A. DIHYBRID CROSSES

- Involve **two** different genes.
- Gregor Mendel studied two characteristics in **pea plants**, controlled by **unlinked** genes.

In pea plants, **seed colour** and **seed type** are controlled by genes.

Yellow seeds are dominant to green seeds.
Smooth seeds are dominant to wrinkled seeds.

A **pure breeding** plant with **yellow, wrinkled** seeds was mated with a **pure breeding** plant with **green, wrinkled** seeds. The **offspring from this cross were then mated**.

Use a genetic diagram to show the phenotypic ratio of offspring produced from the second cross.

First Cross:

Y = Yellow   S = Smooth
y = green   s = wrinkled

Define the alleles

Parental phenotypes: Smooth Yellow x green wrinkled

Parental genotypes: (SSYY) (ssyy)

Gametes

	SY
sy	SsYy

F1 Offspring genotype

Second Cross:

Parental phenotypes: Smooth Yellow x green wrinkled

Parental genotypes: (SsYy) (SsYy)

Gametes

	SY	**Sy**	**sY**	**sy**
SY	SSYY	SSYy	SsYY	SsYy
Sy	SSYy	SSyy	SsYy	Ssyy
sY	SsYY	SsYy	ssYY	ssYy
sy	SsYy	Ssyy	ssYy	ssyy

F2 Offspring genotypes

Phenotypic ratio of offspring =

9 Smooth Yellow : 3 Smooth green : 3 wrinkled Yellow : 1 wrinkled green

Two things to note

- A **9:3:3:1 ratio** is only obtained if the two parents are double heterozygotes (SsYy) and the two genes are on different chromosomes.
- A parent, who is a double heterozygote (SsYy) can produce four different types of gamete: SY, Sy, sY and sy. This is because of the law of independent assortment:

B. MENDEL'S LAW OF SEGREGATION (ONE GENE)

Individual's Genotype	Gametes That Can Be Produced
Aa	**A** and **a**

The two alleles of a gene separate (segregate) into different haploid gametes during meiosis

C. MENDEL'S LAW OF INDEPENDENT ASSORTMENT (MORE THAN ONE GENE)

Individual's Genotype	Gametes That Can Be Produced
AaBb	**AB, Ab, aB** and **ab**

Any allele of one gene can combine with any allele of another gene in a gamete during meiosis

- **two genes** are **inherited independently** of one another
- this is seen in **genes** that are **not linked**
- due to **homologous chromosomes aligning randomly** on the **equator** during **metaphase I**

D. EPISTASIS

- When **one gene affects the expression** of **another gene**.

Two genes in mice control coat colour.
C = allows coat to be coloured; c = white coat (albino)
A = grey coat (agouti); a = black coat

- Gene **A** can only be expressed if a mouse carries the dominant allele **C**.
- Consider crossing two grey mice as shown below:

Grey **x** **Grey**

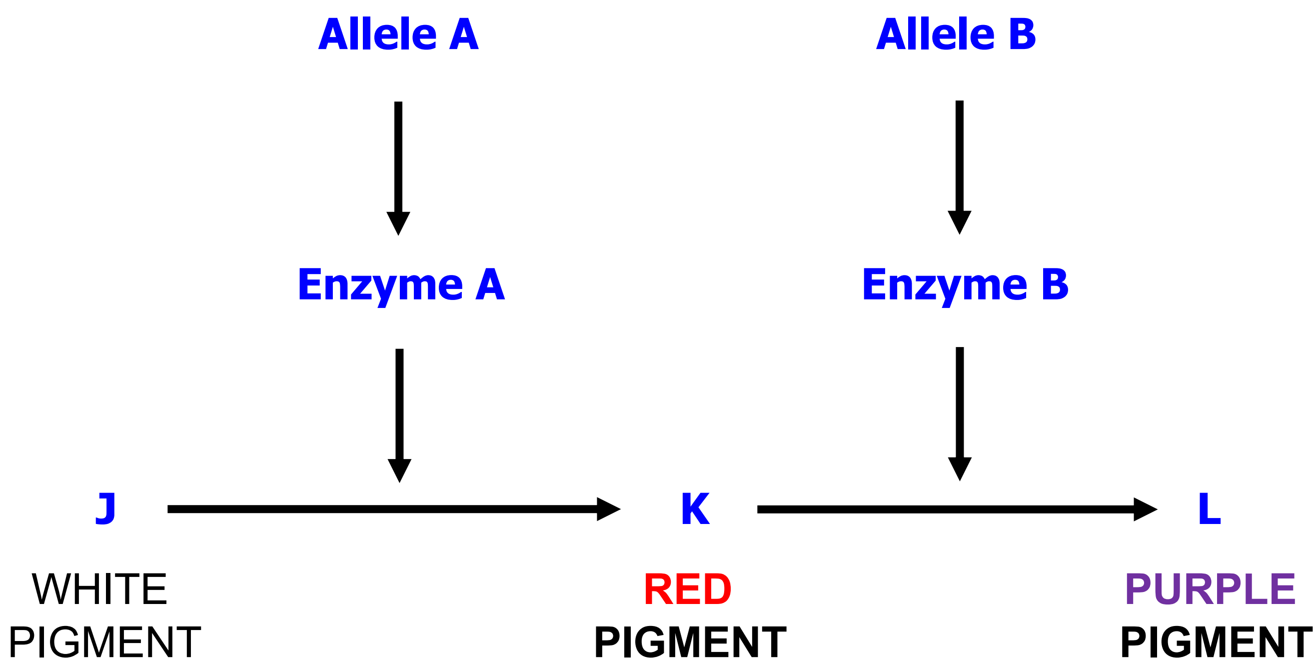
(CcAa) **(CcAa)**

	CA	Ca	cA	ca
CA	CCAA	CCAa	CcAA	CcAa
Ca	CCAa	CCaa	CcAa	Ccaa
cA	CcAA	CcAa	ccAA	ccAa
ca	CcAa	Ccaa	ccAa	ccaa

- **Expected** phenotypic ratio = **9 : 3 : 3 : 1** (if two double heterozygotes are crossed)
- **Actual** phenotypic ratio = **9 grey : 3 black : 4 albino** (because of **epistasis**)

Why Does This Happen?

- It is to do with **having**, or **lacking**, the **correct alleles** to produce the **correct enzymes** for **biochemical pathways**.
- Consider **two genes** that control **flower colour** in a species of flowering plant:



Genotype	Phenotype	Reason
aaBB	White	**Cannot** make **Enzyme A** **Cannot** convert J→K
Aabb	**Red**	**Can** make **Enzyme A** **Can** convert J→K **Cannot** make **Enzyme B** **Cannot** convert K→L
AaBb	**Purple**	**Can** make **Enzyme A** **Can** convert J→K **Can** make **Enzyme B** **Can** convert K→L

E. GENE LINKAGE

- When two genes are located on the same chromosome, they are said to be linked.
- They do not follow the law of independent assortment (segregation).
- This means that the phenotypic ratio of offspring will be different to that expected for unlinked genes.

In guinea pigs, the genes for **hair length** and **coat colour** are **linked**:

- Short hair (H) is dominant to long hair (h)
- Black fur is dominant (B) to white fur (b)

A guinea pig is heterozygous for both genes but its father had long, white fur.

This guinea pig is mated with a guinea pig with long, white fur.

What is the phenotypic ratio of the offspring produced?

H = Short hair   B = Black
h = long hair   b = white

Define the alleles

Parental phenotypes: Heterozygous for both genes x long, white

Parental genotypes:

Heterozygous for both genes		long, white
H —— B h —— b	x	h —— b h —— b

Alleles **cannot assort independently** as they are **on the same chromosome**

Bars are used to represent chromosomes on which genes are linked

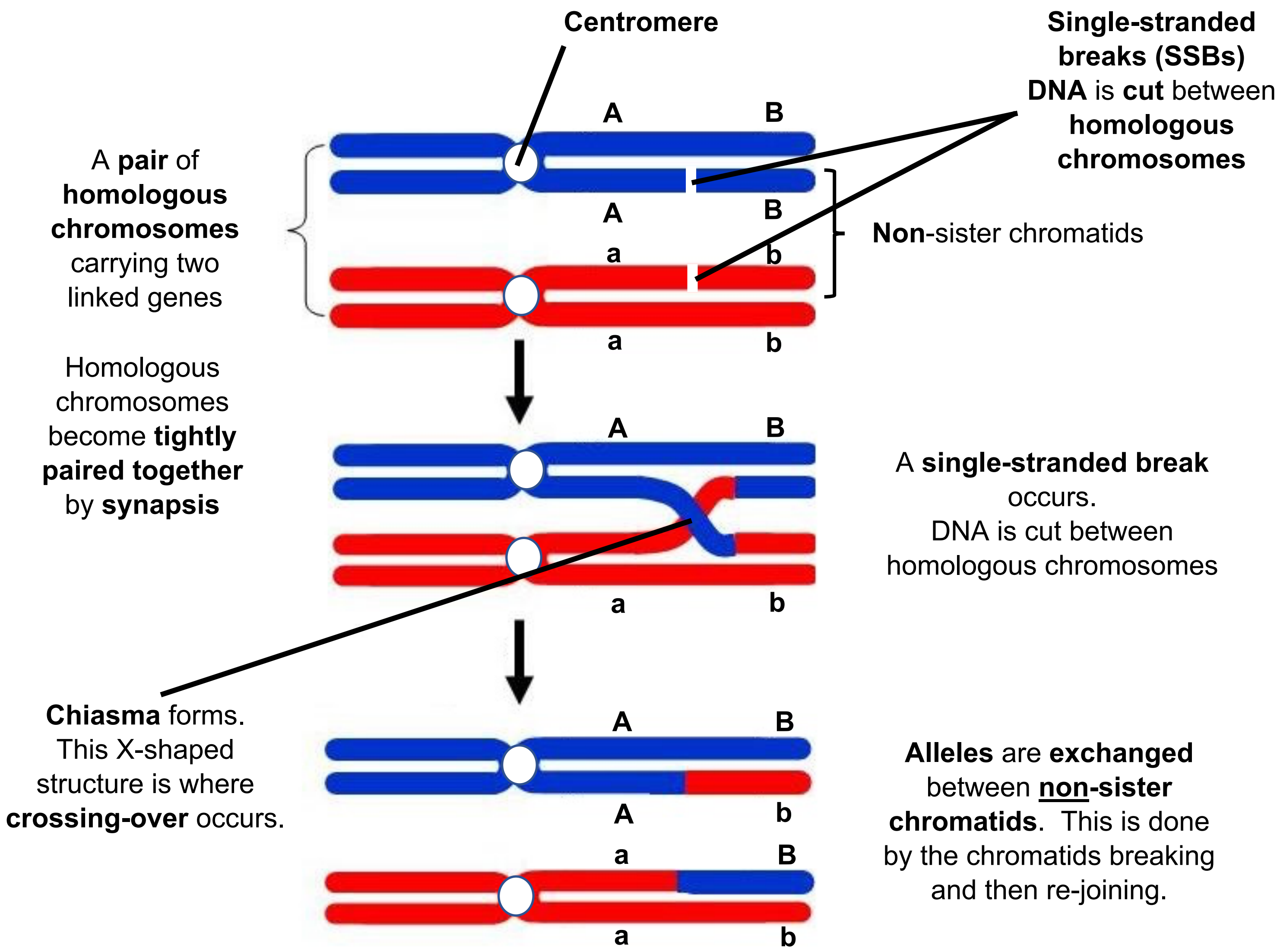
Gametes

	H —— B	h —— b
h —— b	H —— B h —— b	h —— b h —— b

Offspring genotypes

Phenotypic ratio of offspring = <u>1 Short Black : 1 long white</u>

F. CROSSING OVER IN PROPHASE I



- **Crossing over increases the number of genetically different gametes that are possible.**
- **Without crossing over**, only **AB** and **ab** normal gametes could be produced.
- **Crossing-over** has made it possible to **also** produce **Ab** and **aB** gametes.
- **Ab** and **aB gametes** are known as **recombinant gametes** as they have been produced by **crossing-over**.
- **Crossing over** is a **rare** event.
- For this reason, the **normal gametes** (**AB** and **ab**) are produced in a **much higher number** than the **recombinant gametes** (**Ab** and **aB**).
- The **greater the distance between the two linked genes**,
  the **greater the chance of crossing over** and
  the **greater the proportion of recombinant gametes**

G. GENE LINKAGE AND RECOMBINANTS

Recombinant gametes are produced due to **crossing-over**

Recombinant offspring **phenotypes** are those that **neither parent** has

- The best way to understand this is with the example from earlier, where there was **no crossing over**:

H = Short hair
h = long hair

B = Black
b = white

Define the alleles

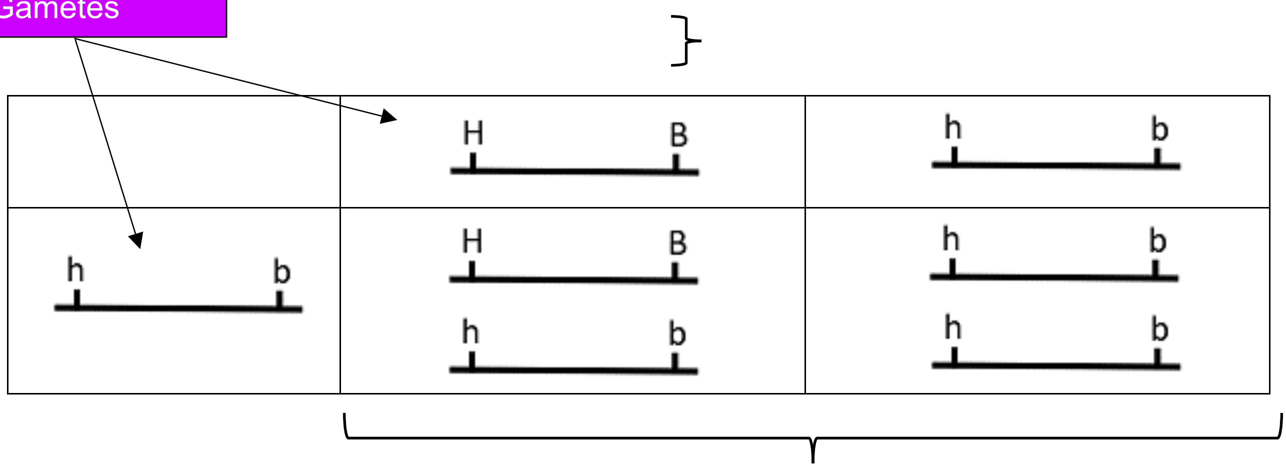
Parental phenotypes: Heterozygous for both genes x long, white

Parental genotypes:

Alleles **cannot assort independently** as they are **on the same chromosome**

Bars are used to represent chromosomes on which genes are linked

Gametes



Offspring genotypes

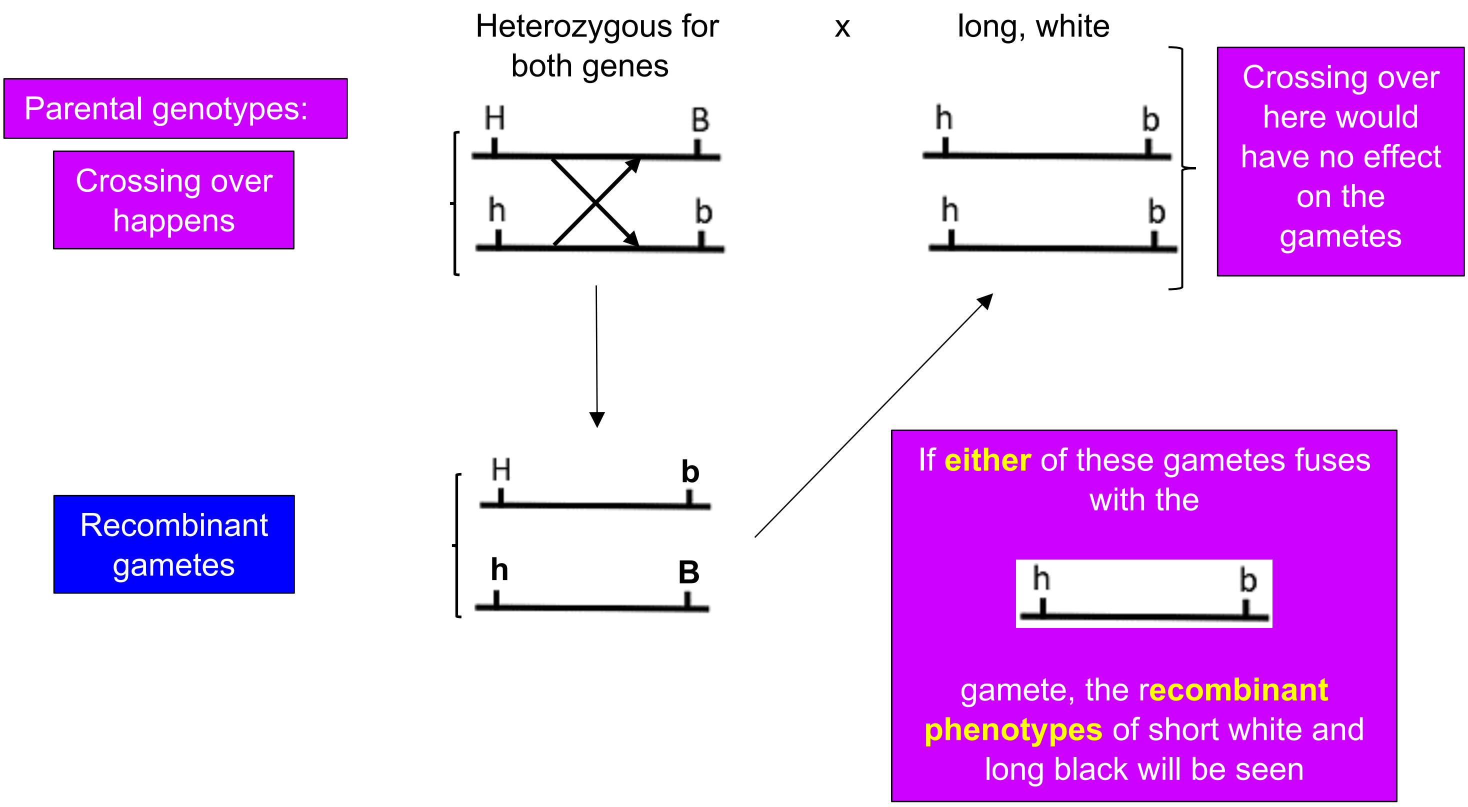
Phenotypic ratio of offspring = <u>1 Short Black : 1 long white</u>

What if we saw a small number of offspring that were short white and long black?

It seems impossible to produce these recombinant phenotypes!

It is possible because crossing-over has happened

Look at the **parents** again:



There are usually only a **small number** of individuals with **recombinant phenotypes** due to **crossing-over** being a **rare** and **random** event

H. QUICK SUMMARY ABOUT EXPECTED RATIOS

1. If two genes are **not linked**, crossing two **double heterozygotes** will give an **expected offspring phenotypic ratio** of **9 : 3 : 3 : 1**.

2. If two genes **are linked**, crossing two **double heterozygotes** will **not** give this expected ratio.

3. If two genes **are linked** and **crossing-over** has occurred, a **small number** of **offspring** will have **recombinant phenotypes** that their **parents do not have**.

I. EXAM TIP

Scientists studied two genes in *Drosophila* (fruit flies).

- Allele **G** is dominant and produces a grey body; allele **g** produces a black body.
- Allele **N** is dominant and produces normal (long) wings; allele **n** produces vestigial (short) wings

They mated a grey, normal fly heterozygous for both genes with a black, vestigial fly.

The table shows their results.

Offspring phenotype from a mating	Number counted
Grey, Normal	192
black, vestigial	188
Grey, vestigial	7
black, Normal	9

LOW NUMBERS OF RECOMBINANT PHENOTYPES INDICATE YOU MAY BE DEALING WITH LINKED GENES AND THAT CROSSING OVER HAS OCCURED

J. THE TWO WAYS OF PRODUCING RECOMBINANTS

Recombinants can be produced in **two** ways:

1. **Crossing over** between **LINKED** genes.
   Allows **alleles to be swapped** between **non-sister chromatids**.

2. **Random assortment** of **UNLINKED** genes.
   Any allele of **one gene** can go with **any allele** of **another gene** in a **sex cell**.

K. EXAM QUESTIONS ON RECOMBINATION

Question 1

A cross is performed between two organisms with the genotypes **AaBb** and **aabb**.

What genotypes in the offspring are the result of recombination?

A. Aabb, AaBb

B. AaBb, aabb

C. aabb, Aabb

D. Aabb, aaBb

THE KEY: **recombinants are different to both parents**

A. and B. contain the same genotype as the first parent (AaBb).
C. contains the same genotype as the second parent (aabb).
D. is correct as it has different genotypes to both parents.

Question 2

In garden peas, the pairs of alleles coding for seed shape and seed colour are unlinked.

The allele for smooth seeds (S) is dominant over the allele for wrinkled seeds (s).
The allele for yellow seeds (Y) is dominant over the allele for green seeds (y).

If a plant of genotype **Ssyy** is crossed with a plant of genotype **ssYy**, which offspring are recombinants?

A. SsYy and Ssyy

B. SsYy and ssYy

C. SsYy and ssyy

D. Ssyy and ssYy

THE KEY: **recombinants are different to both parents**

A. contains the same genotype as the first parent (Ssyy).
B. contains the same genotype as the second parent (ssYy).
C. is correct as it has different genotypes to both parents.
D. contains the same genotypes as both parents.

<u>Question 3</u> – more challenging and popular on the HL paper

Morgan did experiments with *Drosophila* (fruit flies) that led to the discovery of **non-Mendelian ratios**. Morgan explained this by saying that the genes must be **linked**.

He studied two genes that controlled body colour and wing shape.

B^+ = Grey body $\quad$ vg^+ = Normal wings
b = black body $\quad$ vg = vestigial wings

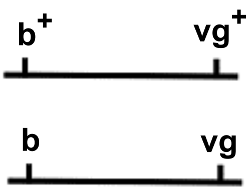
This is the cross that led to this discovery:

Parents: Grey body, Normal wings x black body, vestigial wings

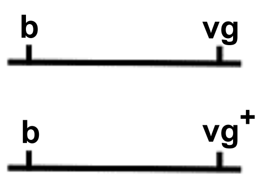
Parental genotypes:

Which of these is a recombinant offspring genotype?

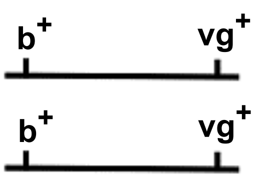
A.



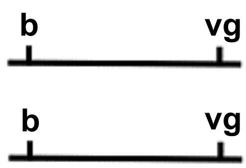
B.



C.



D.



THE KEY: **recombinants are different to both parents**

A. and D. are incorrect as they are the same as one of the parents.

C. is incorrect as there is no way that the second parent can produce the gamete 

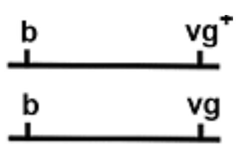
THE KEY: **recombinants are produced by crossing-over**

Look at the cross-over lines I have added to the question in blue.

Crossing-over would have no effect for the second parent.

First parent can produce two recombinant gametes. one of which is

This can combine with a gamete from the other parent containing



B is correct

L. MORGAN'S WORK ON DROSOPHILA (FRUIT FLIES)

- **Morgan** did experiments with *Drosophila* (fruit flies) that led to the discovery of **non-Mendelian ratios**. As mentioned previously, he studied two genes that controlled body colour and wing shape.

B^+ = Grey body　　　vg^+ = Normal wings
b = black body　　　vg = vestigial wings

- This probably seems strange notation to use, as we usually use capital and lowercase letters to show the dominant and recessive alleles. However, this is what he used!

This is the cross that led to this discovery:

Parents: Double heterozygous Grey body, Normal wings x black body, vestigial wings

If these two genes were **unlinked** and followed the **law of independent assortment**, they would be **inherited** in a typical **Mendelian** manner

Parental genotypes: ($B^+b\ vg^+vg$)　　　(bb vg vg)

Offspring genotypes:

	B^+ vg^+	**B^+ vg**	**b vg^+**	**b vg**
b vg	$B^+b\ vg^+vg$	B^+b vg vg	bb vg^+vg	bb vg vg

Phenotypic ratio of offspring: **1** Grey Normal : **1** Grey vestigial : **1** black Normal : **1** black vestigial

However, Morgan **did not see this phenotypic ratio of offspring**.

He concluded that these two genes must be **linked** – found on the **same chromosome**.

So they **cannot assort independently**.

This changes things:

Parents: Double heterozygous Grey body, Normal wings x black body, vestigial wings

If these two genes were linked and did not follow the law of independent assortment

Parental genotypes:

Offspring genotypes:

	b^+ vg^+	b vg
b vg	b^+ vg^+ b vg	b vg b vg

Phenotypic ratio of offspring: **1** Grey Normal : **1** black vestigial

This phenotypic ratio of offspring is a **more accurate** reflection of what **Morgan** saw.

These two genes **are linked** – found on the **same chromosome**.

So they **cannot assort independently**.

M. FACTORS THAT CAN AFFECT THE EXPECTED OFFSPRING PHENOTYPIC RATIO

C-CELLS

- **CROSSING OVER**
- **CODOMINANCE**
- **EPISTASIS**
- **LINKED GENES (AUTOSOMAL)**
- **LOW SAMPLE SIZE**
- **SEX LINKED GENES**

N. TYPES OF VARIATION

CONTINUOUS VARIATION	DISCONTINUOUS (DISCRETE) VARIATION
Controlled by **two or more genes (polygenic)** and the **environment**	Controlled by **genes only (usually one gene),** with **no environmental influence**
Individuals fit within a **range** of **two extreme groups**	**Individuals fit** into **one** of a **number** of **separate (non-overlapping) groups**
Results in a **range** of **phenotypes** or **features between two extremes**	Results in a **limited (lower) number** of **separate phenotypes** with **no intermediates**
Tend to be **quantitative** (**measured** with **numbers**)	Tend to be **qualitative** (**not measured** with **numbers**)
e.g. **human height, weight, intelligence, skin colour**	e.g. **human A, B, O blood groups, tongue rolling**
Drawn as a frequency histogram with **ranges** along the x-axis	**Drawn as a bar chart**

O. POLYGENIC INHERITANCE