive at gene 1 masks gene 2 entirely
12 : 3 : 1	Dominant epistasis	One dominant allele at gene 1 masks gene 2 entirely
9 : 7	Duplicate recessive (complementary genes)	Dominant allele needed at BOTH genes to show the trait; either alone recessive gives the alternate phenotype
15 : 1	Duplicate dominant epistasis	A dominant allele at EITHER gene alone is sufficient to produce the same phenotype
9 : 6 : 1	Polymeric gene interaction	Two genes contribute additively/cumulatively to the phenotype
13 : 3	Inhibitory (dominant) epistasis	A dominant inhibitor allele at gene 1 suppresses expression of gene 2's dominant allele only

7. Master Comparison Table

Concept	Number of genes involved	Defining feature
Complete dominance	1	Heterozygote looks identical to homozygous dominant
Semi-dominance	1	Heterozygote shows a blended, intermediate phenotype
Co-dominance	1	Heterozygote shows both alleles' effects simultaneously, unblended
Multiple alleles	1 (with more than 2 alleles in the population)	More than two allelic forms exist; hierarchy or co-dominance among them

Concept	Number of genes involved	Defining feature
Epistasis	2 or more	One gene's alleles mask/modify another gene's phenotype

8. Key Takeaways

- A **test cross** (unknown dominant phenotype × homozygous recessive) reveals whether the tested individual is homozygous or heterozygous; a **back cross** is the broader category that also includes crossing F1 back to the dominant parent.
- **Semi-dominance** produces a genuinely new, blended phenotype in heterozygotes, with phenotypic ratio = genotypic ratio (1:2:1).
- **Co-dominance** shows both parental phenotypes together, unblended, in the heterozygote (e.g. MN blood group, roan cattle, AB blood group).
- **Multiple alleles** means more than two versions of a gene exist in a population, though each individual carries only two (e.g. ABO blood groups; rabbit coat colour series).
- **Epistasis** is a gene-gene interaction (not allele-allele) that modifies the classic 9:3:3:1 dihybrid ratio into ratios such as 9:3:4, 12:3:1, 9:7, 15:1, 9:6:1, or 13:3.

9. Practice Questions for Revision

A. Short Answer Questions

Q1. Differentiate between semi-dominance and co-dominance.

Ans: In semi-dominance the heterozygote shows a blended, intermediate phenotype (e.g. pink from red × white). In co-dominance the heterozygote shows both parental phenotypes fully and separately, without blending (e.g. roan cattle, MN blood group).

Q2. Why is a test cross always performed with a homozygous recessive individual, and not a heterozygous one?

Ans: Because a homozygous recessive individual contributes only recessive alleles to every offspring, the offspring's phenotype directly reflects the allele contributed by the unknown parent — giving an unambiguous result. A heterozygous tester would itself contribute a mix of alleles, confusing the interpretation.

Q3. What result would a dihybrid test cross ($RrYy \times rryy$) give if the two genes were linked rather than independently assorting?

Ans: Instead of the expected 1:1:1:1 ratio, the parental-type combinations ($RrYy$ and $rryy$ -type gametes) would appear in excess over the recombinant classes ($Rryy$ -type and rYy -type), since linked genes are inherited together more often than not.

Q4. Define multiple alleles with an example.

Ans: Multiple alleles occur when a single gene exists in more than two allelic forms in a population, although each individual carries only two. Example: the ABO blood group gene, with alleles I^A , I^B , and i .

Q5. How does epistasis differ from simple dominance?

Ans: Dominance is an interaction between two alleles of the SAME gene. Epistasis is an interaction between alleles of TWO DIFFERENT genes, where one gene's genotype affects whether or how another gene's phenotype is expressed.

Q6. A cross between two agouti mice ($AaCc \times AaCc$) gives 9 agouti : 3 black : 4 albino instead of 9:3:3:1. What type of gene interaction does this indicate?

Ans: Recessive epistasis: the C gene (pigment/albino) is epistatic to the A gene (agouti/black); ' cc ' individuals are albino regardless of genotype at the A locus, combining what would be two separate 3-part classes into one 4-part albino class.

Q7. What blood groups are possible among children of an $I^A i$ (Group A) mother and an $I^B i$ (Group B) father?

Ans: All four blood groups are possible: $A (I^A i)$, $B (I^B i)$, $AB (I^A I^B)$, and $O (ii)$, each with probability $1/4$.

B. Numerical / Punnett Square Problems

- A pink-flowered snapdragon (Rr) is test-crossed with a white-flowered plant (rr). What phenotypic ratio is expected in the offspring? (Answer: 1 Pink : 1 White.)
- In the rabbit coat-colour series ($C > c^{ch} > c^h > c$), what is the phenotype of a rabbit with genotype $c^{ch}c^h$? (Answer: Chinchilla, since c^{ch} is dominant over c^h .)

- In summer squash, a white-fruited plant ($WwYy$) is crossed with a green-fruited plant ($wwyy$). What phenotypic ratio is expected in the offspring? (Answer: the $WwYy$ parent makes four equally likely gametes — WY , Wy , wY , wy — while the $wwyy$ parent contributes only wy ; the resulting offspring are $WwYy$ (white), $Wwyy$ (white), $wwYy$ (yellow), and $wwyy$ (green), each $1/4$, giving 2 White : 1 Yellow : 1 Green.)
- Two roan cattle ($R^R R^W$) are crossed. What phenotypic ratio is expected among the offspring? (Answer: 1 Red ($R^R R^R$) : 2 Roan ($R^R R^W$) : 1 White ($R^W R^W$.)

C. Multiple Choice Questions

1. A test cross is performed between an organism of unknown genotype and one that is:
(a) Heterozygous (b) Homozygous dominant (c) Homozygous recessive (d) Also of unknown genotype
2. Roan coat colour in cattle is an example of:
(a) Semi-dominance (b) Co-dominance (c) Epistasis (d) Multiple alleles only
3. The 9:3:4 ratio results from which type of gene interaction?
(a) Dominant epistasis (b) Recessive epistasis (c) Duplicate recessive epistasis (d) Polymeric interaction
4. Which of the following best describes multiple alleles?
(a) Two genes affecting one trait (b) More than two allelic forms of one gene in a population (c) Two alleles blending in the heterozygote (d) A gene with only dominant alleles
5. A back cross to the dominant parent ($Tt \times TT$) is expected to produce:
(a) A 3:1 ratio (b) A 1:1 ratio (c) All dominant-phenotype offspring (d) All recessive-phenotype offspring
6. In the ABO blood group system, I^A and I^B alleles are:
(a) Both recessive to i (b) Co-dominant with each other (c) Incompletely dominant (d) Epistatic to i

Answer key: 1-c 2-b 3-b 4-b 5-c 6-b