

MULTIPLE ALLELES & SEX-RELATED INHERITANCE

ABO Blood Groups • Sex-Linked Inheritance • the White-Eye Locus • Sex-Influenced Genes

Sex-Linked vs Sex-Influenced vs Sex-Limited Traits

Sex-linked	Gene located ON a sex chromosome (usually X) <i>Examples: Colour blindness, haemophilia, Drosophila eye colour</i>
Sex-influenced	Gene is AUTOSOMAL, but dominance depends on sex hormones <i>Examples: Pattern baldness in humans, horns in sheep</i>
Sex-limited	Gene is AUTOSOMAL and present in both sexes, but expressed in only ONE sex <i>Examples: Milk yield (cattle), beard growth, egg production</i>

Comprehensive Illustrated Study Notes

Genetics & Biology | Multiple Allelism, Chromosomal Sex Determination, X-linked Inheritance, and Hormone-Dependent Gene Expression

Prepared for academic study & examination revision

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1. Introduction

This set of notes covers four related but distinct genetics concepts. The **ABO blood group system** is the classic textbook example of **multiple alleles** combined with co-dominance. **Sex-linked inheritance** describes genes carried on the sex chromosomes themselves, producing inheritance patterns that differ between males and females. The **white-eye locus** in the fruit fly *Drosophila melanogaster* is the historic case study that first proved genes are physically located on chromosomes. Finally, **sex-influenced inheritance** describes ordinary autosomal genes whose dominance is altered by an individual's sex hormones — a related but fundamentally different phenomenon from sex-linkage.

2. Multiple Alleles: The ABO Blood Group System

A gene showing **multiple allelism** exists in more than two allelic forms within a population, even though any one diploid individual carries only two of them. The human ABO blood group gene (*I*) is the most widely taught example, with three alleles: I^A , I^B , and *i*.

Multiple Alleles: The Human ABO Blood Group System

Three alleles in the population — I^A , I^B , *i* — but each person carries only two

Dominance: $I^A = I^B$ (co-dominant with each other) > *i* (recessive to both)

Genotype(s)	Blood Group	Antigen on RBC	Antibody in Plasma
$I^A I^A$ or $I^A i$	A	A	Anti-B
$I^B I^B$ or $I^B i$	B	B	Anti-A
$I^A I^B$	AB	A and B	None
<i>i i</i>	O	None	Anti-A and Anti-B

Group O is the "universal donor" (no antigens); Group AB is the "universal recipient" (no antibodies)

Figure 1. The ABO gene: dominance relationships, and the antigen/antibody profile associated with each blood group.

I^A and I^B are **co-dominant** with each other (both are expressed together when both are present), while *i* is recessive to both.

2.1 Worked Cross Example

ABO Cross Example: 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

Note: a Group AB or Group O child from Group A × Group B parents is a classic exam trap — both are perfectly possible whenever both parents are heterozygous (carriers of i)

Figure 2. A cross between heterozygous Group A ($I^A i$) and Group B ($I^B i$) parents can produce children of all four blood groups.

2.2 The Bombay Phenotype — an Important Exception

A rare exception, the **Bombay phenotype** (genotype hh at a separate, second gene), prevents the H-antigen precursor from being made at all — so even a person who inherits I^A or I^B tests as blood group O, because the A and B antigens cannot be built without the H substrate. This is a classic example of **epistasis** acting on the ABO system from a completely separate gene locus.

3. Sex-Linked Inheritance

Sex-linked genes are genes carried on the sex chromosomes themselves (in humans, usually the X chromosome), rather than on one of the 22 pairs of autosomes. Because males (XY) and females (XX) carry different numbers of the X chromosome, sex-linked inheritance produces characteristic patterns that differ between the sexes.

3.1 Sex Determination — the Foundation

Sex Determination in Humans (XX-XY System)

Mother (XX) can only contribute an X; Father (XY) contributes an X or a Y

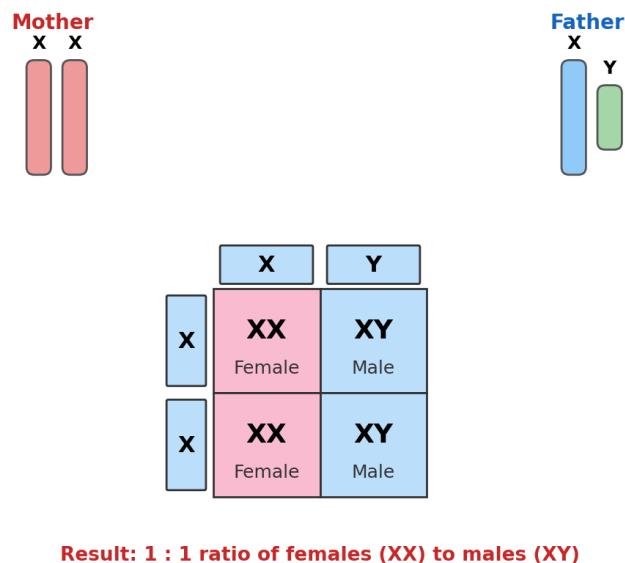


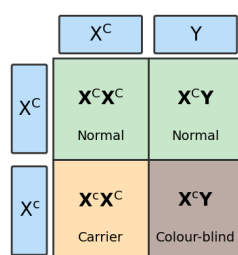
Figure 3. Human sex is determined by which sperm fertilises the egg: an X-bearing sperm produces a daughter, a Y-bearing sperm a son.

3.2 X-linked Recessive Inheritance — the Criss-Cross Pattern

A male has only **one** X chromosome (he is **hemizygous** for X-linked genes), so a single copy of a recessive X-linked allele is enough to produce the trait in him — he cannot be a silent "carrier" the way a female can. This asymmetry produces the distinctive **criss-cross** inheritance pattern.

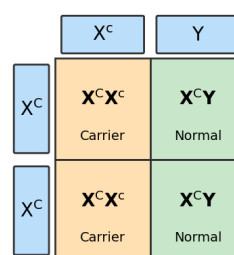
X-linked Recessive Inheritance — the "Criss-Cross" Pattern (e.g. Red-Green Colour Blindness)

Cross A: Carrier mother × Normal father
($X^C X^c$) × ($X^C Y$)



Result: 1/2 of SONS affected;
daughters normal but 1/2 carriers

Cross B: Affected father × Normal mother
($X^c Y$) × ($X^C X^C$)



Result: ALL daughters carriers
(never affected); ALL sons normal

Criss-cross inheritance: an X-linked recessive allele passes from an affected father to his daughters (as carriers), and from a carrier mother to her affected sons — never father to son

Figure 4. X-linked recessive inheritance (e.g. red-green colour blindness). Note how the trait passes from carrier mother to affected son (Cross A), and from affected father to carrier daughter but never to sons (Cross B).

3.3 Common X-linked Traits in Humans

Condition	Inheritance	Notes
Red-green colour blindness	X-linked recessive	Much more common in males
Haemophilia A / B	X-linked recessive	Clotting factor deficiency; famously traced through European royal pedigrees
Duchenne muscular dystrophy	X-linked recessive	Progressive muscle degeneration, almost exclusively affects males
G6PD deficiency	X-linked recessive	Causes sensitivity to certain drugs/foods (e.g. fava beans)
Hypophosphatemic rickets	X-linked dominant	One of the few X-linked DOMINANT conditions; affects both sexes, but more severely in males

3.4 X-linked Dominant and Y-linked (Holandric) Inheritance

- In **X-linked dominant** inheritance, a single copy of the dominant allele is enough to produce the trait in either sex; affected fathers pass the trait to ALL their daughters (never their sons), while affected heterozygous mothers pass it to half of all children of either sex.
- **Y-linked (holandric)** genes are carried only on the Y chromosome and are therefore passed directly from father to **every** son, and never to daughters. Very few genes are known to be purely Y-linked (mostly genes involved in male sex determination and sperm production, such as the SRY gene).

4. Case Study: The White-Eye Locus in Drosophila

In 1910, **Thomas Hunt Morgan**, working with the fruit fly *Drosophila melanogaster*, discovered a single white-eyed male fly in an otherwise red-eyed laboratory population. By breeding this fly and analysing the inheritance pattern of eye colour across generations, Morgan provided the **first direct experimental proof** that a specific gene is carried on a specific chromosome — confirming the Chromosomal Theory of Inheritance proposed by Sutton and Boveri just a few years earlier.

The White-Eye Locus in *Drosophila* — Morgan's Proof of the Chromosomal Theory (1910)

White eye colour (*w*) is recessive to red (*W*) and located on the X chromosome

Original cross: Red ♀ (*WW*) × White ♂ (*wY*)

F1: *Ww* (♀, red) × *WY* (♂, red) — all F1 are RED

	w	Y
W	Ww Red	WY Red
W	Ww Red	WY Red

Reciprocal cross: White ♀ (*ww*) × Red ♂ (*WY*)

F1 immediately splits by sex:

	W	Y
w	wW Red	wY White
w	wW Red	wY White

F1 self-cross (*Ww* × *WY*) → F2:

	W	Y
W	WW Red	WY Red
w	wW Red	wY White

F2 result: white eyes appear ONLY in males (1/4 of all flies)

F1 result

ALL daughters: red (*Ww*, carriers)

ALL sons: white (*wY*)

— completely different from the original cross's F1!

Why this mattered

The two reciprocal crosses gave DIFFERENT results depending on which parent carried the allele — proving the white-eye gene travels with the X chromosome. First direct proof that genes are located on chromosomes.

Figure 5. Morgan's original and reciprocal crosses. The fact that the two reciprocal crosses gave completely different results was the key evidence that the white-eye gene travels with the X chromosome.

4.1 Why the Reciprocal Cross Was the Critical Experiment

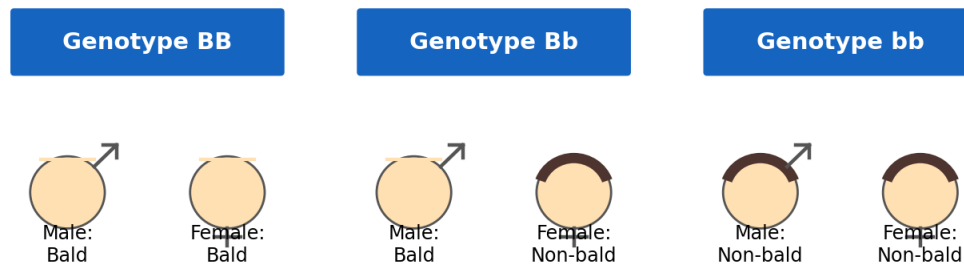
For an ordinary autosomal gene, it does not matter which parent contributes which allele — reciprocal crosses (swapping which parent shows which trait) give identical results. Morgan found that his two reciprocal white-eye crosses gave **strikingly different** results depending on whether the mother or the father was white-eyed. This sex-dependent asymmetry could only be explained if the gene for eye colour resided on the X chromosome — a landmark result that helped found the field of chromosomal genetics.

5. Sex-Influenced Inheritance

Sex-influenced genes are **autosomal** (not located on a sex chromosome), but their pattern of dominance is altered by the sex hormones of the individual carrying them. The same heterozygous genotype can therefore produce different phenotypes in males and females.

Sex-Influenced Inheritance: Pattern Baldness in Humans

Same autosomal genotype, different phenotype in males vs females (hormone-dependent dominance)



Key point

The Bb heterozygote is the deciding case: the SAME genotype behaves as functionally "dominant" in males (bald) but functionally "recessive" in females (non-bald), because the allele's expression depends on the level of testosterone present.

The gene itself is AUTOSOMAL, not sex-linked — only its expression is sex-influenced.

Figure 6. Pattern baldness in humans: the heterozygous genotype (Bb) is expressed as bald in men but non-bald in women, because the allele's dominance depends on testosterone levels.

5.1 Another Example: Horn Presence in Sheep

In certain sheep breeds, the gene for horns behaves similarly: the heterozygous genotype produces horns in rams (males) but not in ewes (females), again because of differing hormone environments — exactly the same underlying logic as human pattern baldness.

6. Sex-Linked vs Sex-Influenced vs Sex-Limited Traits

These three terms are frequently confused with one another because all three involve a connection between a trait and biological sex — but the underlying mechanism is different in each case.

Sex-Linked vs Sex-Influenced vs Sex-Limited Traits

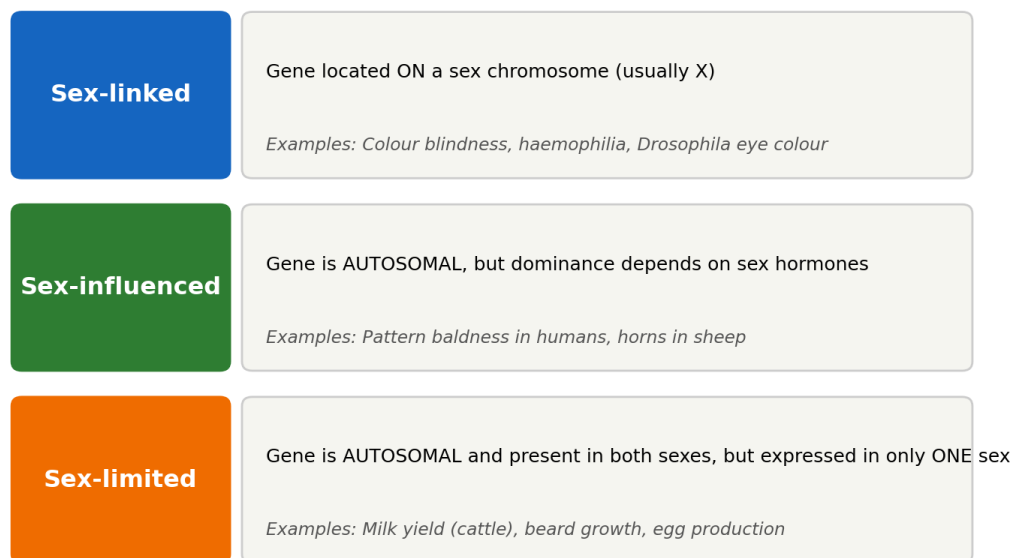


Figure 7. The key distinguishing feature of each category is WHERE the gene is located, not merely whether the trait differs between the sexes.

Feature	Sex-linked	Sex-influenced	Sex-limited
Gene location	On a sex chromosome	Autosomal	Autosomal
Expressed in	Depends on genotype + which sex chromosomes are present	Both sexes, but with different dominance	Only ONE sex, though the gene is present in both
Example	Colour blindness, Drosophila eye colour	Pattern baldness, horns in sheep	Milk yield, beard growth, egg production

7. Key Takeaways

- The ABO blood group gene has **three alleles** (I^A , I^B , i); I^A and I^B are co-dominant, and both are dominant over i .
- Sex-linked** genes are physically located on a sex chromosome; because males are hemizygous for the X, X-linked recessive traits appear far more often in males and show a characteristic **criss-cross** inheritance pattern.
- Morgan's **white-eye locus** experiments in Drosophila (1910) gave the first direct proof that genes reside on chromosomes, by showing that reciprocal crosses give different results for an X-linked gene.
- Sex-influenced** genes are ordinary autosomal genes whose dominance relationship changes depending on the sex hormones of the carrier (e.g. pattern baldness).
- Do not confuse sex-linked, sex-influenced, and **sex-limited** traits — the key question is always WHERE the gene is located, not simply whether the trait differs by sex.

8. Practice Questions for Revision

A. Short Answer Questions

Q1. Why can a man never be a symptomless "carrier" of an X-linked recessive condition the way a woman can?

Ans: *Because a man has only one X chromosome (he is hemizygous), a single copy of a recessive X-linked allele is always expressed — there is no second X allele to mask it, as there is in a heterozygous female.*

Q2. Why was Morgan's reciprocal cross with white-eyed flies so significant?

Ans: *Because the two reciprocal crosses (red female × white male, vs white female × red male) gave completely different results, which could only be explained if the eye-colour gene was carried on the X chromosome — providing the first direct proof that genes are located on chromosomes.*

Q3. A Group A mother (heterozygous) and a Group O father have a child. What blood groups are possible for the child?

Ans: *Group A or Group O only, each with probability 1/2 — the father can only contribute the i allele, and the mother contributes either I^A or i.*

Q4. Explain why pattern baldness is described as "sex-influenced" rather than "sex-linked."

Ans: *Because the gene for pattern baldness is located on an autosome (not a sex chromosome) — it is present and can be inherited by both sexes equally. What differs between the sexes is the DOMINANCE of the heterozygous genotype, which depends on testosterone levels, not the chromosomal location of the gene.*

Q5. A colour-blind man and a homozygous normal woman have children. What are the possible phenotypes of their sons and daughters?

Ans: *All sons will be normal (they receive their only X from the mother, who carries only the normal allele). All daughters will have normal vision but will be carriers (heterozygous), having received the affected X from their father.*

Q6. What is the Bombay phenotype, and what does it illustrate about the ABO gene?

Ans: *The Bombay phenotype occurs when a separate gene (H/h) is homozygous recessive (hh), preventing the antigen precursor substance from forming — so even a person carrying I^A or I^B tests as blood group O. It illustrates epistasis: a completely different gene can mask the expression of the ABO gene.*

B. Numerical / Punnett Square Problems

- A carrier mother for haemophilia (X^HX^h) and a normal father (X^HY) have children. What fraction of their SONS are expected to have haemophilia? (Answer: 1/2 — daughters are unaffected, but half are carriers.)
- Two parents, both Group AB, have children. What blood groups are possible among the children, and in what ratio? (Answer: 1 A (I^AI^A) : 2 AB (I^AI^B) : 1 B (I^BI^B) — Group O is impossible from two AB parents.)
- A heterozygous (Bb) man and a heterozygous (Bb) woman have a son and a daughter. What is the probability the son is bald? What is the probability the daughter is bald? (Answer: the son has a 3/4 chance of being bald (BB or Bb both bald in males); the daughter has only a 1/4 chance of being bald (only BB is bald in females).)

C. Multiple Choice Questions

1. A father with haemophilia (X-linked recessive) cannot pass the allele to:
(a) Any of his children (b) His sons (c) His daughters (d) Either sons or daughters
2. The white-eye locus in *Drosophila* is located on the:
(a) Y chromosome (b) An autosome (c) The X chromosome (d) Mitochondrial DNA
3. Which blood group is considered the "universal recipient"?
(a) O (b) A (c) B (d) AB
4. Pattern baldness in humans is best classified as:
(a) Sex-linked recessive (b) Sex-linked dominant (c) Sex-influenced autosomal (d) Y-linked (holandric)
5. A trait present in both sexes' genomes but expressed in only one sex (e.g. milk yield) is called:
(a) Sex-linked (b) Sex-influenced (c) Sex-limited (d) Holandric
6. I^A and I^B alleles of the ABO gene show what relationship to each other?
(a) Complete dominance (b) Incomplete dominance (c) Co-dominance (d) Epistasis

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

— End of Notes —