CHAPTER 4

GENETIC INHERITANCE

(Hours: 2L + 7T)

CHAPTER 4: GENETIC INHERITANCE

4.1 Mendelian genetics: Monohybrid and Dihybrid

4.2 Deviations from the Mendelian Inheritance

4.3 Genetic mapping

UPS 2	PSPM 1
7 MCQ	13 marks

LEARNING OUTCOMES

4.1 Mendelian genetics : Monohybrid and dihybrid

a) Define the terminologies used in genetic inheritance: allele, gene, locus, genotype, phenotype, homozygous, heterozygous, dominant allele, recessive allele, self-cross and test cross (C1) Lecture
b) State the characteristics of Mendel's pea plants (C1) Lecture
c) State Mendel's first law (Law of Segregation) (C1) Lecture
d) Construct genetic diagram on the monohybrid cross and include the genotypic ratio (1:2:1) & phenotypic ratio (3:1) of F_2 generation (C3) Tutorial
e) Construct genetic diagram on the Mendelian monohybrid test cross and include the genotypic ratio (1:1) & phenotypic ratio (1:1) (C3) Tutorial

LEARNING OUTCOMES

4.1 Mendelian genetics : Monohybrid and dihybrid

f) State Mendel's second law (Law of Independent Assortment) (C1) Lecture

g) Construct genetic diagram on Mendelian dihybrid cross and include only the phenotypic ratio (9:3:3:1) of F_2 generation using Punnett square. (C3) Tutorial

h) Construct genetic diagram on Mendelian dihybrid test cross and include the phenotypic ratio (1:1:1:1) of F_2 generation using Punnett square (C3) Tutorial

Terminologies

1. Alleles
2. Genes
3. Locus
4. Genotype
5. Phenotype
6. Homozygous
7. Heterozygous
8. Dominant allele
9. Recessive allele
10. Self cross
11. Test cross



1. Allele

Definition

The alternative forms / versions of a gene that occupies the same locus on homologous chromosome

- Causes different development of the same trait
- Alleles of a gene occupy same loci on homologous chromosomes
- Alleles control the same character do not necessarily contain the same genetic information

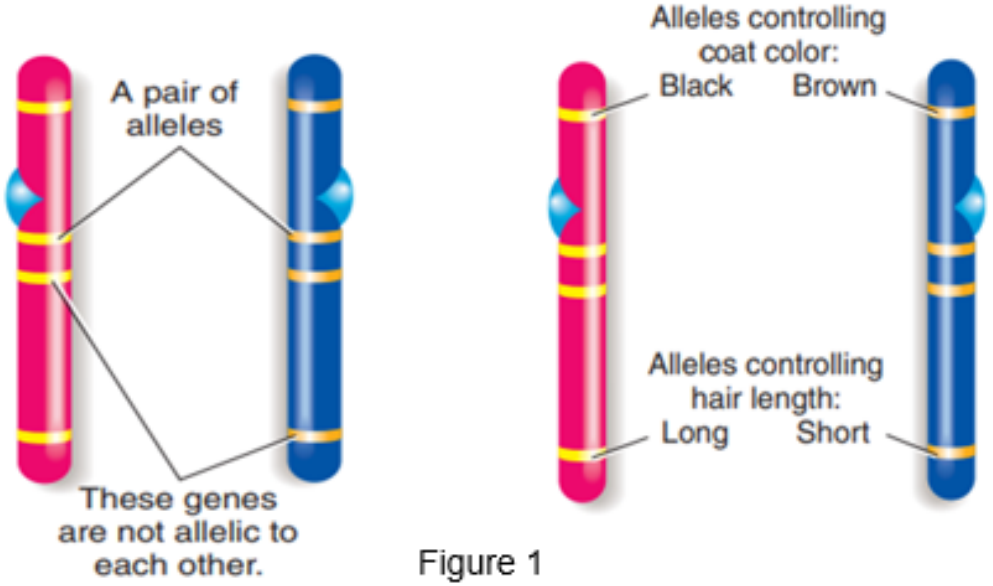


Figure 1

- **A gene usually has 2 alternative alleles**
- Eg: Gene for flower colour; alleles for purple & white flower
- Alleles are usually represented by the same alphabet
- Eg: Alphabet P : Allele P – dominant allele for purple flower
  : Allele p – recessive allele for white flower
- One individual must always has 2 alleles for each gene (can be any combination of the 2 alternative alleles)

Individual	Allelic pairs	
Plant A	Purple (P)	Purple (P)
Plant B	Purple (P)	White (p)
Plant C	White (p)	White (p)

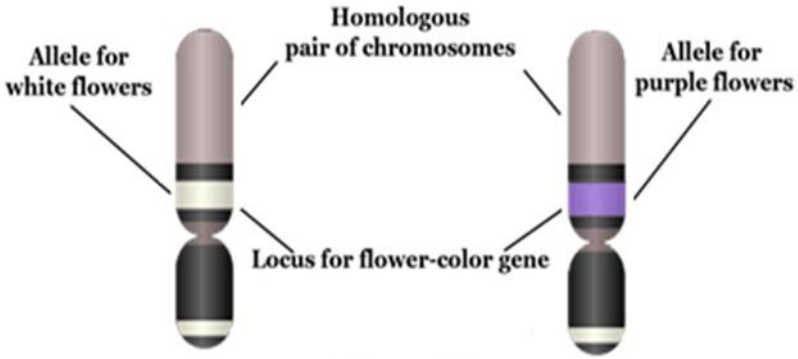


Figure 2

P – dominant allele for purple flower
p – recessive allele for white flower

Genes	Allelic pairs		Genotype	Observed traits
Flower colour	P	P	PP	Purple
	P	p	Pp	Purple
	p	P	Pp	Purple
	p	p	pp	White

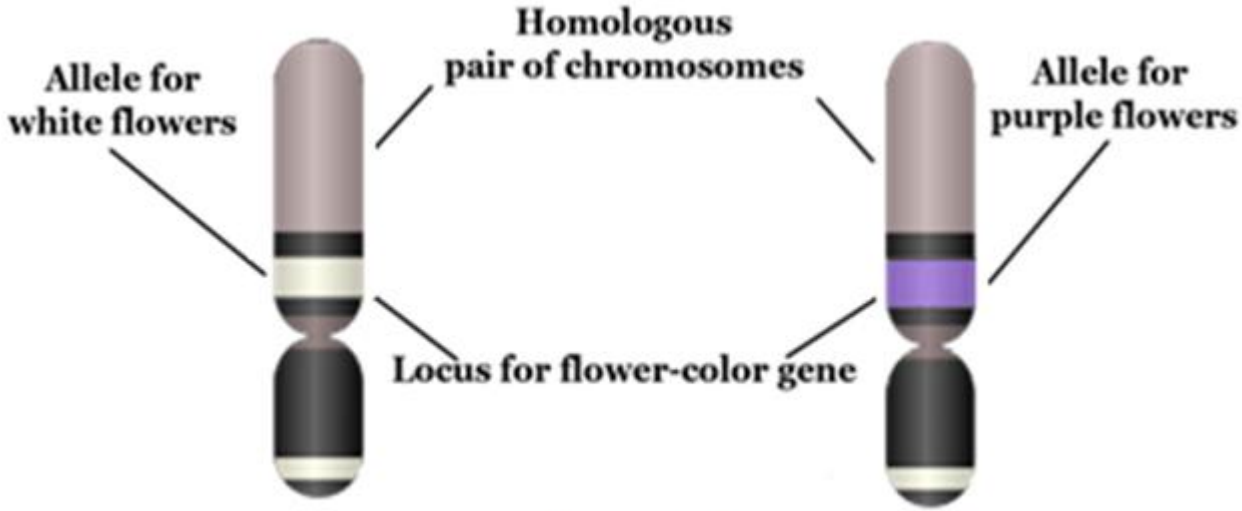


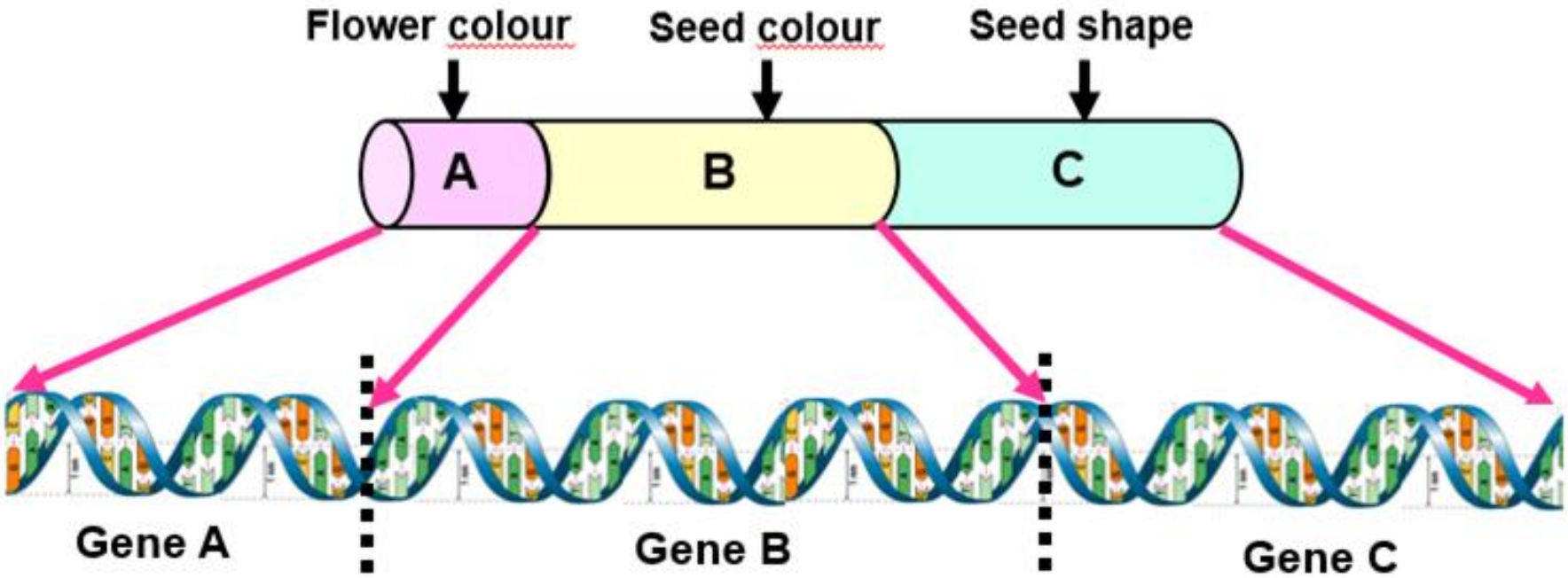
Figure 2

2. Gene

Definition

A segment of DNA that act as a unit of hereditary information

- It **codes for specific protein** that determines a **specific character**
- Eg: gene for flower colour, seed colour and seed shaped

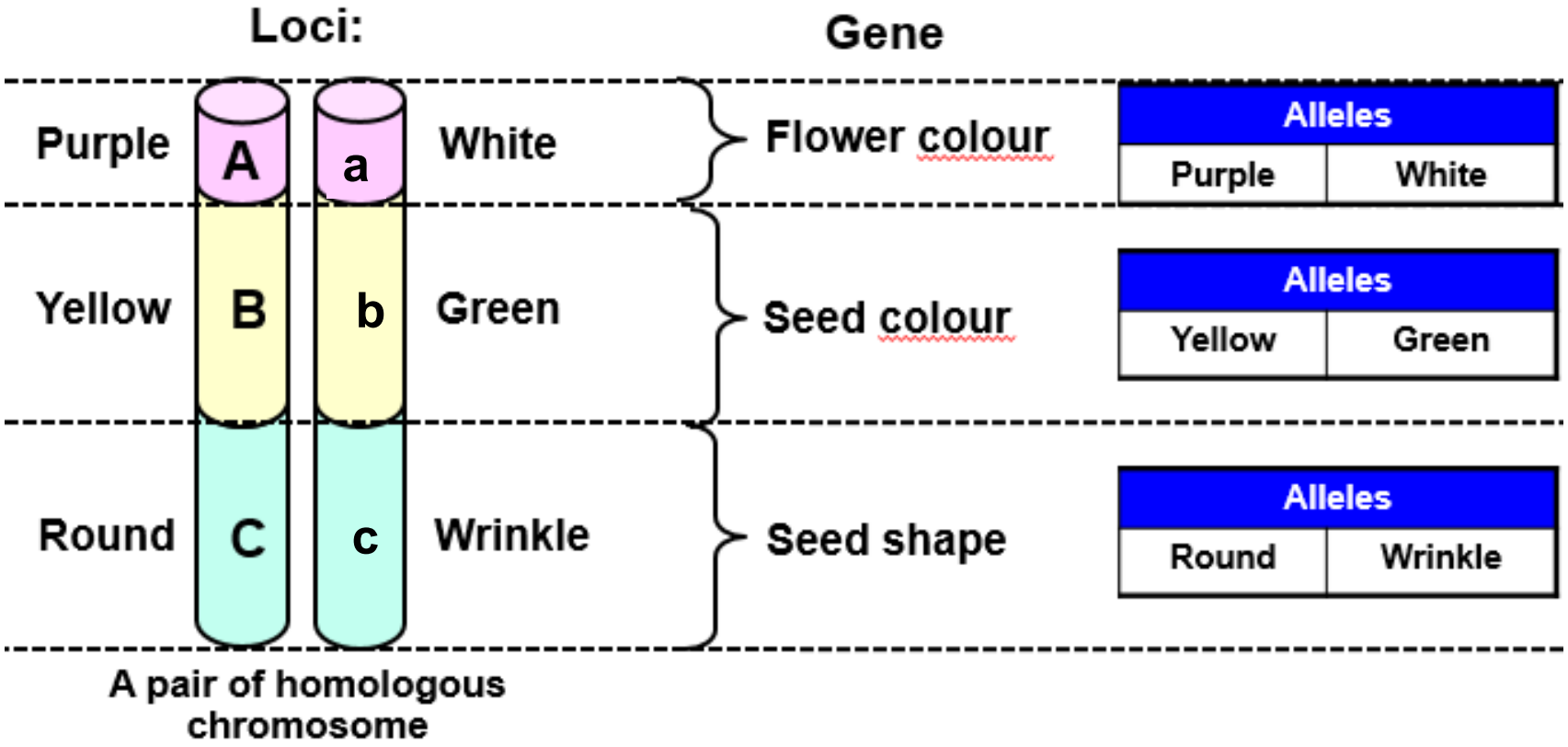


3. Locus

Definition

A location of a specific gene on a chromosome

- Alleles of a gene are located at the same locus on homologous chromosome



4. Genotype

Definition
The genetic makeup of an individual

- With respect to the alleles under consideration
- The **combination of alleles** it has for a specific gene
- Eg: PP, Pp, CCSS, CcSs

5. Phenotype

Definition
Observable traits of an organism

- Which is determined by its genotype & by the interaction between genotype & environment in which development occurs
- Eg: Genotype : Pp
  Phenotype : Purple flower

6. Homozygous

Definition

Organism which has 2 identical alleles for a gene / character at a given locus on homologous chromosome

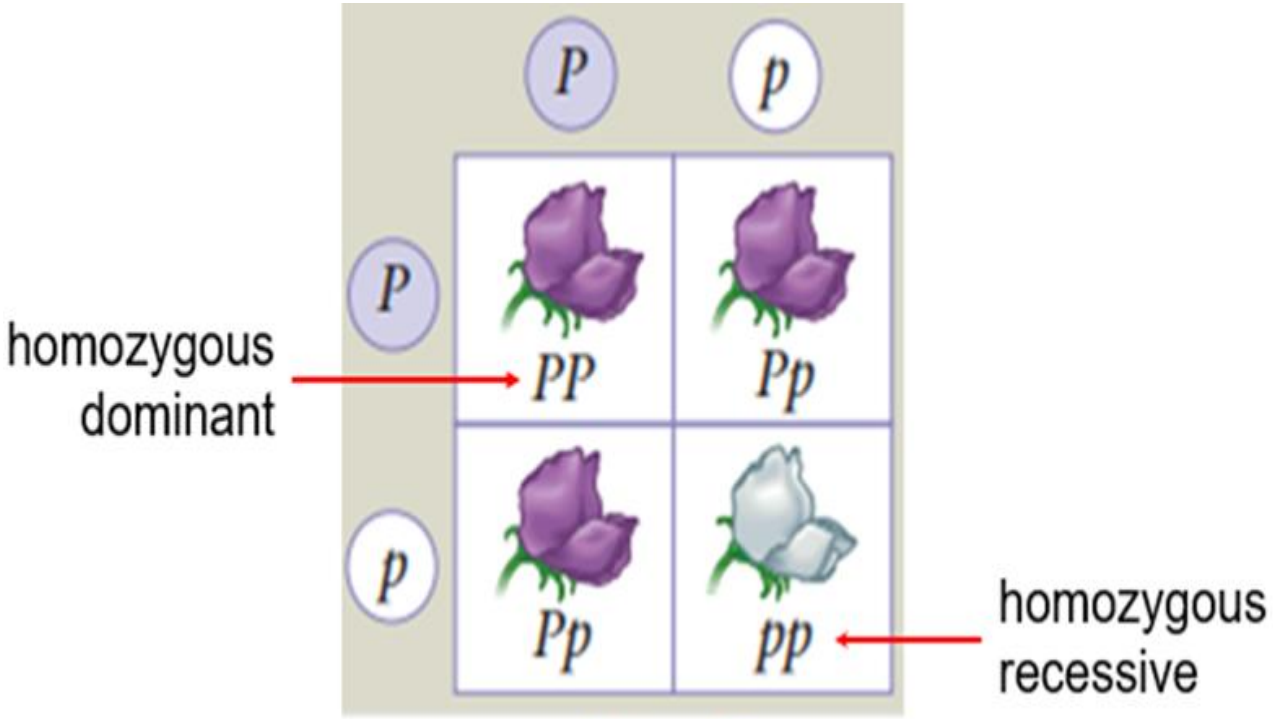


Figure 3

Character: colour of flowers

Genotype:
Homozygous
PP; pp
(identical alleles)

7. Heterozygous

Definition

Organism which has 2 different alleles for a gene / character at a given locus on homologous chromosome

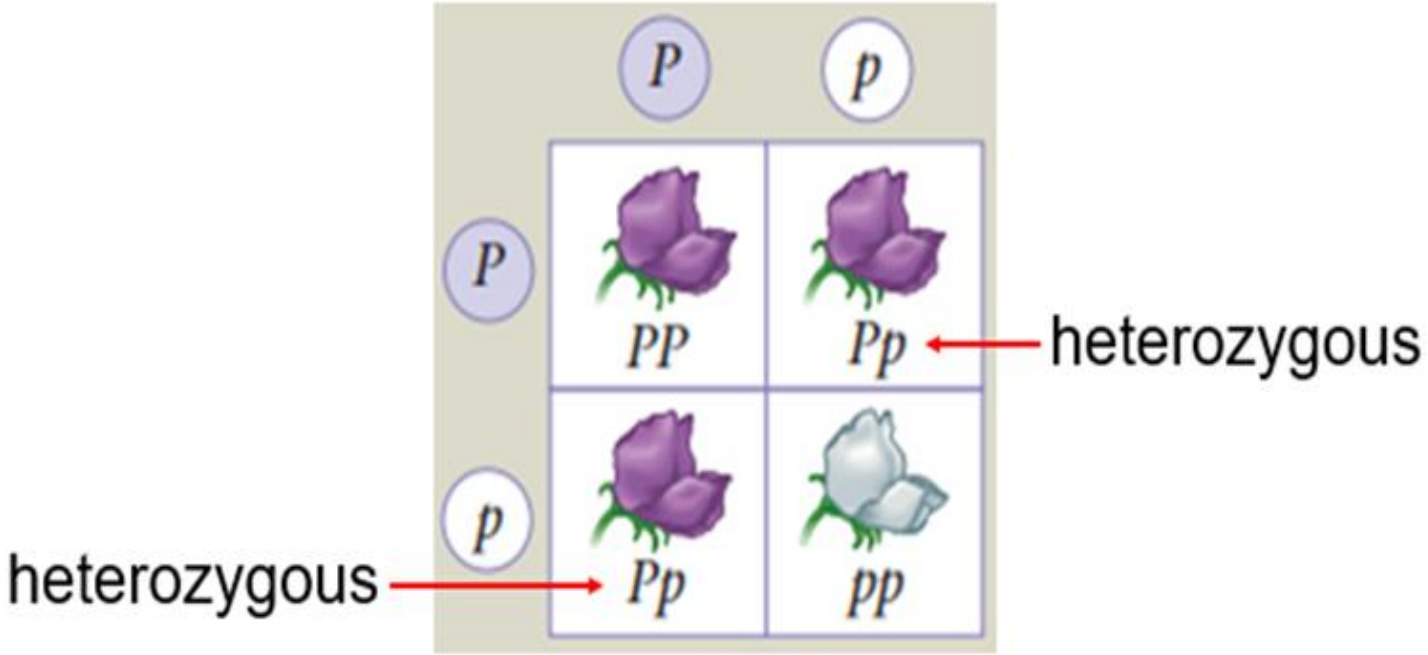


Figure 3

Character: colour of flowers

Genotype:
Heterozygous
Pp
(different alleles)

8. Dominant allele

Definition

Allele which is **fully expressed in the phenotype of a heterozygous or fully expressed when it is present; even in the presence of another allele**

- Has same character; both in homozygous and heterozygous condition
- Symbol using capital letter
- Eg: allele P ~ dominant allele for purple flower

PP – purple
Pp – purple

P – dominant allele

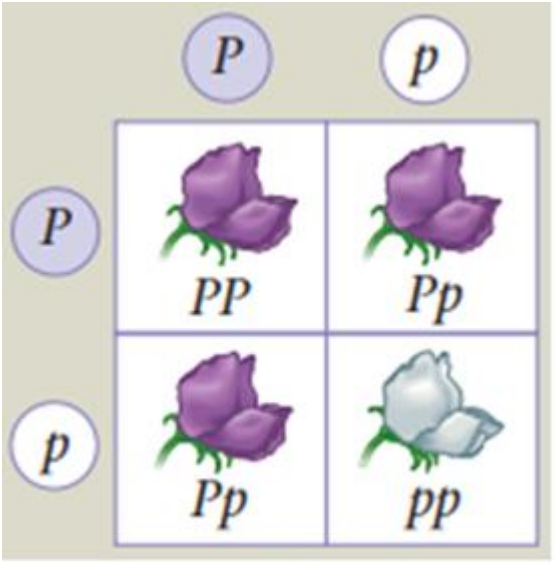


Figure 3

9. Recessive allele

Definition

Alleles whose **phenotypic effect is not observed in a heterozygote** / Alleles which express its trait only in the presence of another identical allele (homozygous condition)

- Symbol using small letter
- Eg: allele p ~ recessive allele for white flower

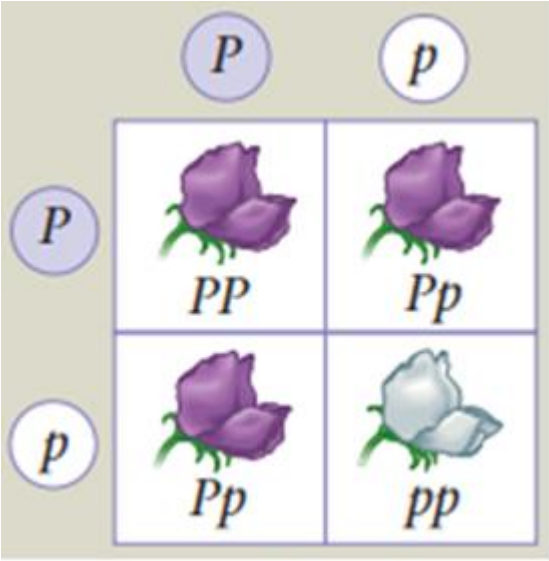


Figure 3

Pp – purple
pp - white

p – recessive allele

10. Self cross

Definition

A cross between **male and female parts** of the **same flower** / **same individual**

- The consequences of self cross is self fertilization

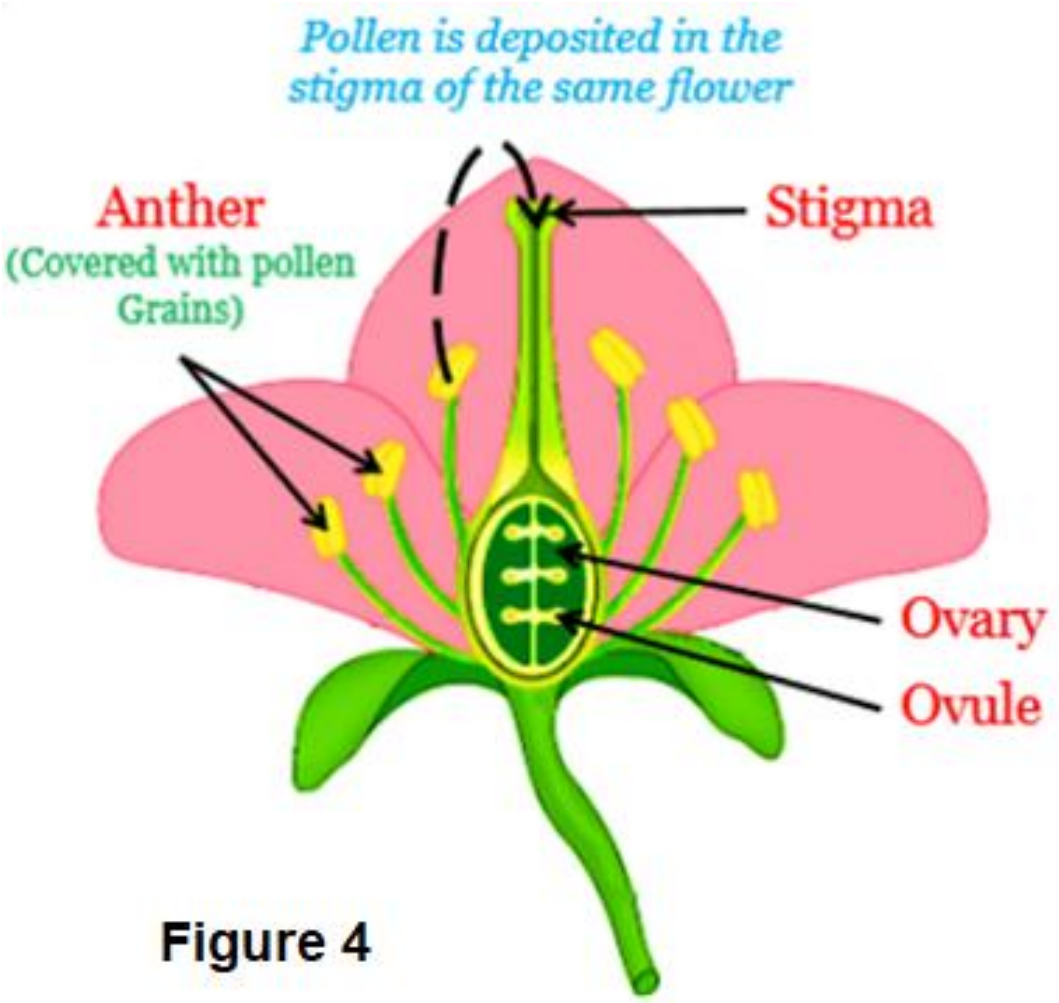


Figure 4

11. Test cross

Definition

A cross between a homozygous recessive individual with an organism of dominant phenotype but unknown genotype

- The ratio of phenotypes in the offspring reveals the unknown genotype

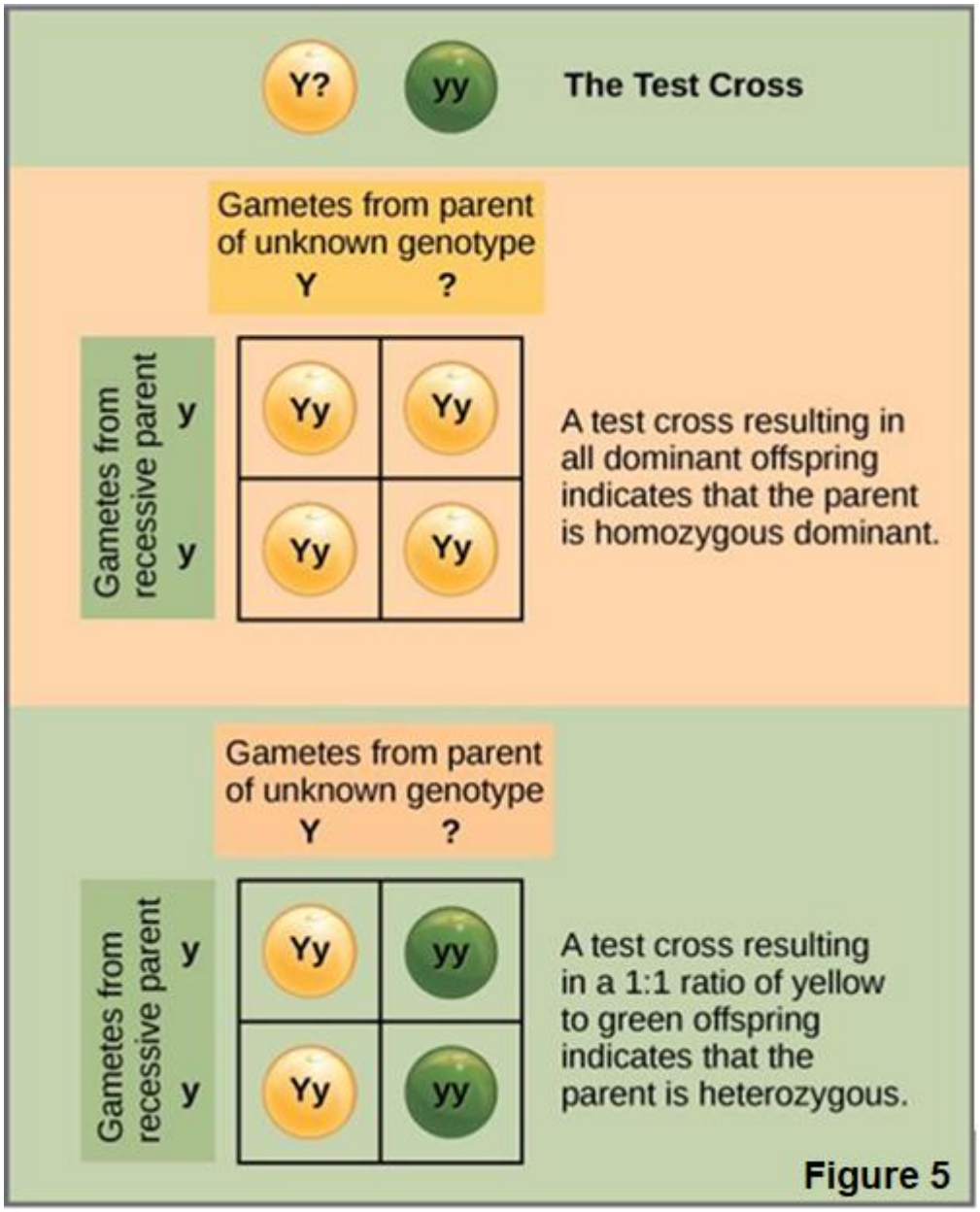
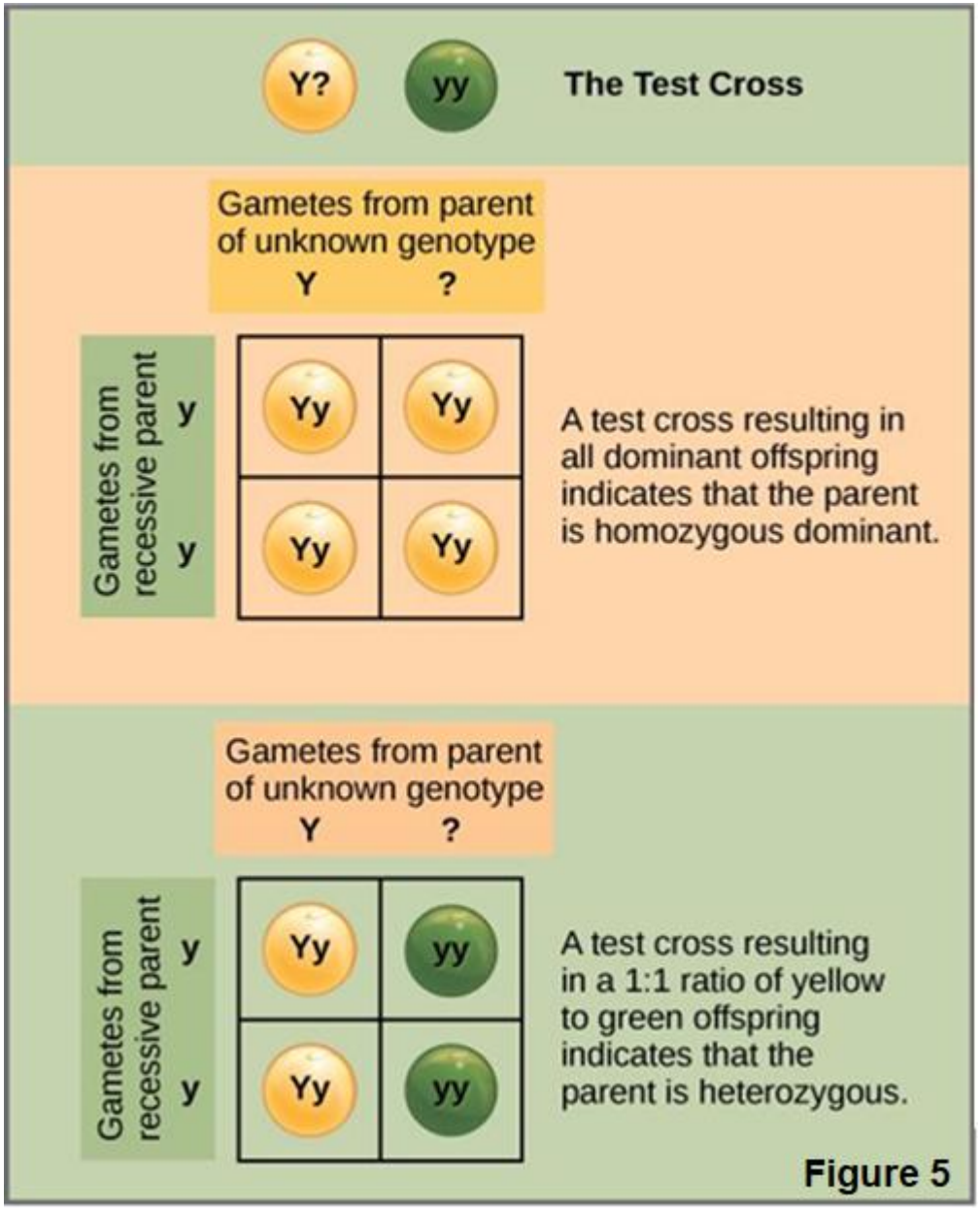


Figure 5

11. Test cross

- A cross between a **recessive homozygous** Eg. (yy) with an organism to determine the genotype eg. either YY/Yy
- If all the **offspring show the dominant characteristic**, the **unknown organism is homozygous** (YY)
- But if **half show the recessive characteristic** (yy), the **unknown organism is heterozygous** (Yy)



Character

Definition

A heritable feature that varies among individuals

- Eg: flower colour & height

Trait

Definition

Each variant for a character of individuals

- Character : flower colour
- Traits : purple flower, white flower



purple flower



white flower

True/Pure breeding

Definition

Referring to organisms that produce offspring of the same variety over many generations of self-pollination

- All true breeding individuals are homozygous

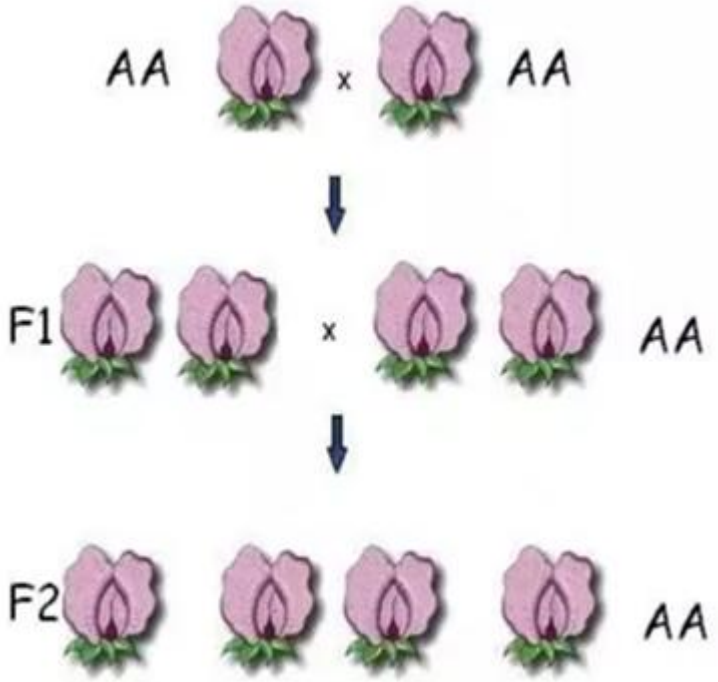


Figure 6

Symbols Used In Genetic Diagram

P generation - parental generation

F_1 generation - first filial generation (i.e offspring produced from a cross between individuals of P generation)

F_2 generation - second filial generation
(i.e offspring produced from a cross between F_1 individuals)

MENDEL EXPERIMENT

- **Gregor Mendel** was an Austrian monk who begins to study the inheritance of garden peas in 1856



Figure 7



Figure 8

- Mendel study genetic inheritance in pea plant (*Pisum sativum*) because of **5 reasons** :

1) Easy to grow in large numbers
2) Short life cycle
3) Many easily observable characters

➢ 7 characteristics of pea plant



Figure 9

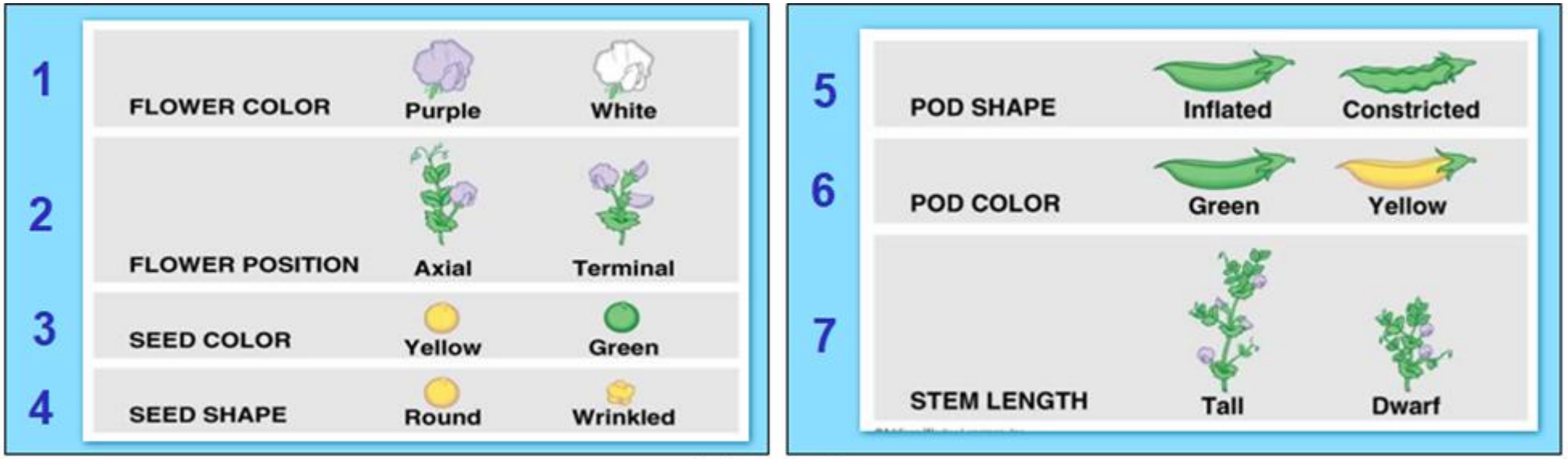


Figure 10

- Mendel study genetic inheritance in pea plant (*Pisum sativum*) because:

4) Pollination could be easily controlled

(Has close reproductive structure inside petals)

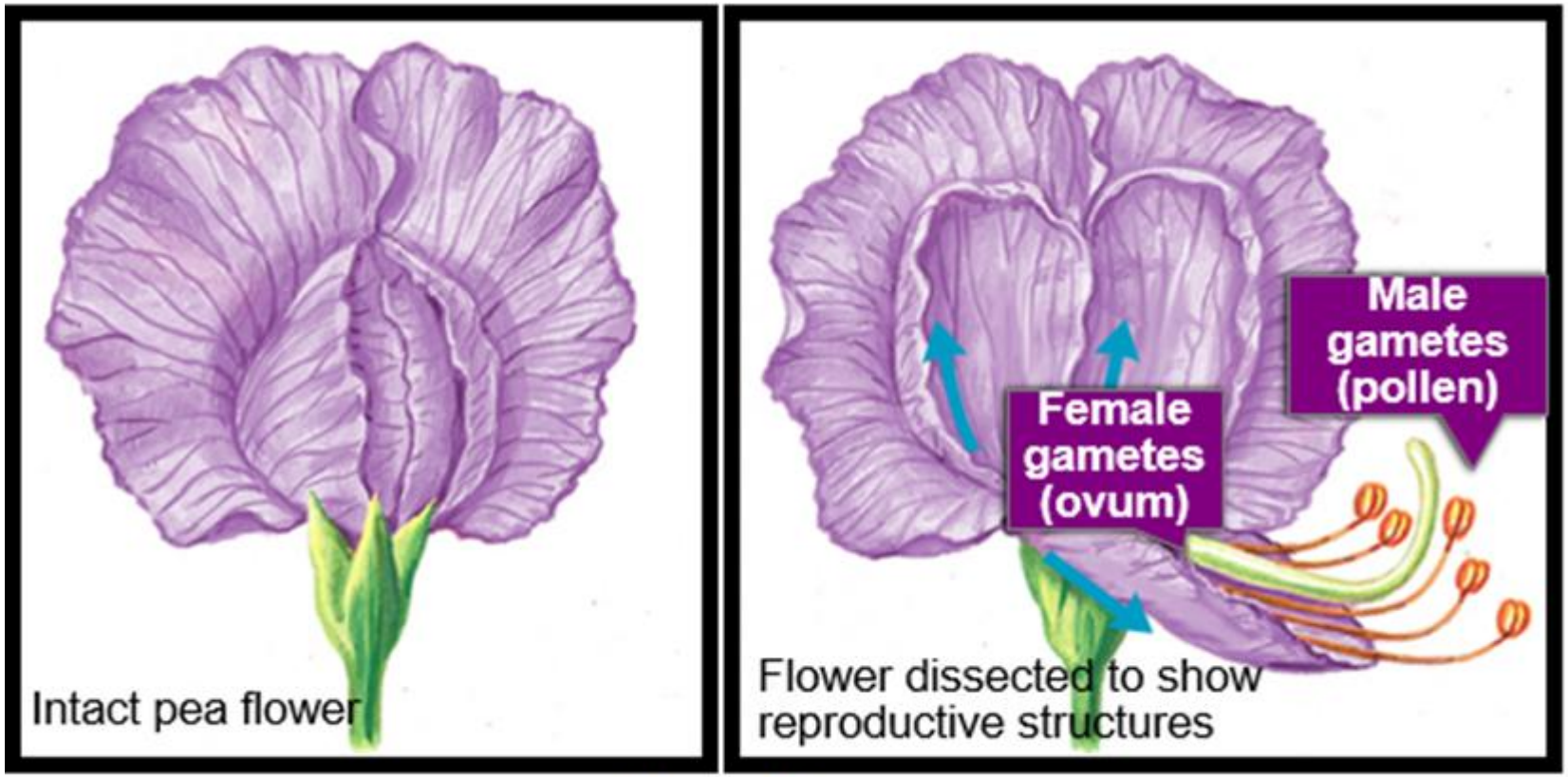


Figure 11

- Mendel study genetic inheritance in pea plant (*Pisum sativum*) because:

5) Have both male & female parts
(Can be manipulated; can self pollinate, cross pollinate)

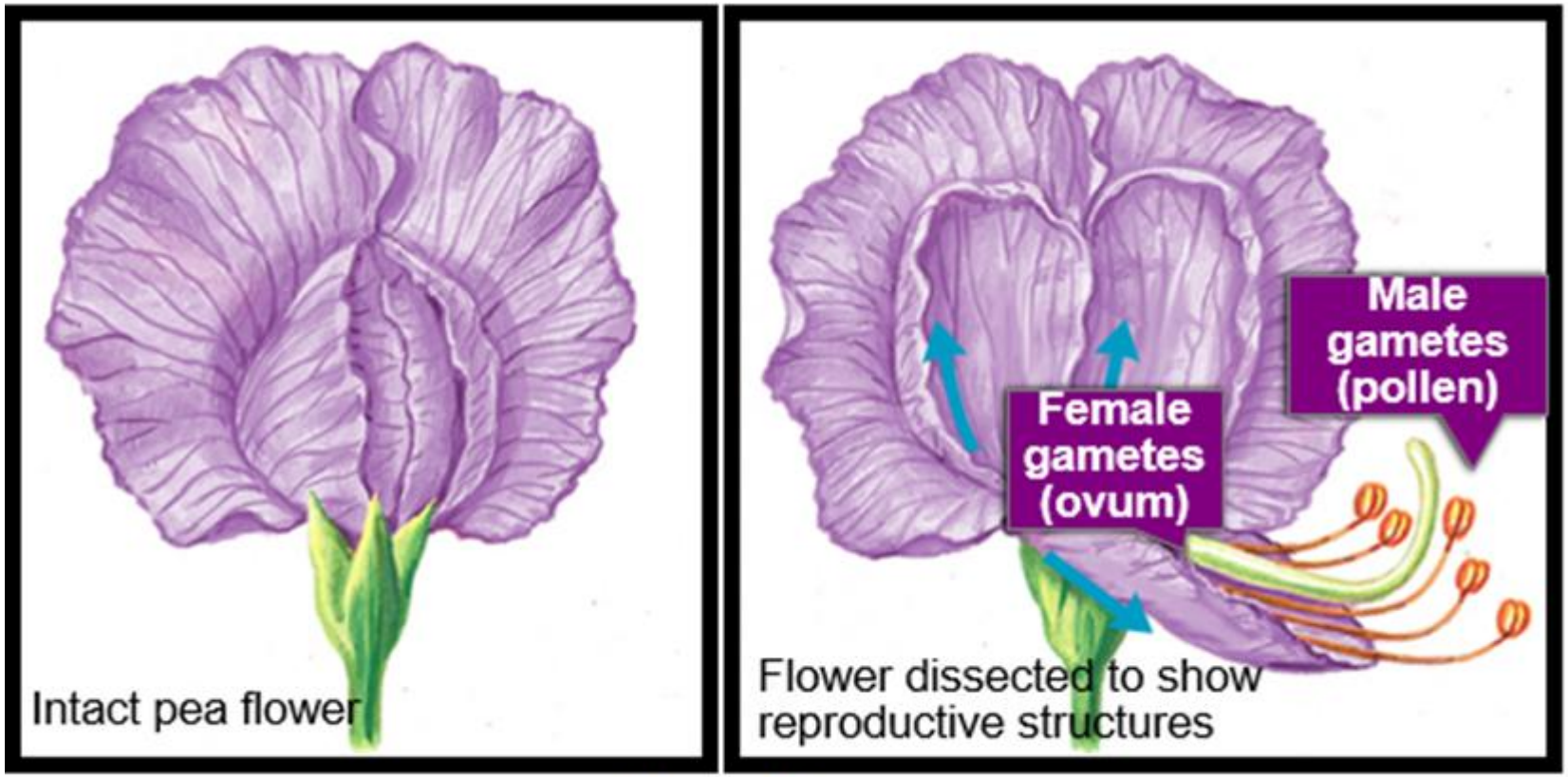
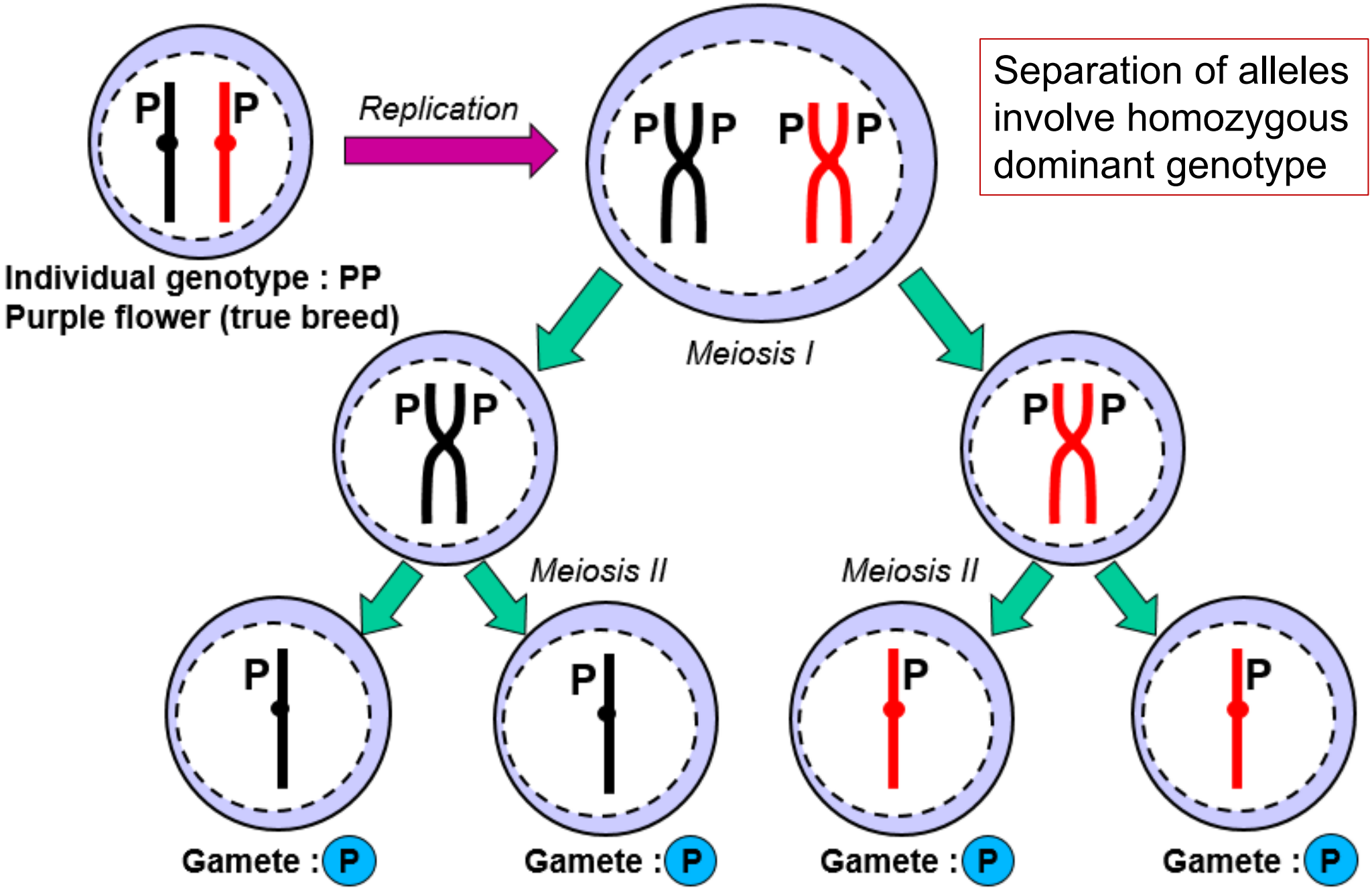


Figure 11

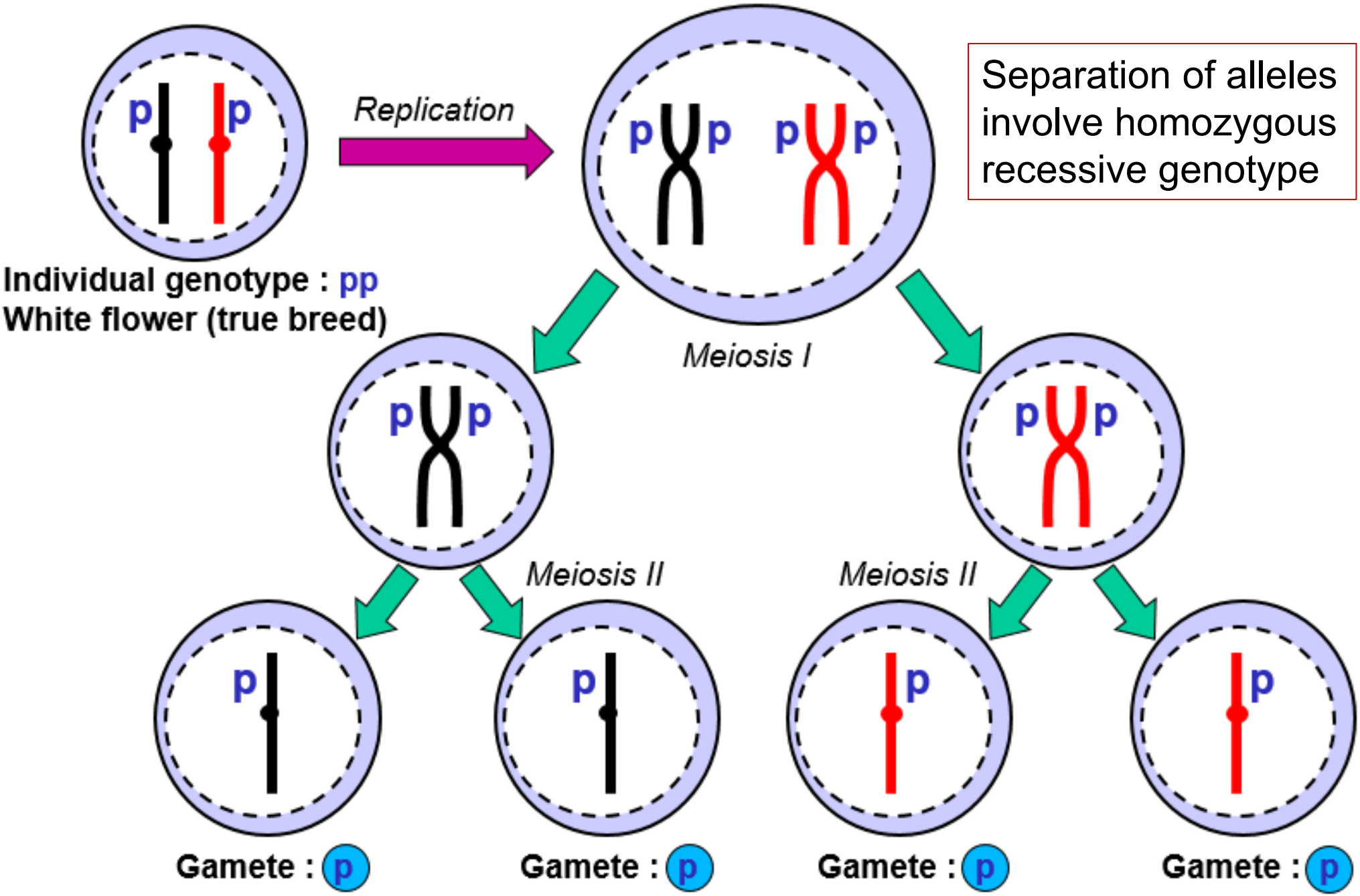
Mendel's 1st Law ~ "Law of Segregation"

States that:

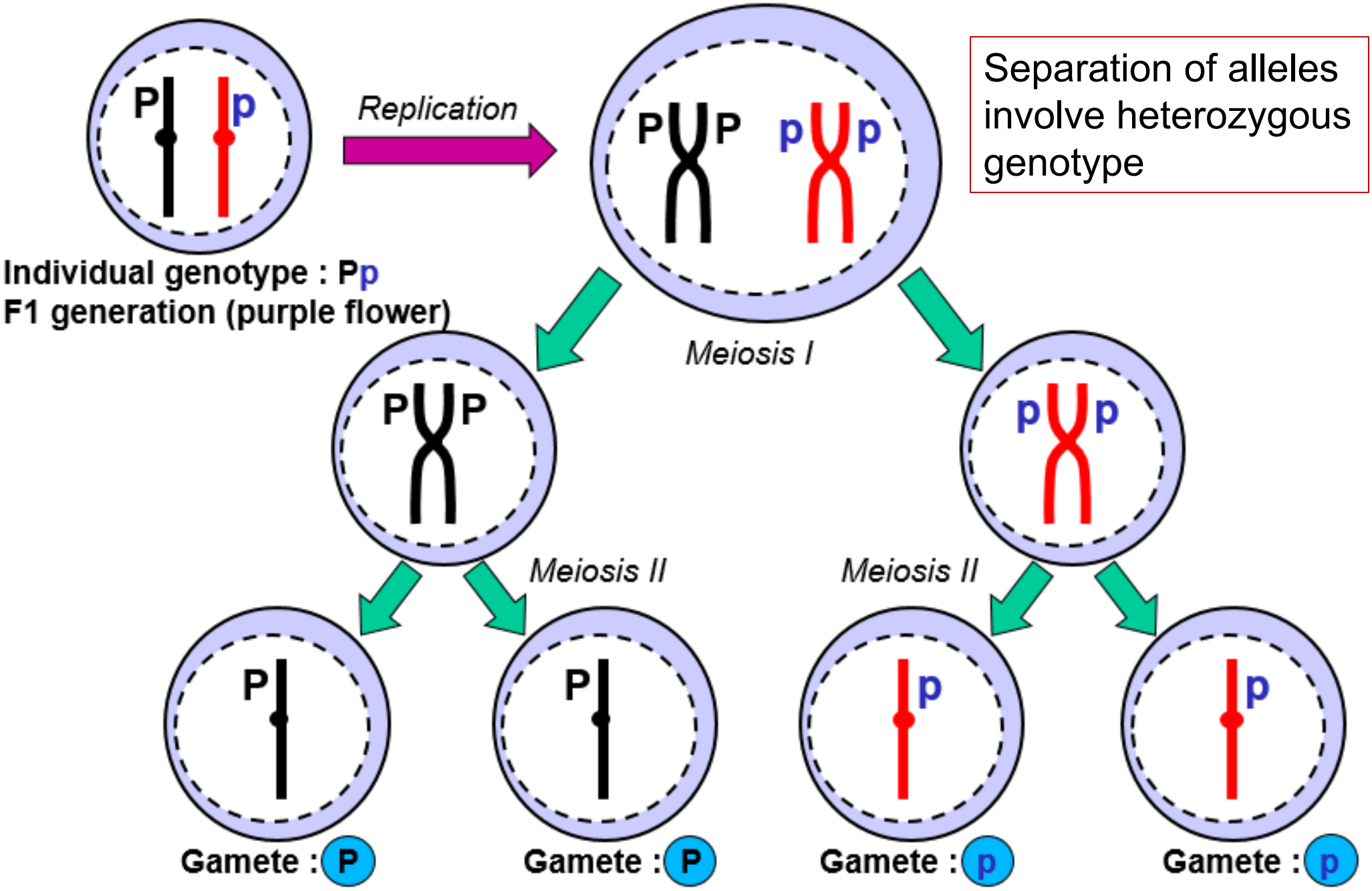
- **The two alleles for heritable character segregate during gamete formation and end up at different gamete**



Separation of alleles involve homozygous dominant genotype

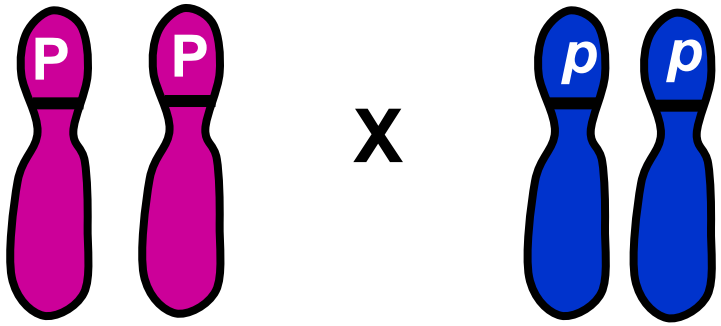


Separation of alleles involve homozygous recessive genotype


P
p
Replication
P P
p p
Separation of alleles involve heterozygous genotype
Individual genotype : Pp
F1 generation (purple flower)
Meiosis I
P P
p p
Meiosis II
Meiosis II
P
P
p
p
Gamete : P
Gamete : P
Gamete : p
Gamete : p

Monohybrid Cross

- Only 1 character is observed that determined by 1 gene
- Eg: flower colour
- Involves crossing between 2 individuals (true breeding) with different phenotypes:-
  i. purple flower (homozygous dominant, PP)
  ii. white flower (homozygous recessive, pp)



Allele P : dominant allele for purple flower
Allele p : recessive allele for white flower

Mendel's Monohybrid Cross Experiment

- **3 steps of Mendel's experiment** :
  1) Produce P generation (true breeding)
  2) Produce F_1 generation
  3) Produce F_2 generation
- Mendel study traits in **3 generations of pea plant**

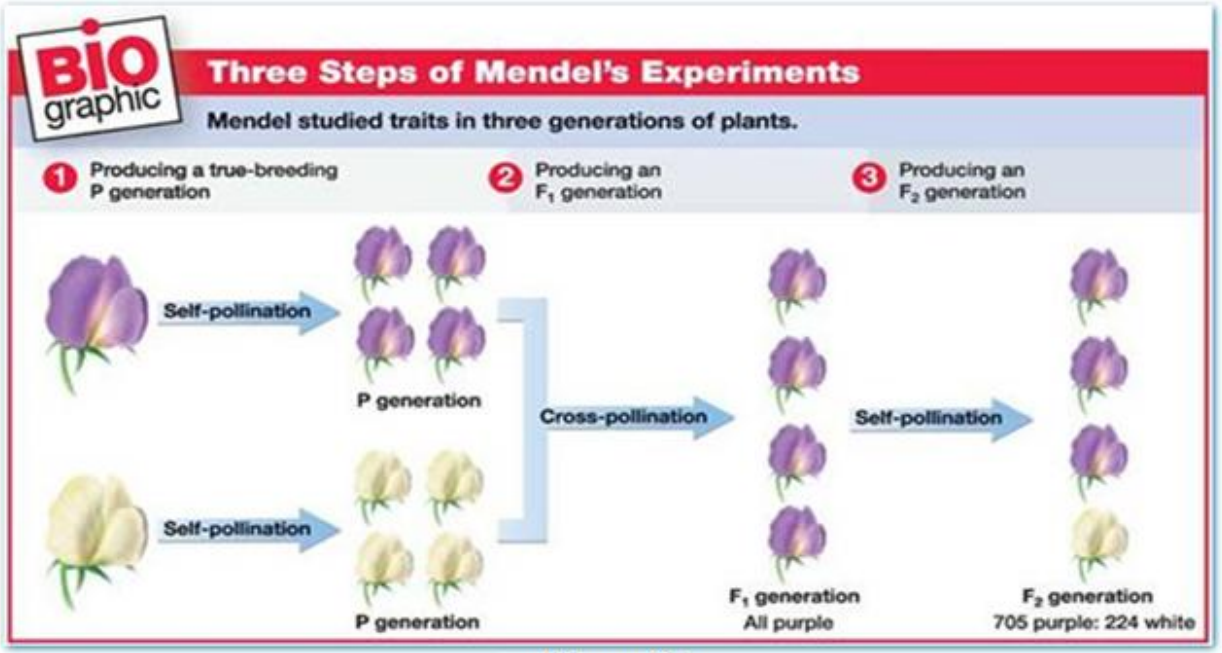
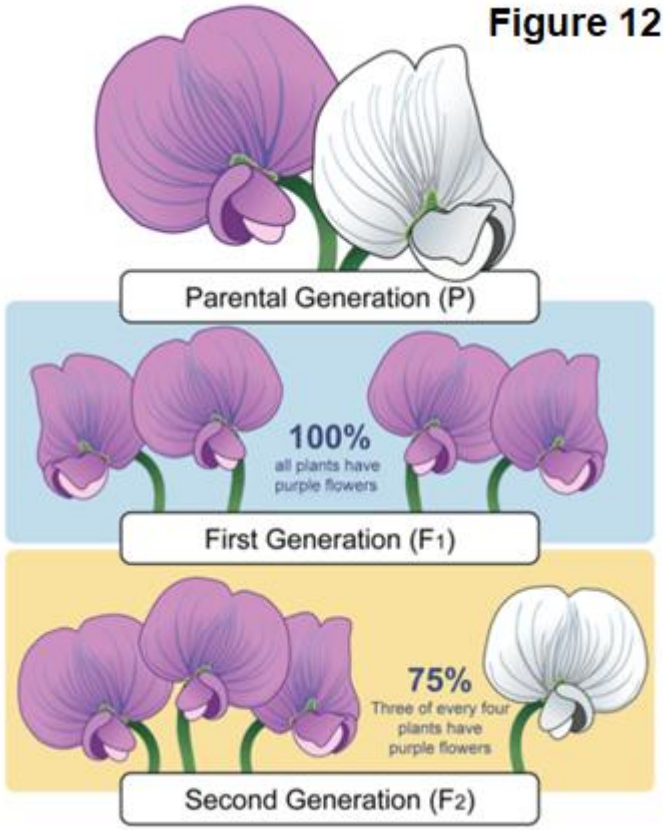


Figure 13

Figure 12



True / Pure Breed

- **Organisms that are homozygous** for the trait under consideration
- When they are self fertilized, they produce offspring that has the same phenotype as the parent; generation after generation
- Consider only 1 specific character, eg. flower colour
- Eg: Pure breed for white flower colour; pp

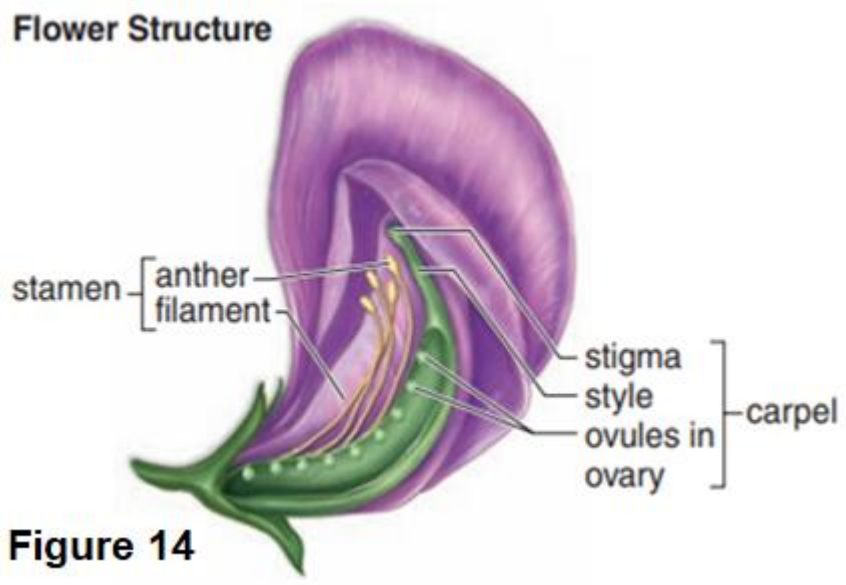


Figure 14

Step 1 : Produce P generation (True breeding plants)

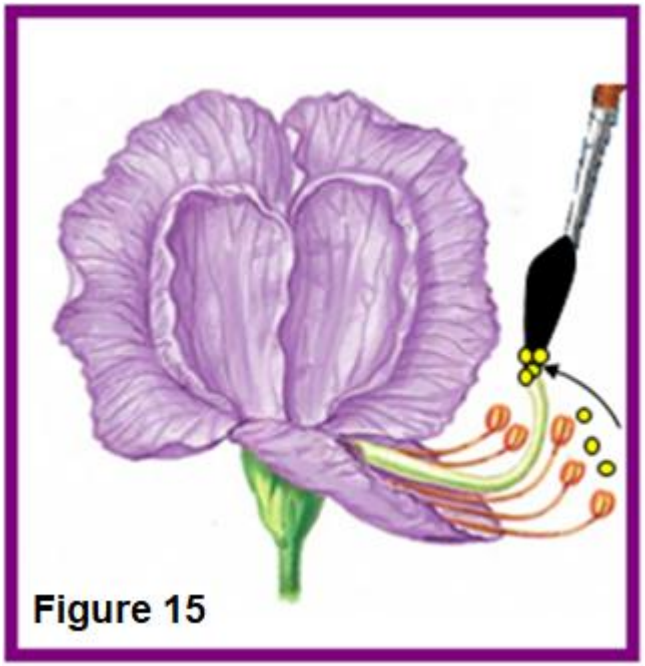


Figure 15

- Mendel select plants with 2 varieties (has different traits)
- Eg: purple flower & white flower plant
- These plants were allowed to self pollinate for several generations

Step 1 : Produce P generation (True breeding plants)

- Seeds collected from purple flowered plants is planted
- Their offspring always produce purple flowered plants (and white produce white)
- These 2 varieties of true breeding plants is known as parental or *P generation*

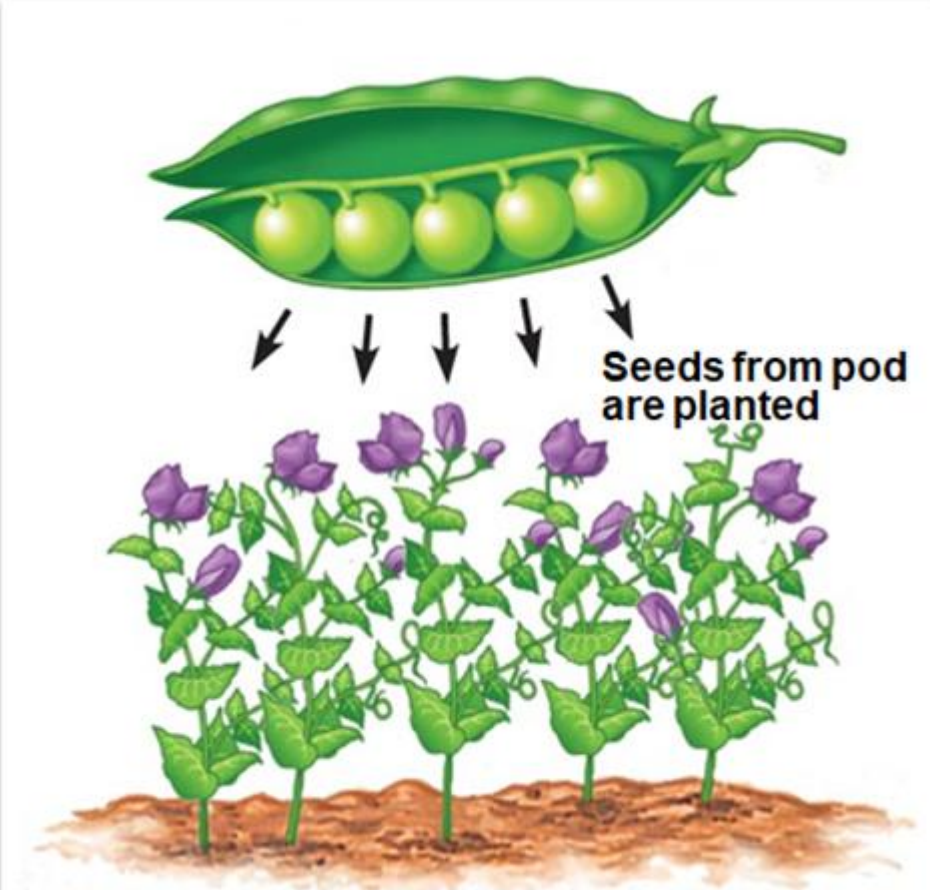
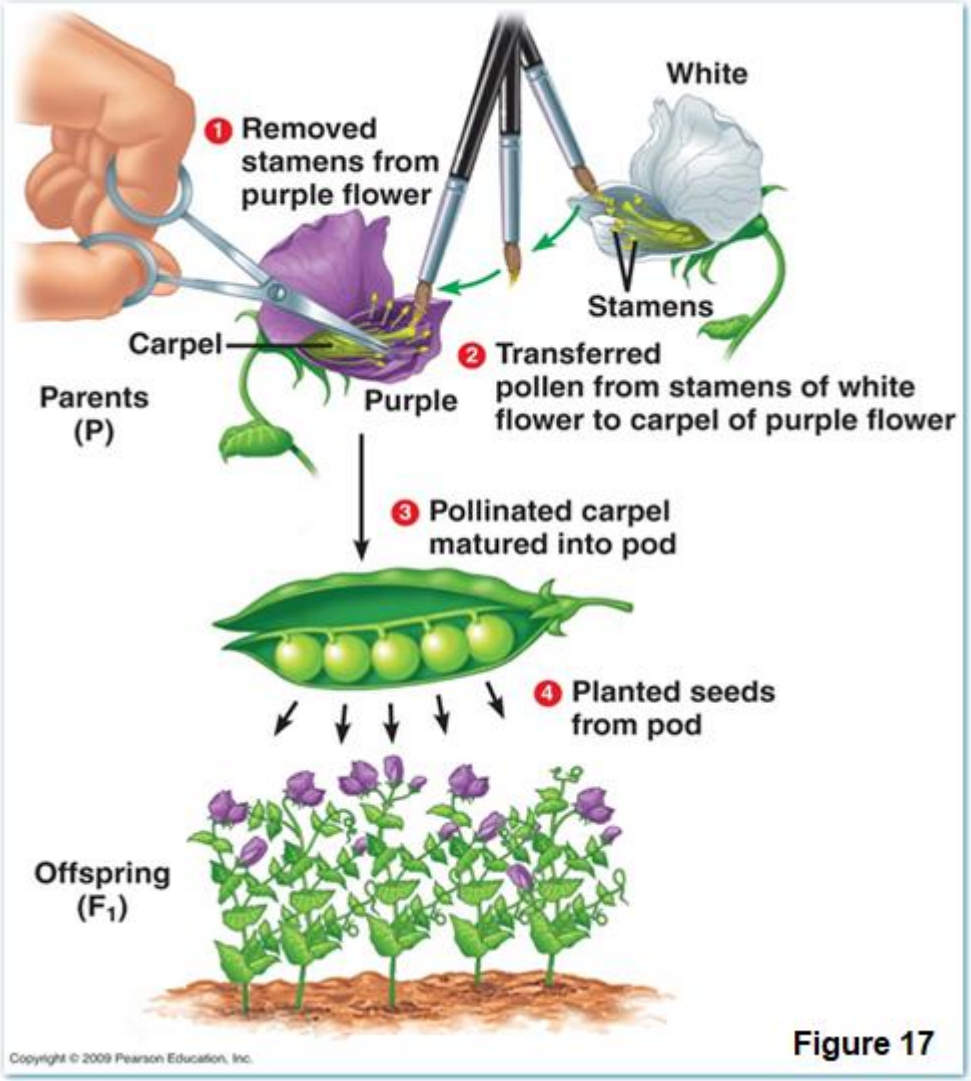


Figure 16

Step 2 : Produce F_1 generation

- Mendel remove the stamens from purple flowered plant
- Pollen from white flower is transferred to the stigma of purple flower (cross fertilized)
- Seeds obtained is planted



RESULTS

- All offspring → purple flower
- Offspring is first filial or *F_1 generation*

P : dominant allele for purple flower; p : recessive allele for white flower





Parental phenotype: **Purple flower** **white flower**

Parental genotype: **PP** **X** **pp**

Gamete : **P** **p**

F_1 genotype: **Pp**

F_1 phenotype: **Purple flower**



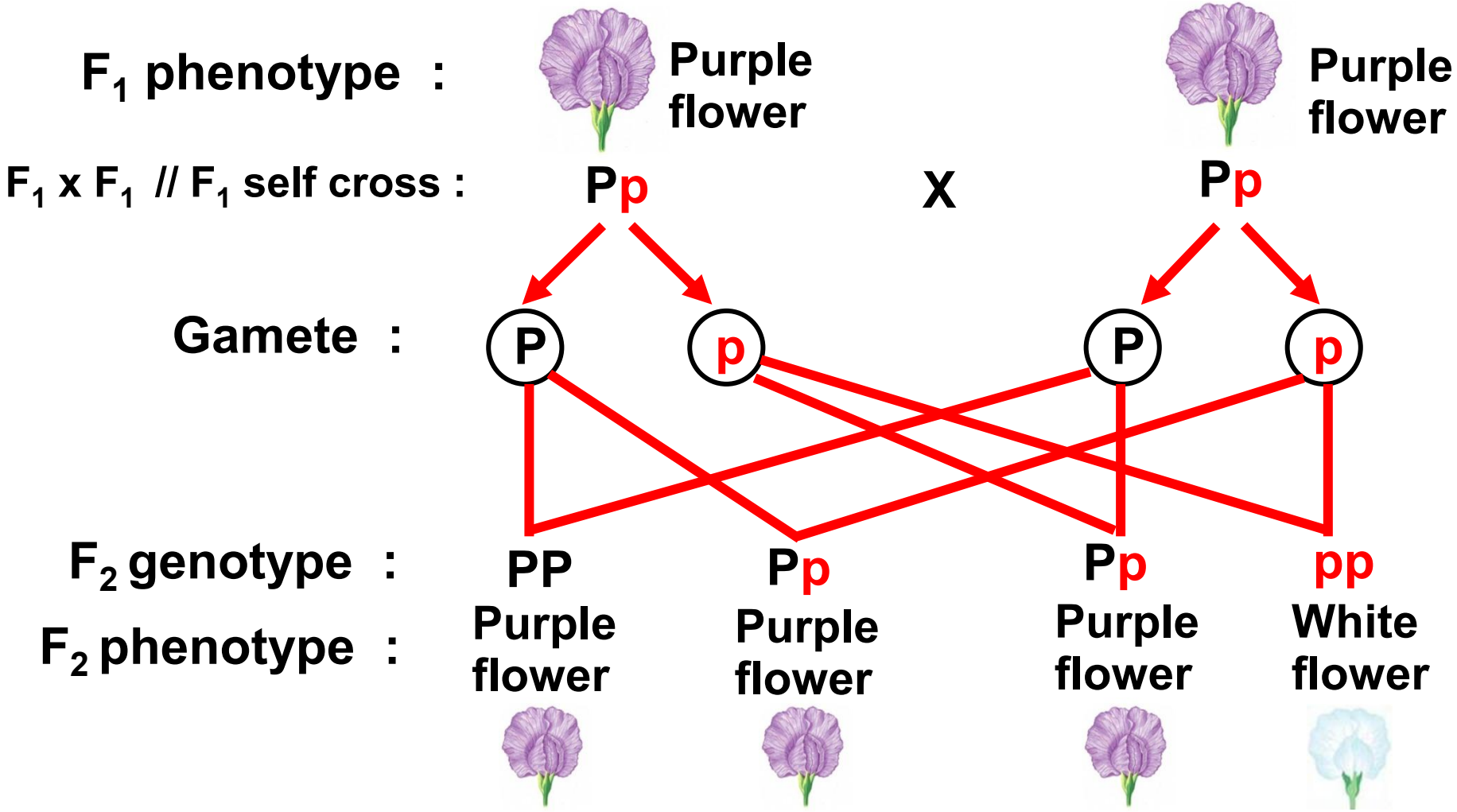
F_1 genotypic ratio : All Pp

F_1 phenotypic ratio: All purple flower

Remark for Genetic Diagram:

Parental/ P
Gamete/ G

Learning Outcomes :
4.1 (d) Construct genetic diagram on the monohybrid cross and include the genotypic ratio (1:2:1) and phenotypic ratio (3:1) of F2 Generation.(tutorial)



F_2 genotypic ratio :	1 PP : 2 Pp : 1 pp
F_2 phenotypic ratio:	3 Purple : 1 White

Punnett Square

- A diagram used to predict the allele composition of offspring from a cross between individuals of known genetic makeup[15].
- The possible gametes (from each parent) is written in the green coloured grid
- The possible combinations of gametes (**possible F_2 genotypes**) are written into the blue coloured grid. Plus with its phenotypes

Eg: F_1 x F_1 : Pp x Pp

Gamete	P	p
P	PP  Purple flower	Pp  Purple flower
p	Pp  Purple flower	pp  White flower

Test cross

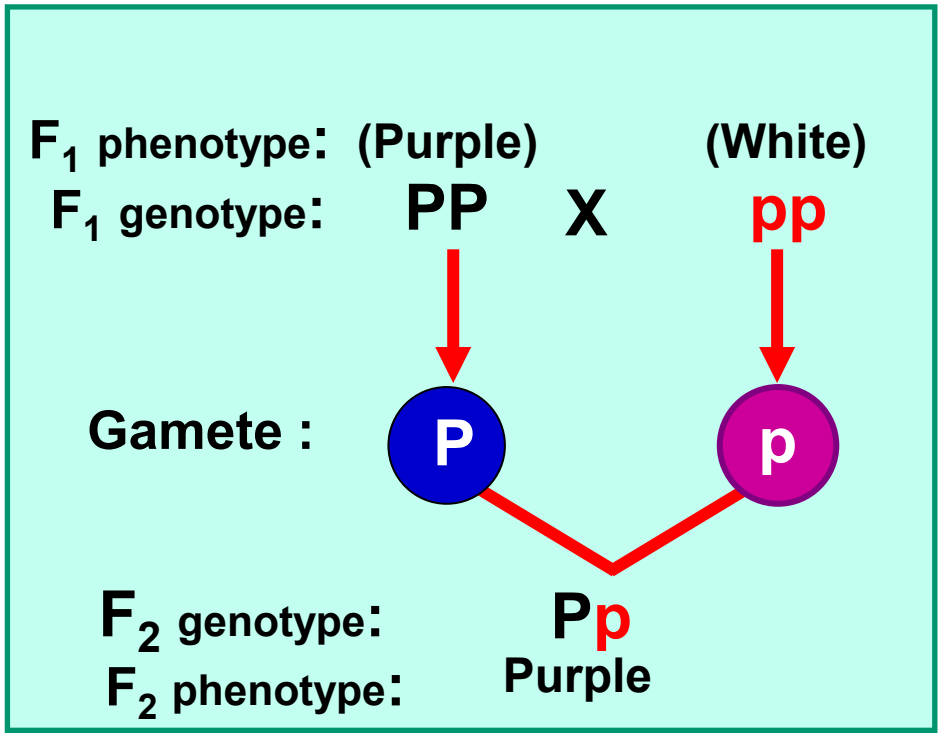
- A cross between a homozygous recessive individual with an organism of dominant phenotype but unknown genotype
- To determine the exact genotype of unknown genotype

Prediction :-

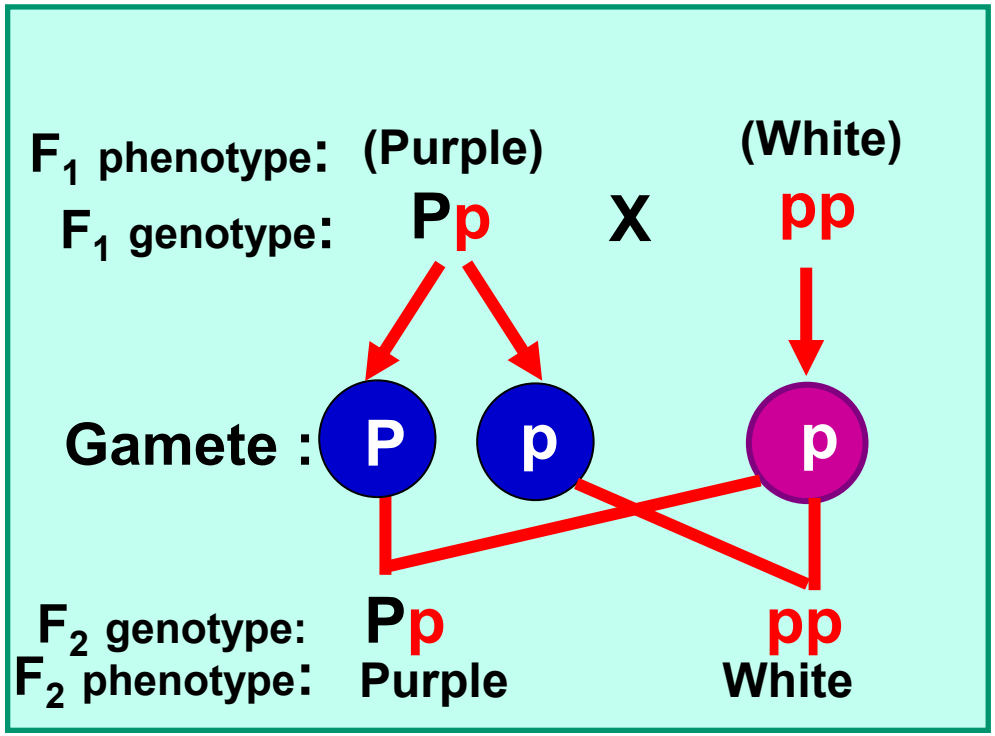
- If all offspring show dominant phenotype, genotype of unknown parent → homozygous dominant
- If half of the offspring show dominant phenotype & another half offspring show recessive phenotype, genotype of unknown parent → heterozygous

Monohybrid F_1 Test Cross

- Test cross is conducted between :-
  i. Dominant phenotype (F_1 : purple flower, PP or Pp)
  ii. Homozygous recessive (white flower, pp)



F_2 phenotypic ratio:- All purple

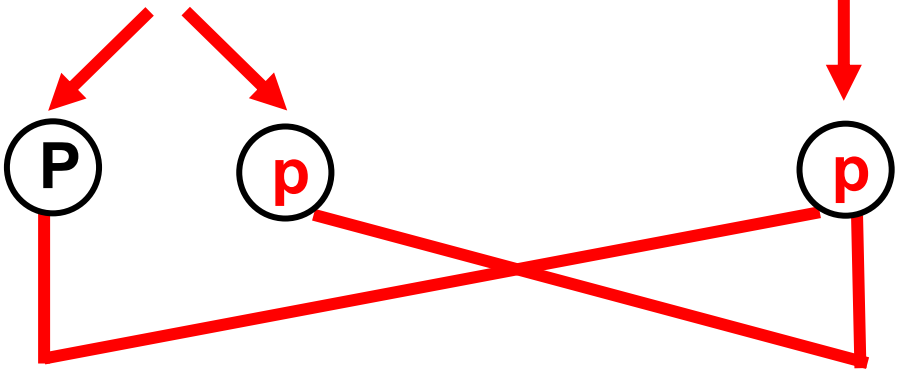


F_2 phenotypic ratio:- 1 purple : 1 white

Monohybrid F_1 Test Cross

Purple flower  White flower 

F_1 test cross: Pp X pp



F_2 genotype : Pp pp

F_2 phenotype : Purple flower  White flower 

F_2 genotypic ratio : 1 Pp : 1 pp

F_2 phenotypic ratio: 1 Purple : 1 White

Summary ~ Monohybrid Crossing

- **F_1 self cross (Pp x Pp) :-**

F_2 genotypic ratio : 1 PP : 2 Pp : 1 pp

F_2 phenotypic ratio: 3 Purple : 1 White

- **F_1 test cross (Pp x pp) :-**

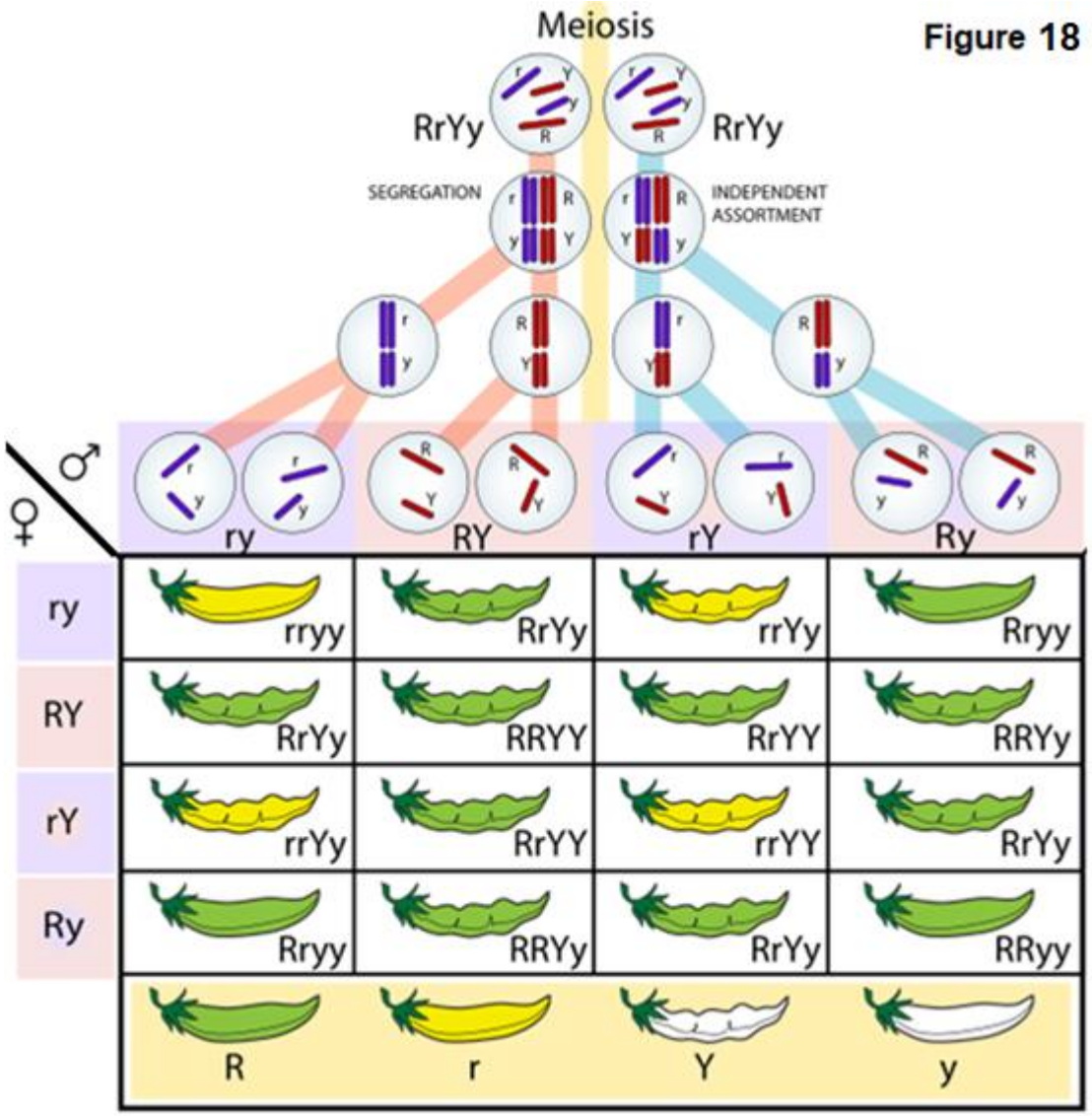
F_2 genotypic ratio : 1 Pp : 1 pp

F_2 phenotypic ratio: 1 purple : 1 white

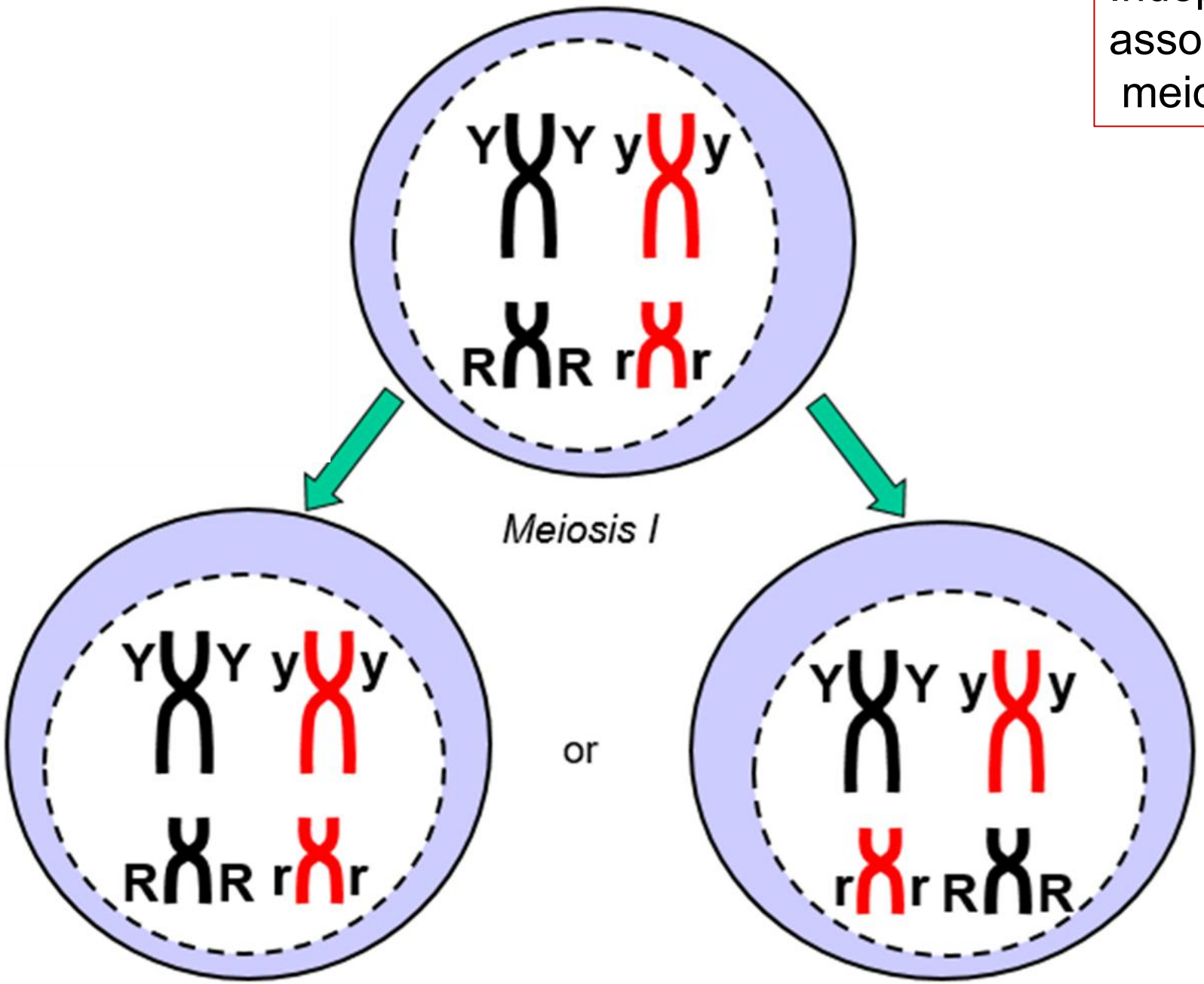
Mendel's 2nd Law ~ Law of Independent Assortment

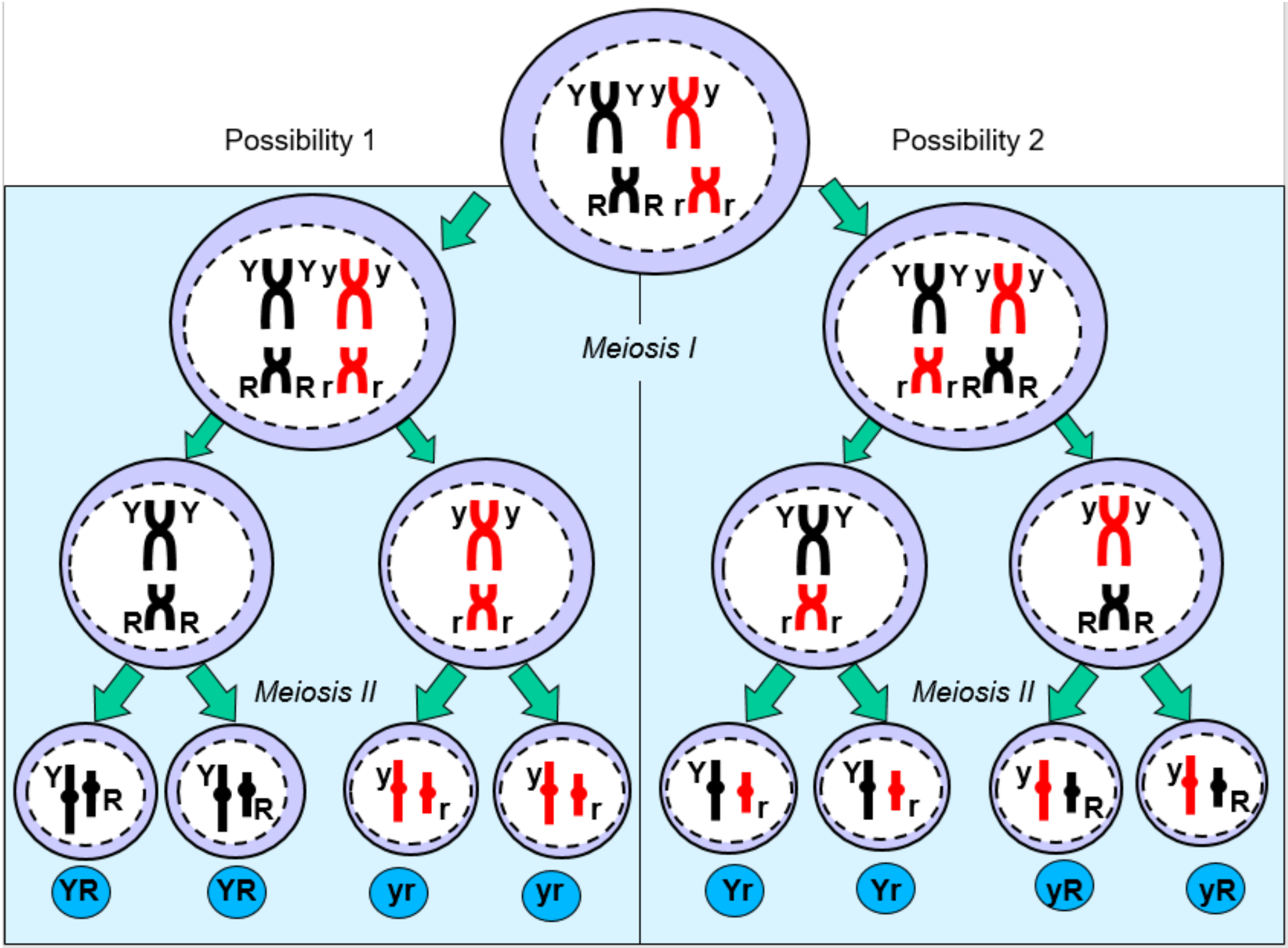
States that :

- Each pair of alleles segregates independently of any other pair of alleles during gamete formation



Independent assortment during meiosis I




Possibility 1
Possibility 2
Meiosis I
Meiosis II
Meiosis II
YR
YR
yr
yr
Yr
Yr
yR
yR

Y : dominant allele for yellow seed; y : recessive allele for green seed
R : dominant allele for round seed; r : recessive allele for wrinkle seed

Parental phenotype : Yellow, round seed X Green, wrinkle seed

Parental genotype : YYRR X yyrr

Gamete : YR, yr

F_1 genotype : YyRr

F_1 phenotype : Yellow, round seed

F_1 x F_1

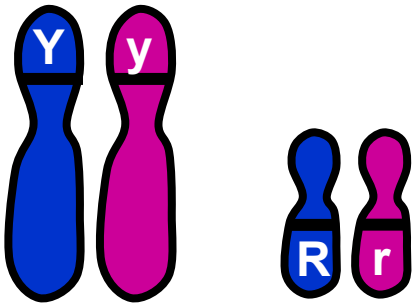
F_1 self cross : YyRr X YyRr

Gametes : YR, Yr, yR, yr X YR, Yr, yR, yr

Four types of gametes produced in F_1 generation

Dihybrid Cross

- 2 characters are observed
- Eg: 1) seed colour
  2) seed shape
- Involves crossing between 2 individuals (true breeding) with different phenotypes
  i. Yellow round seed (homozygous dominant, YYRR)
  ii. Green wrinkle seed (homozygous recessive, yyrr)



Allele Y : dominant allele for yellow seed
Allele y : recessive allele for green seed
Allele R : dominant allele for round seed
Allele r : recessive allele for wrinkle seed

Mendel's Dihybrid Cross Experiment

- 3 steps of Mendel's experiment :
  1) Produce P generation (true breeding)
  2) Produce F_1 generation
  3) Produce F_2 generation

- Mendel study traits in 3 generations of pea plant

Dihybrid Cross

1. Produce P generation (true breeding parents)
   - yellow round seed (YYRR) and green wrinkle seed (yyrr)



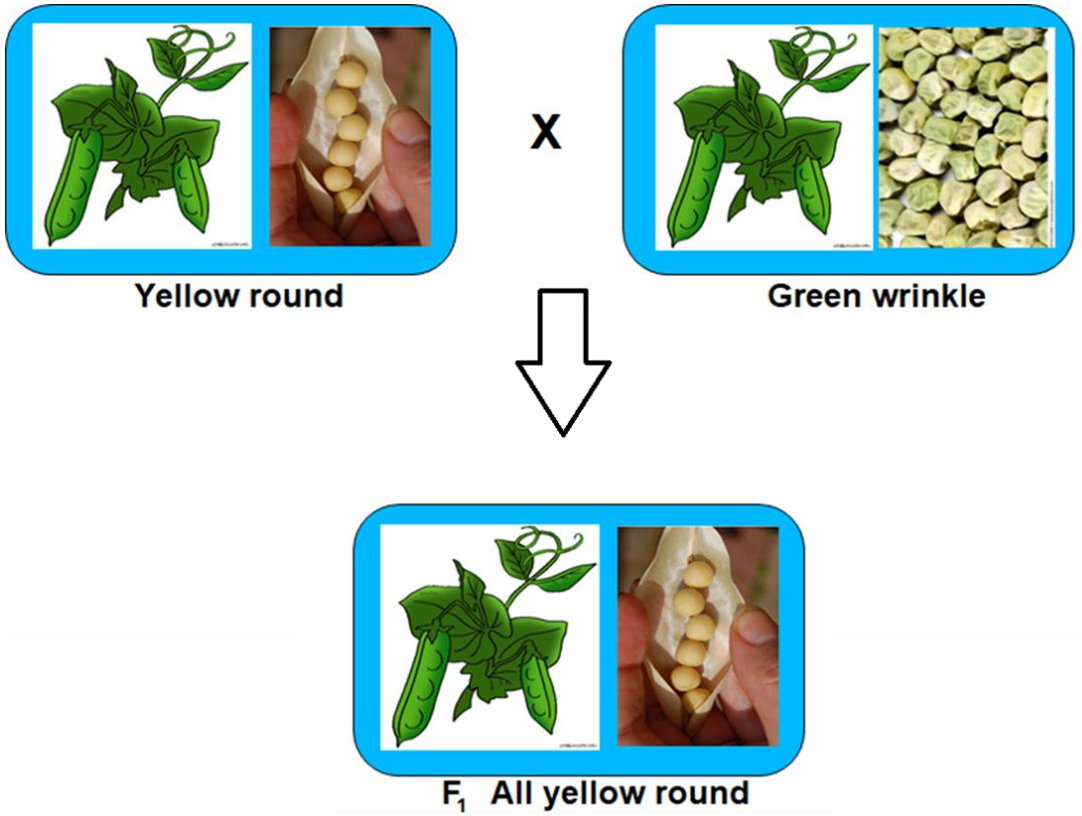
Yellow round



Green wrinkle

Dihybrid Cross

2. Produce F_1 generation
   - 2 true breeding varieties is cross fertilized
   - Results : All F_1 offspring have yellow & round seed



Dihybrid Self Cross

3. Produce F_2 generation
   - F_1 is self fertilized to produce F_2 generation



F_1 X F_1



F_2 generation has 4 phenotypes
- Yellow round
- Green round
- Yellow wrinkle
- Green wrinkle

Y : dominant allele for yellow seed; y : recessive allele for green seed

R : dominant allele for round seed; r : recessive allele for wrinkle seed





Parental phenotype: Yellow, round seed Green, wrinkle seed

Parental genotype: **YYRR** **X** **yyrr**

Gamete : **YR** **yr**

F_1 genotype: **YyRr**

F_1 phenotype: **Yellow, round seed**

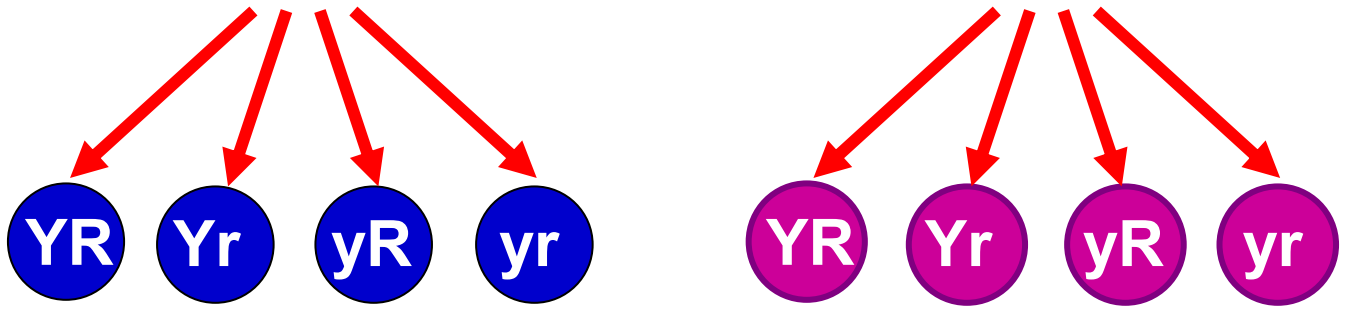


F_1 genotypic ratio : All YyRr

F_1 phenotypic ratio: All yellow, round seed

F_1 phenotype : Yellow, round seed

F_1 x F_1 // F_1 self cross : **YyRr** **X** **YyRr**



F_2 generation: **Punnett square**

Punnett square

F_2 genotype & phenotype:

Gametes	YR	Yr	yR	yr
YR	YYRR Yellow & round seed	YYRr Yellow & round seed	YyRR Yellow & round seed	YyRr Yellow & round seed
Yr	YYRr Yellow & round seed	YYrr Yellow & wrinkle seed	YyRr Yellow & round seed	Yyrr Yellow & wrinkle seed
yR	YyRR Yellow & round seed	YvRr Yellow & round seed	yyRR Green & round seed	yyRr Green & round seed
yr	YyRr Yellow & round seed	Yyrr Yellow & wrinkle seed	yyRr Green & round seed	yyrr Green & wrinkle seed

F_2 phenotypic ratio :-

9 yellow, round seed: **3** yellow, wrinkle seed: **3** green, round seed: **1** green, wrinkle seed

Dihybrid Test Cross

- The genotype YYRR, YyRR, YYRr and YyRr all have the phenotype round and yellow. A test cross can be carried out to determine the genotype of the plant.
- Test cross is conducted between :-
  i. Dominant phenotype (F_1 : yellow round, YyRr)
  ii. Homozygous recessive (green wrinkled, yyrr)
- A genotypic and phenotypic ratio is 1:1:1:1 is obtained

Yellow, round seed  Green, wrinkle seed 

F_1 test cross: **YyRr** **X** **yyrr**

Gametes : **YR** **Yr** **yR** **yr** **yr**

F_2 genotype :	**YyRr**	**Yyrr**	**yyRr**	**yyrr**
F_2 phenotype :	**Yellow, round seed**	**yellow, wrinkle seed**	**green, round seed**	**green, wrinkle seed**

F_2 genotypic ratio : **1** YyRr : **1** Yyrr : **1** yyRr : **1** yyrr

F_2 phenotypic ratio : **1** yellow, round seed : **1** yellow, wrinkle seed : **1** green, round seed : **1** green, wrinkle seed

Dihybrid Test Cross

OR by using Punnett square

Yellow, round seed  Green, wrinkle seed 

F_1 test cross : **YyRr** **X** **yyrr**

Gametes : **YR** **Yr** **yR** **yr** | **yr**

Gametes	YR	Yr	yR	yr
yr	YyRr  Yellow round	Yyrr  *Yellow wrinkle*	yyRr  *Green round*	yyrr  *Green wrinkle*

F_2 genotype & phenotype

F_2 phenotypic ratio :- 1 yellow, round seed **: 1** yellow, wrinkle seed **: 1** green, round seed **: 1** green, wrinkle seed

Summary ~ Dihybrid Crossing

- **F_1 self cross (YyRr x YyRr) :-**

F_2 phenotypic ratio: 9 : 3 : 3 : 1

- **F_1 test cross (YyRr x yyrr) :-**

F_2 genotypic ratio : 1 YyRr : 1 Yyrr : 1 yyRr : 1 yyrr

F_2 phenotypic ratio: 1 : 1 : 1 : 1

LKC : 2023/24 : penggunaan terma tidak lengkap dan tidak tepat semasa pembinaan rajah genetic.
LKC : 2025/26 : Calon memberikan nisbah sahaja tanpa menyebut fenotip,

CHAPTER 4: GENETIC INHERITANCE

4.1 Mendelian genetics: Monohybrid and Dihybrid

4.2 Deviations from the Mendelian Inheritance

4.3 Genetic mapping

LEARNING OUTCOMES

4.2 Deviations from the Mendelian inheritance

a) Explain briefly types of inheritance that deviate from Mendelian:

i. Codominat alleles: Construct the genetic diagram to show codominant alleles using human MN blood group and include phenotypic ratio and genotypic ratio (1:2:1) (C3) Tutorial

ii. Incomplete dominant alleles: Construct genetic diagram to show incomplete dominant alleles using *Antirrhinum* sp. (Snapdragon) flower colour and include phenotypic ratio and genotypic ratio (1:2:1) (C3) Tutorial

iii. Multiple alleles: Construct genetic diagram to show multiple allele using ABO blood group (C3) Tutorial

iv. Polygenes: Explain polygenes/ polygenic inheritance using human skin colour (C3) Tutorial

v. Linked genes: Illustrate the effects on linked genes with crossing over on the dihybrid test cross ratio (C3) Tutorial

vi. Sex-linked genes: Construct genetic diagram to show sex-linked genes using haemophilia. (C4) Tutorial

Deviations from the Mendelian inheritance

i. Codominant alleles
ii. Incomplete dominant alleles
iii. Multiple alleles
iv. Polygenes / Polygenic inheritance
v. Sex-linked genes
vi. Linked genes

REMARK :
-Jika soalan berkaitan probality, pastikan ditulis dalam bentuk pecahan terkecil

i. Codominant alleles

Definition

A condition when both alleles of a locus are fully expressed in a heterozygous

- Both alleles are equally dominant, each affect the phenotype in separate, distinguishable way
- Heterozygous displays a different phenotype from the phenotypes of the homozygous.
- Example: MN blood group

e.g. MN blood group

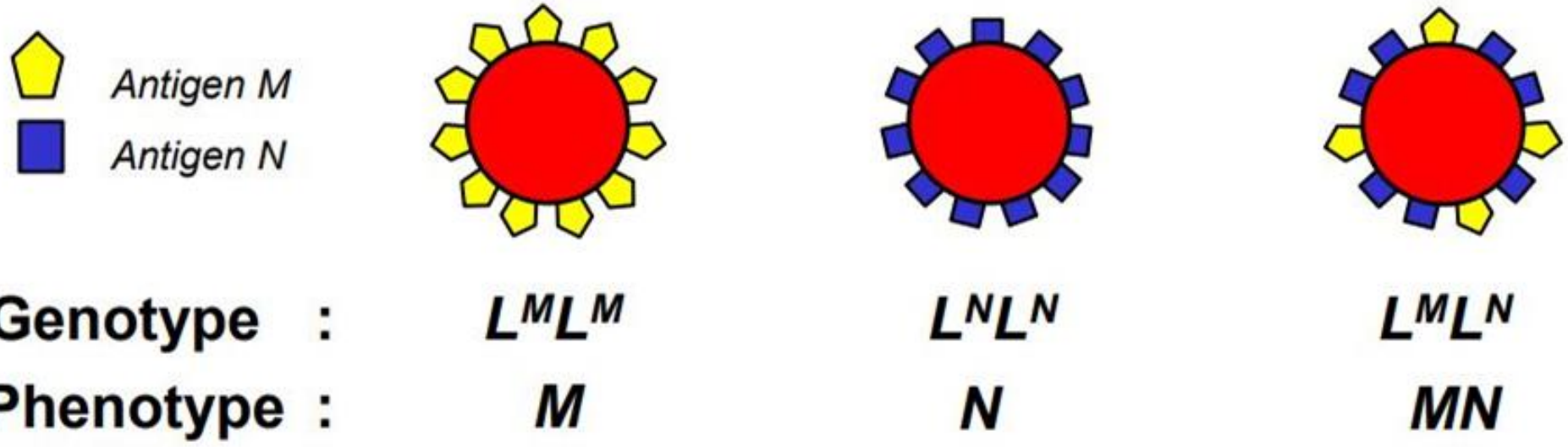
- Due to the presence of two specific molecule (M and N molecules) at the surface of the red blood cell (RBC)

- L^ML^N individuals express both M & N glycoproteins on RBC

Phenotype (blood group)	Genotype	Condition
M	L^ML^M	M glycoprotein on the surface of RBC
N	L^NL^N	N glycoprotein of the surface of RBC
MN	L^ML^N	Both M and N glycoprotein on the surface of RBC

L^M = allele for the ability to produce antigen M

L^N = allele for the ability to produce antigen N

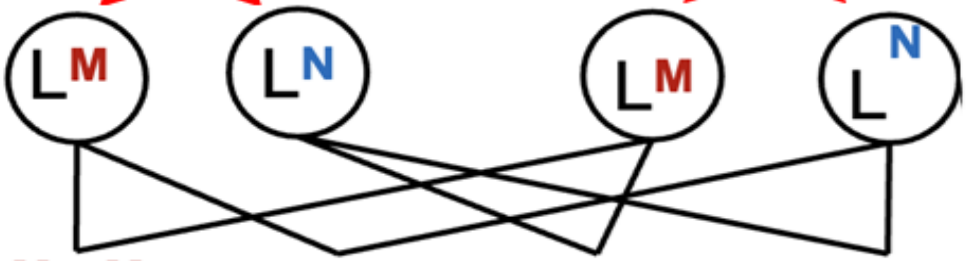


Parental Phenotype	:	M blood group N blood group
Parental Genotype	:	L^ML^M X L^NL^N
Gametes	:	L^M L^N
F_1 Genotype	:	L^ML^N
F_1 Phenotype	:	MN blood group
F_1 Genotypic ratio	:	All L^ML^N
F_1 Phenotypic ratio	:	All MN blood group

F_1 Phenotype : **MN** blood group **MN** blood group

F_1 X F_1 : L^ML^N X L^ML^N

Gametes :



F_2 Genotype : L^ML^M L^ML^N L^ML^N L^NL^N

F_2 Phenotype : **M** blood group | **MN** blood group | **MN** blood group | **N** blood group

F_2 Genotypic ratio : 1 L^ML^M : 2 L^ML^N : 1 L^NL^N

F_2 Phenotypic ratio: 1 **M** blood group : 2 **MN** blood group : **1 N** blood group

ii. Incomplete dominant alleles

Definition

- Neither allele is completely dominant over the other allele
- Phenotype of heterozygotes is intermediate between the phenotypes of homozygous individuals for either allele



Figure 19

e.g. Snapdragon flower colour (*Antirrhinum* sp.)

- Segregation of alleles into gamete of the F_1 plants results in an F_2 generation with a 1:2:1 ratio for both genotype and phenotype.

- Neither allele is fully dominant

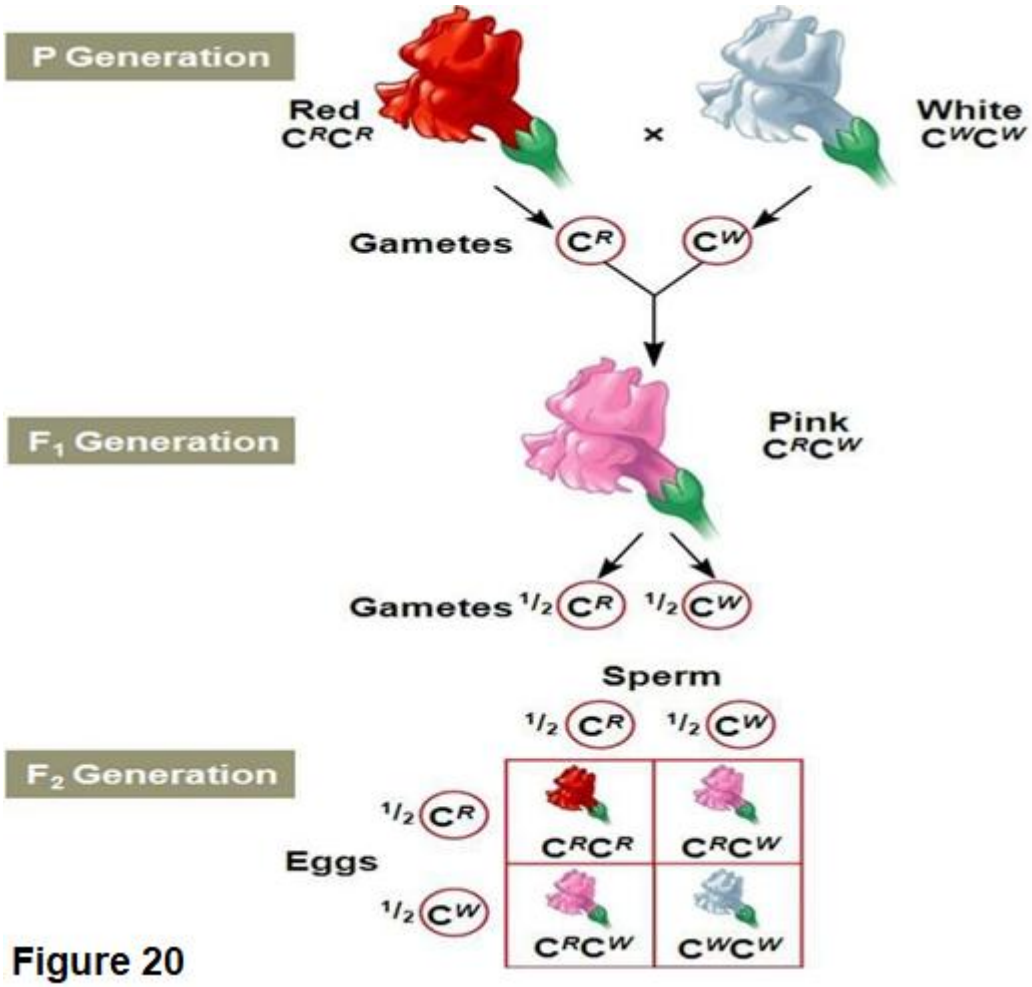


Figure 20

- Controlled by TWO alleles; C^R and C^W
- C^R allele for red flower
- C^W allele for white flower

GENOTYPE	C^RC^R	C^RC^W	C^WC^W
PHENOTYPE	Red 	Pink (intermediate phenotype) 	White 

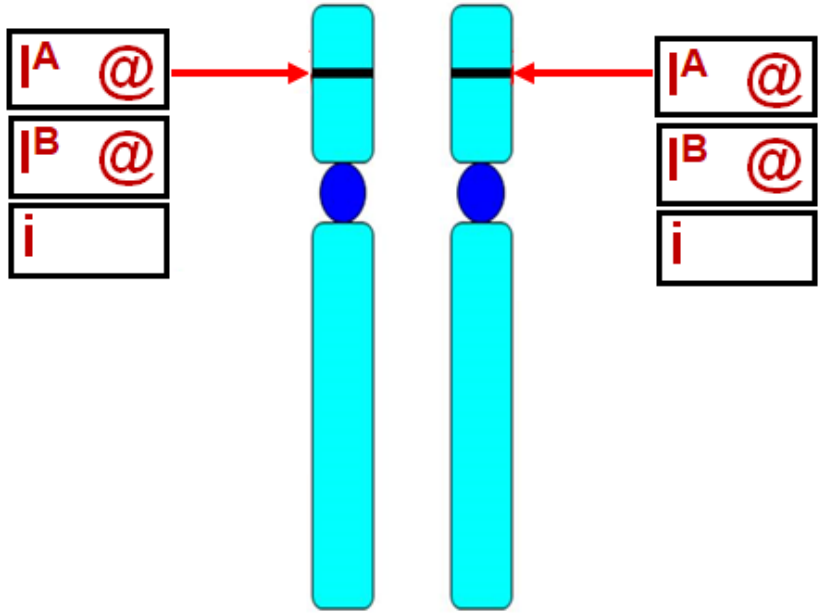
Parental Phenotype	:	Red flower X White flower
Parental Genotype	:	$C^R C^R$ X $C^W C^W$
Gametes	:	C^R and C^W
F_1 Genotype	:	$C^R C^W$
F_1 Phenotype	:	Pink flower
F_1 Genotypic ratio	:	All $C^R C^W$
F_1 Phenotypic ratio	:	All pink flower

		Pink flower Pink flower
F_1 X F_1	:	$C^R C^W$ X $C^R C^W$
Gametes	:	C^R C^W C^R C^W
F_2 Genotype	:	$C^R C^R$ $C^R C^W$ $C^R C^W$ $C^W C^W$
F_2 Phenotype	:	Red Flower, Pink Flower, Pink Flower, White Flower
F_2 Genotypic ratio	:	1 $C^R C^R$: 2 $C^R C^W$: 1 $C^W C^W$
F_2 Phenotypic ratio	:	1 red flower : 2 pink flower : 1 white flower

iii. Multiple alleles

Definition

- Three or more alleles for a given locus exist within the population
- All alleles control the same characteristic



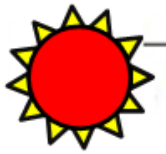
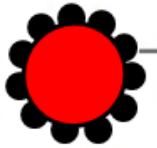
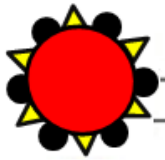
e.g. ABO blood groups in human

- Determine by three alleles of a single gene: I^A, I^B and i
- alleles I^A and I^B are dominant
- allele i is recessive
- I^A and I^B are codominant; both are expressed if the genotype is heterozygous

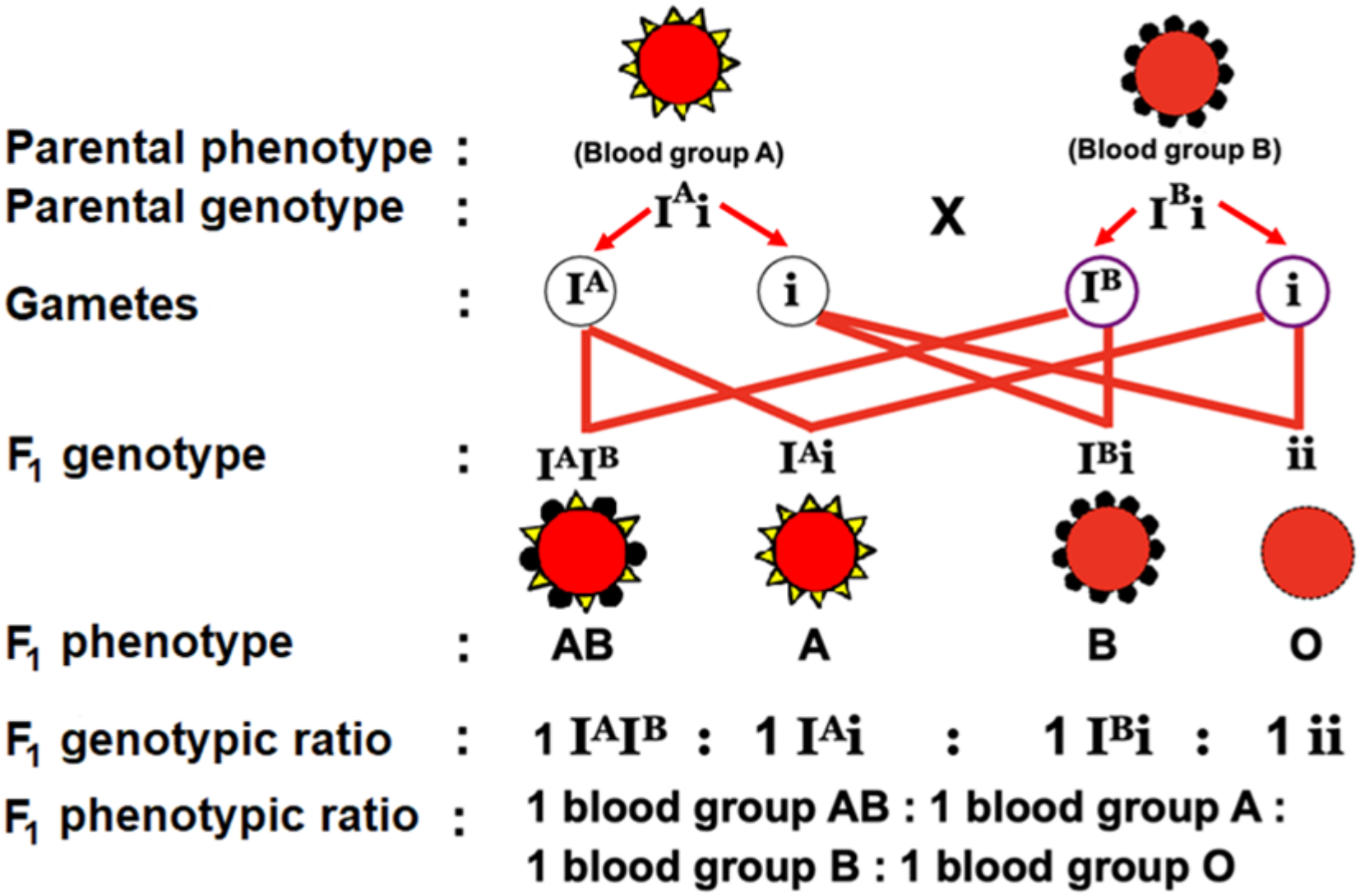
Allele I^A : express antigen A
Allele I^B : express antigen B
Allele i : no antigen

Gametes	I^A	I^B	i
I^A	I^AI^A A	I^AI^B AB	I^Ai A
I^B	I^AI^B AB	I^BI^B B	I^Bi B
i	I^Ai A	I^Bi B	ii O

- 6 possible allele combinations (genotypes)
- 4 possible blood types (phenotypes)

Genotypes	Phenotypes (Blood Group)	Antigen on the surface of RBC
$I^A I^A$ or $I^A i$	A	 Antigen A
$I^B I^B$ or $I^B i$	B	 Antigen B
$I^A I^B$	AB	 Antigen B Antigen A
ii	O	 No antigen

iii. Multiple alleles



iv. Polygenes / Polygenic inheritance

Definition

- An additive effect of two or more genes on a single phenotypic character // A character controlled by two or more genes

- Each dominant allele has a quantitative effect on the phenotype

- Thus, a population shows continuous variation for polygenic character
- Example: human height & skin colour

e.g Human skin colour

- Skin colour in human is controlled by many separately inherited genes (to simplify, we consider only three genes)
- **Dark skin** is controlled by allele A, B, and C.
- **Light skin** is controlled by allele a, b, and c.
- An **AABBCC** person would be very dark, while an **aabbcc** individual would be very fair.
- An **AaBbCc** person would have skin of an intermediate shade.

- The additive effects on the skin colour.
- Environmental factors such as exposure to the sun also affect the skin colour phenotypes.

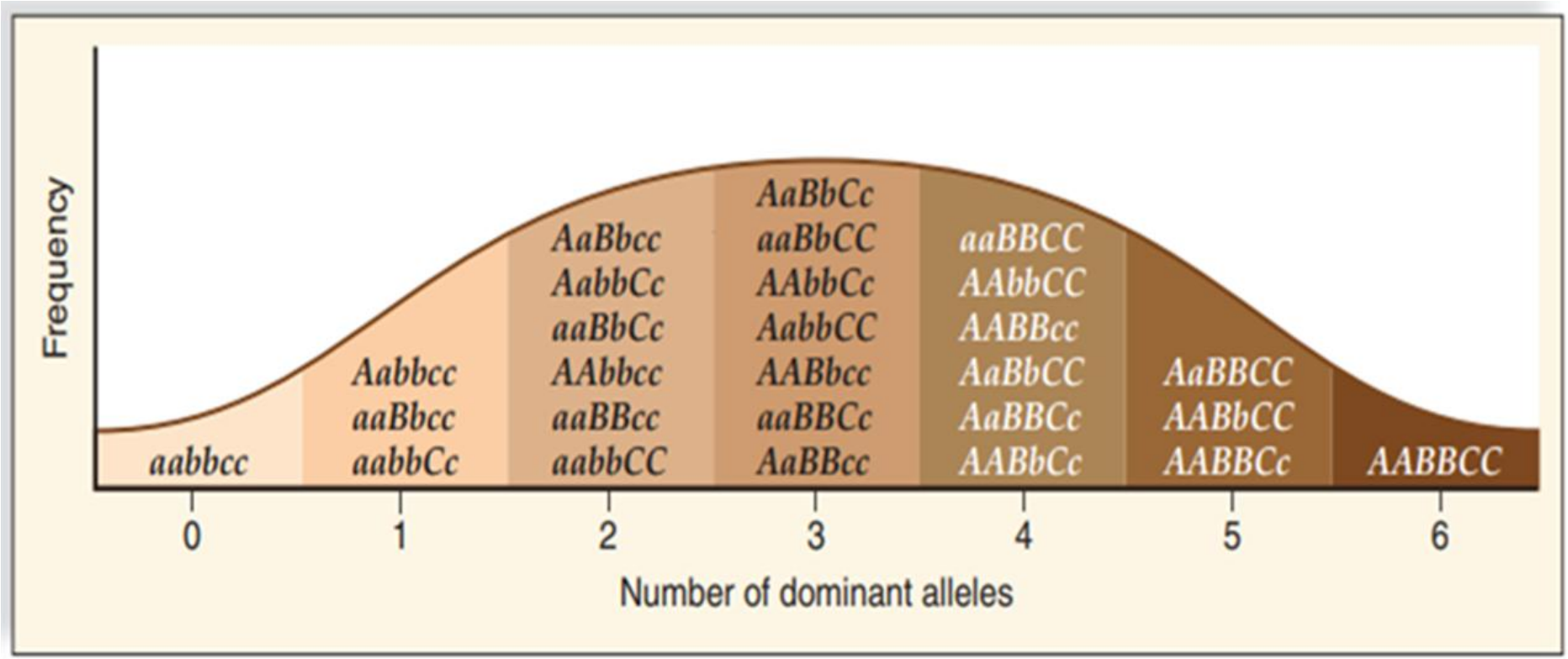


Figure 21

Differences Between Multiple Alleles & Polygenes

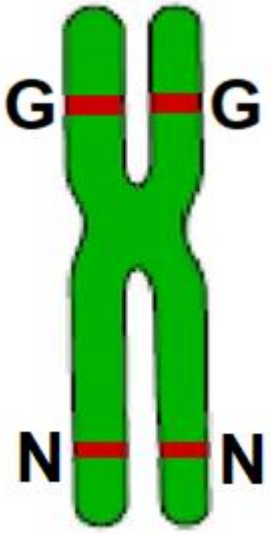
Multiple alleles	Polygenes
One characteristic is controlled by many alleles	One characteristic is controlled by many genes
All alleles are located on same locus	All alleles are located on different locus
Only 2 alleles are required to express the phenotype in an individual.	All alleles are required to express the phenotype in an individual.
No intermediate groups	Has intermediate groups
Discrete distribution curve	Normal distribution curve
Influenced by genetic factor only	Influenced by genetic and environmental factor

v. Linked genes

Definition

- Genes located close enough together on the same chromosome, that tend to be inherited together

- The linked genes cannot be separated independently during meiosis
  - ➢ they **do not follow** the **Law of Independent Assortment**
  - ➢ crossing over can cause recombination of linked genes
    - produce 2 types of offspring; parental types offspring and recombinant type offspring



Effect of Crossing Over on Linked Genes

- Linked genes that are located on the same chromosome can be separated during **crossing over between non-sister chromatids** of a pair of homologous chromosome **during prophase I of meiosis**

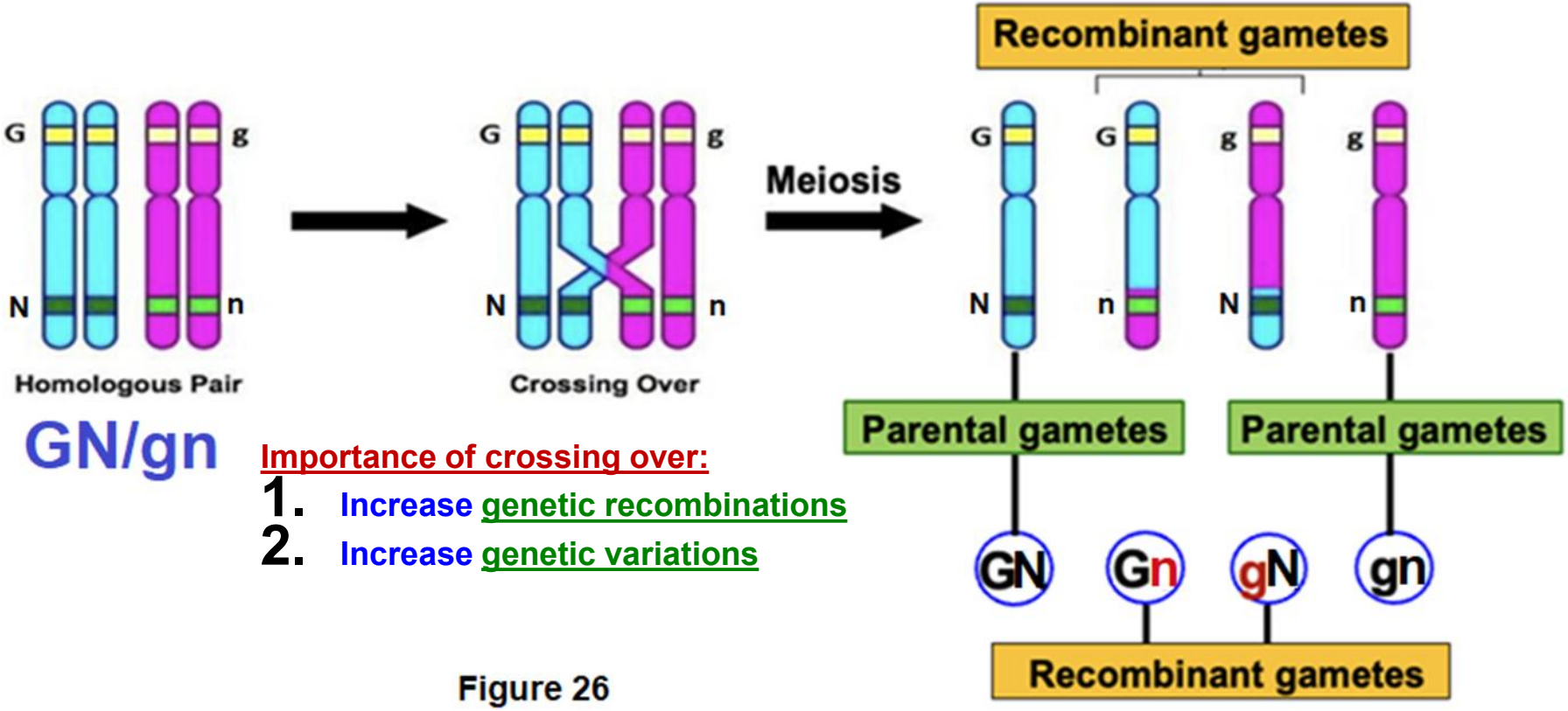


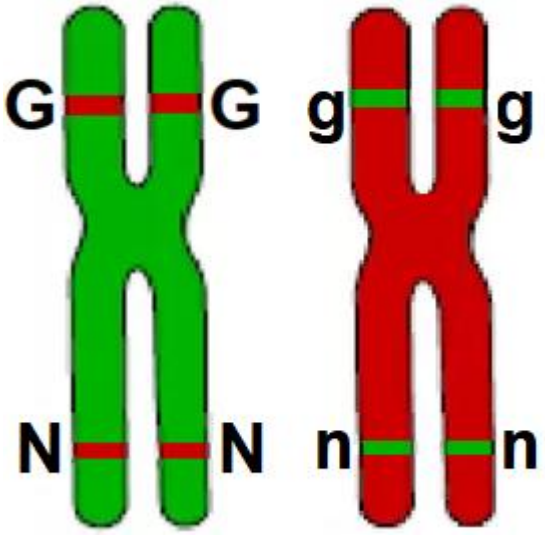
Figure 26

Importance of crossing over:

1. Increase genetic recombinations
2. Increase genetic variations

Representative Symbol

- "Oblique" or slanting line (/)
  - Genes on the left of the oblique are located on the same chromosome.
  - The genes on the right are located on the homologs



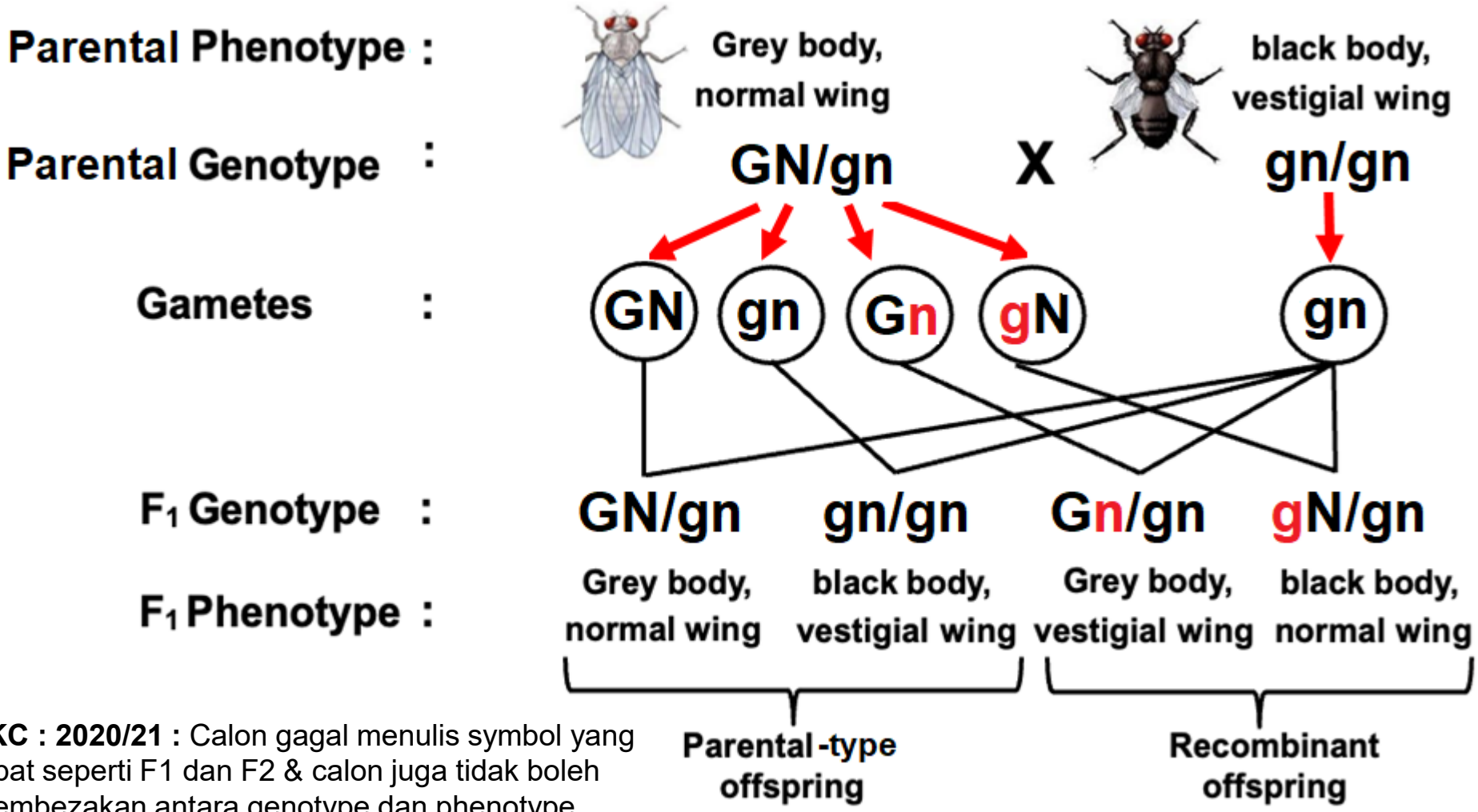
GN/gn

Body colour and wing size of *Drosophila* sp.

Body colour	Wing size	
	Normal	Vestigial
Grey body	Wild type normal 	Gray-vestigial 
Black body	Black-normal 	Black-vestigial 

Figure 27

- **Genes for both characters are linked**
  - Dominant allele for grey body : G
  - Recessive allele for black body : g
  - Dominant allele for normal wings : N
  - Recessive allele for vestigial wings : n



LKC : 2020/21 : Calon gagal menulis symbol yang tepat seperti F1 dan F2 & calon juga tidak boleh membezakan antara genotype dan phenotype. Calon gagal mengenalipasti “Link Gene” maka calon gagal menulis penulisan genetic dengan tepat.

Effect of Linked Genes on dihybrid test cross if crossing over occur

Phenotypic ratio of the **test cross** is **NOT 1:1 or 1:1:1:1**

The offspring produced:

- **Big number** of **parental** combination progenies / parental types
- **Small number** of **recombinant** progenies / recombinant types.

LKC : 2023/24 : Calon tidak memberi alasan yang tepat untuk link gene.
2023/24 : Calon tidak mampu menulis symbol link gene dengan betul
2025/26 : Calon tidak memahami konsep linked gene atau memberi jawapan sebagai kacukan dyhibrid

vi. Sex-linked genes

Definition

- A gene located on either sex chromosome is called a sex-linked gene

- In human, there are 23 pairs of chromosomes
  - 22 pairs of autosomes
  - 1 pair of sex chromosome (for sex determination)

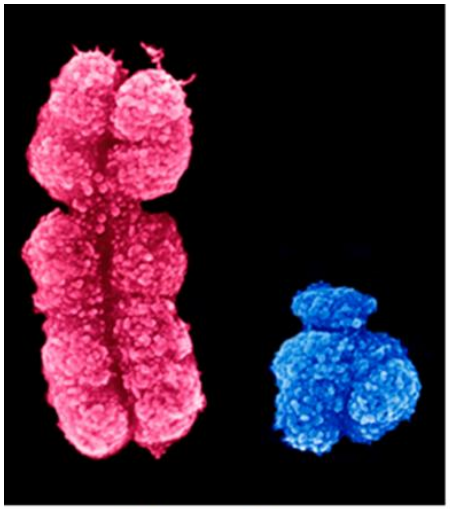


Figure 22

Human Karyotype

Chromosome 1 – 22 :
Autosomal chromosome

Chromosome 23 :
Sex chromosome

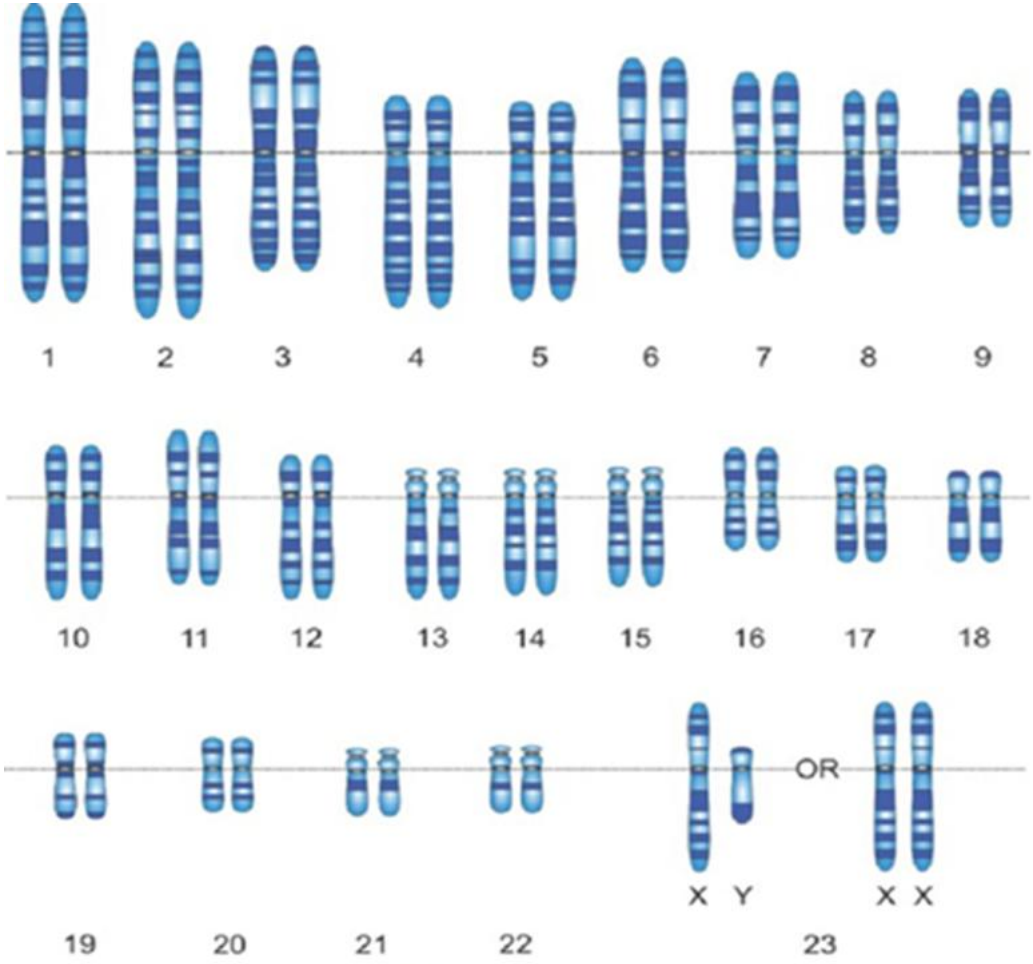


Figure 23

Sex determination in human

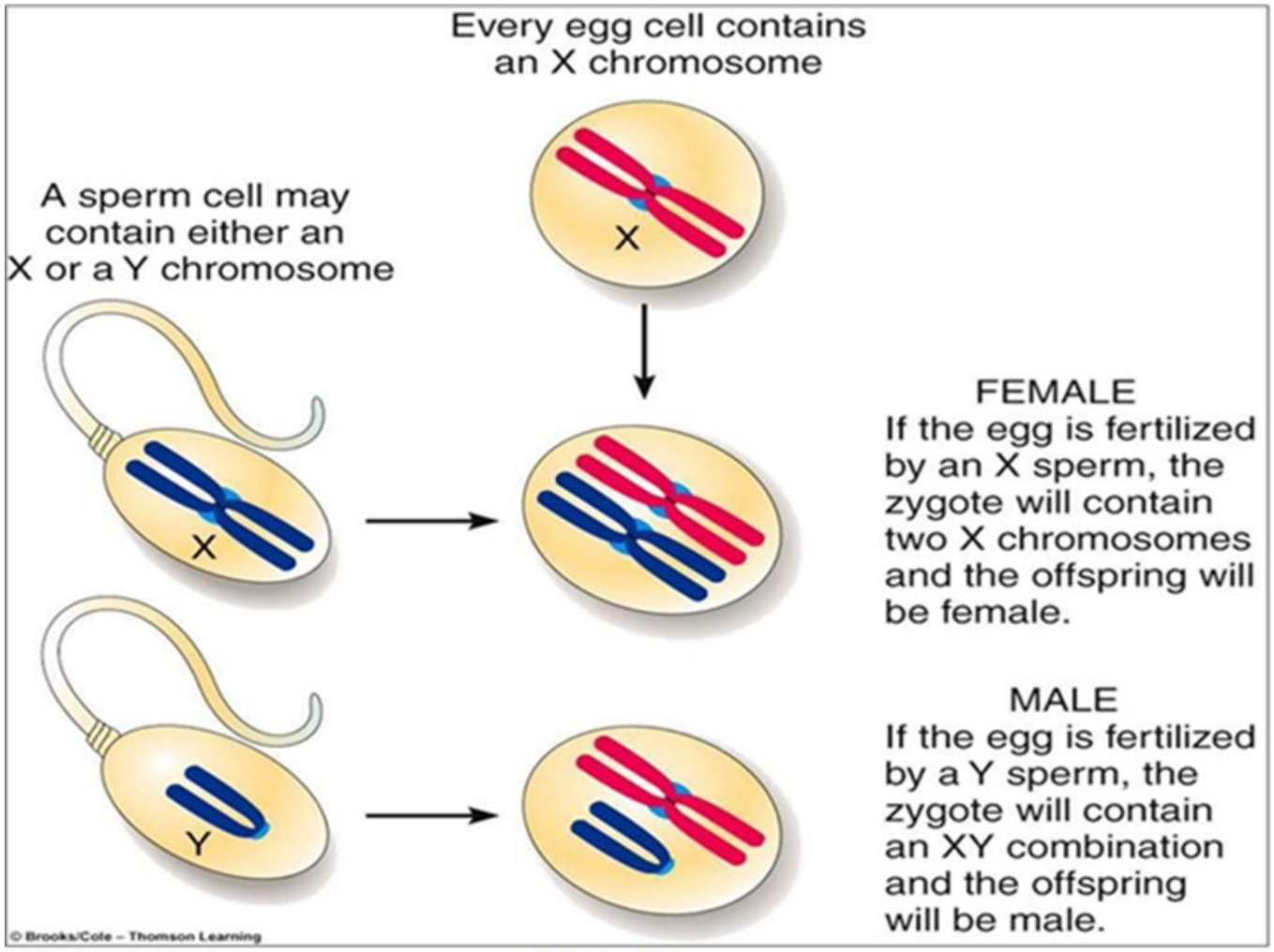


Figure 24

Female : **XX**

Male : **XY**

- X chromosome have many genes that have nothing to do with gender but are located on the X chromosome
- Thus is called **X-linked genes**

- In males, Y chromosome is smaller than X chromosome, thus carries few genes
  - ➢ Half of the genes are expressed only in the testis, and some are required in normal testicular function

- Male is **hemizygous** (neither homozygous nor heterozygous)
- Males usually suffer the effects of sex-linked gene diseases (as they carry only one copy of the X chromosome)

E.g Hemophilia (sex-linked recessive disorder)

Genotype	Phenotype
X^HX^H	**Normal female**
X^HX^h	**Normal female (carrier)**
X^hX^h	**Hemophilic female**
X^HY	**Normal male**
X^hY	**Hemophilic male**

Alleles

H : dominant allele for normal

h : recessive allele for hemophilia

- Defective recessive allele of the gene that controls the factor are located on the X chromosome
- The absence of 1 or more protein required for blood clotting, thus:
  - blood clot slowly
  - prolonged bleeding following injury
  - spontaneous bleeding

E.g Hemophilia (sex-linked recessive disorder)

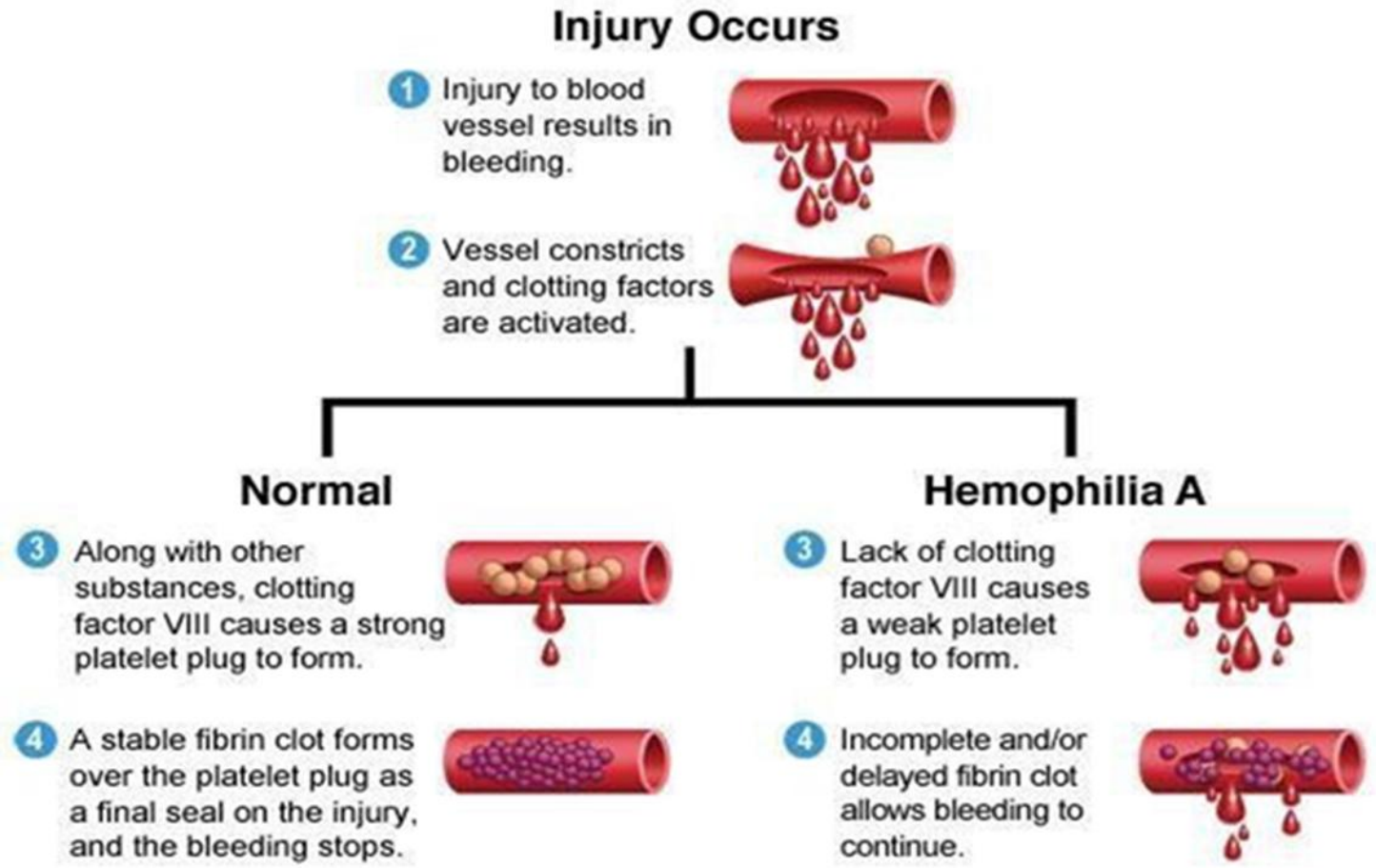


Figure 25

H : dominant allele for normal
h : recessive allele for hemophilia

Example 1

Parental Phenotype	:	Normal female		Haemophilic male
Parental Genotype	:	X^HX^H	X	X^hY
Gametes	:	X^H		X^h, Y
F_1 Genotype	:	X^HX^h		X^HY
F_1 Phenotype	:	Normal female (carrier)		Normal male
F_1 Genotypic ratio	:	X^HX^h	:	X^HY
F_1 Phenotypic ratio	:	1 Normal female (carrier)	:	1 Normal male

H : dominant allele for normal
h : recessive allele for hemophilia

Example 2

Parental Phenotype : Carrier female × Haemophilic male

Parental Genotype : X^HX^h × X^hY

Gametes : X^H, X^h × X^h, Y

F_1 Genotype : X^HX^h, X^HY, X^hX^h, X^hY

F_1 Phenotype : Normal female (carrier), Normal male, Haemophilic female, Haemophilic male

F_1 Genotypic ratio : 1 X^HX^h : 1 X^HY : 1 X^hX^h : 1 X^hY

F_1 Phenotypic ratio : 1 Normal female (carrier) : 1 Normal male : 1 Haemophilic female : 1 Haemophilic male

LKC : 2022/23 : Calon tidak menulis simbul cross (X) pada bahagian kacukan parental genotype semasa pembinaan rajah genetic.
Calon gagal menyenaraikan kesemua genotype yang terhasil dari kacukan tersebut.
Calon juga gagal memberikan alasan betul kepada corak pewarisan anak yang bebas dari penyakit hemofilia.

CHAPTER 4: GENETIC INHERITANCE

4.1 Mendelian genetics: Monohybrid and Dihybrid

4.2 Deviations from the Mendelian Inheritance

4.3 Genetic mapping

LEARNING OUTCOMES

4.3 Genetic Mapping

a) Define genetic mapping (C1) Lecture

b) Explain genetic mapping in relation to recombinant frequency during meiosis (C3) Tutorial

c) Calculate the genetic distance (map unit) between genes using the given recombination data (C3) Tutorial

d) Identify the position or order of genes along a chromosome based on recombination data (C3) Tutortial

Genetic Mapping

Definition

- **Genetic map is an ordered list of the genetic loci along a particular chromosome**

- **A technique used to study the relative position and sequence of genes on a chromosome**

Genetic Mapping

- Can be done only to **linked genes and if crossing over takes place.**
- Genes that are very close to each other cannot be separated by crossing over during meiosis. Usually they are inherited together, they seldom recombine.
- Genes that are **far** from each other have **higher probability** that a **crossing over will occur** between them. Therefore the higher the recombination frequency.
- The recombination frequency is the percentage of recombinant offspring in the total pool of offspring.

Genetic Mapping

- Crossing over produce new combination of genes
- Offspring having new combination of genes are *recombinants*
- The proportion of recombinants offspring from a test cross is used to calculate the ***cross over value***, (a.k.a as ***recombination frequency***)
- **Cross over value** is **used to calculate the distance between 2 genes involved**
- The **lower the value**, the **closer the genes**

Genetic Mapping

- The following formula is used to determine crossing over value or recombination frequencies value

$$\text{Cross over value/ COV @ Recombination frequencies} = \frac{\text{Total number of recombinant offspring}}{\text{Total number of offspring}} \times 100$$

Genetic Mapping

- Distances between genes are expressed in **map unit (m.u) or centiMorgan (cM)**
- **One map unit** as equivalent to a **1% recombination frequencies**
- **Calculation can be accepted until ONE or TWO decimal place**

Dominant allele for grey body : *G* **Recessive allele for black body : *g***
Dominant allele for normal wing : *N* **Recessive allele for vestigial wing : *n***

- The F_2 offspring obtained from F_1 test cross are as follows:-
  - Grey body, normal wings : 237 } ***Parental-type offspring***
  - Black body, vestigial wings : 241 }
  - Grey body, vestigial wings : 44 } ***Recombinant offspring***
  - Black body, normal wings : 48 }

$$\text{Cross over value /recombination frequency} = \frac{\text{Total number of recombinant offspring}}{\text{Total number of offspring}} \times 100$$

$$= \frac{44 + 48}{237+241+44+48} \times 100 = 16.14\%$$

Distance between genes = 16.14 map unit @ centiMorgan

Genetic Mapping

Genotype	Individuals	
CS/cs	480	Parental-type offspring
cs/cs	480	
Cs/cs	20	Recombinant offspring
cS/cs	20	
Total	**1000**	



Crossing over value = 40/1000 x 100 = 4%

Distance between two genes = 4 centiMorgan @ map unit

Genetic Mapping

- P, Q, R and S genes are linked. Crossing over values are:
  - P and Q : 35%
  - P and R : 5%
  - R and Q : 40%
  - Q and S : 10%
  - R and S : 30%

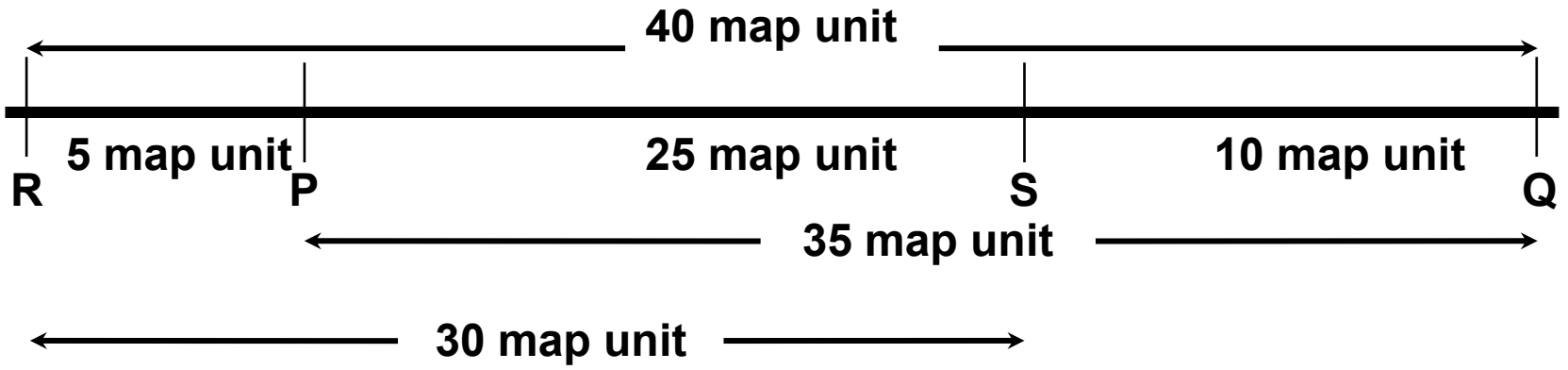
Find the relative position of these genes.

Tips : start with the highest crossing over values (the farthest genes)

LKC : 2021/22 : Calon gagal menulis Langkah dengan tepat dalam pengiraan jarak antara gene.
2023/24 : Calon tidak menyatakan unit untuk jarak antara gene-gene.
2023/24 : Calon tidak menyatakan formula sebelun jalan pengiraan.
2023/24 : Calon tidak memberikan titik perpuluhan atau memberikan lebih 2 titik perpuluhan.
2024/25 : Calon tidak meletakkan istilah“distance” atau menggunakan simbol % pada kerja kiraan

Genetic Mapping

- P, Q, R and S genes are linked. Crossing over frequencies are:
  - P and Q : 35% ✓
  - P and R : 5% ✓
  - R and Q : 40% ✓
  - Q and S : 10% ✓
  - R and S : 30% ✓



Position or order of genes P, Q, R and S along a chromosome is RPSQ or QSPR

Genetic Mapping

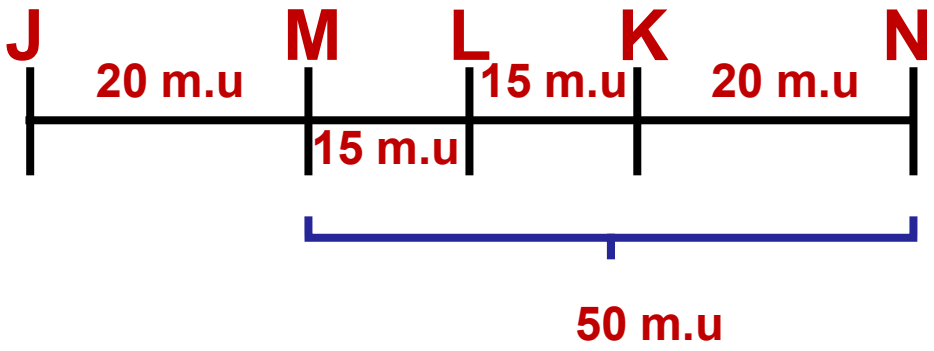
- J, K, L, M and N are linked genes.
- The percentage of crossing over between genes is

J with M = 20%
J with L = 35%
J with N = 70%
L with K = 15%
M with N = 50%
M with L = 15%

- State the sequence of gene along the chromosome

Genetic Mapping

J with M	= 20%	✓
J with L	= 35%	✓
J with N	= 70%	✓
L with K	= 15%	✓
M with N	= 50%	✓
M with L	= 15%	✓



Sequence of genes: **J, M, L, K, N**

REFERENCES

- Campbell N.A , Urry L.A,Cain M.L, Wasserman S.A, Minorsky P.V, Reece J.B Biology, 12th ed. (2021), Pearson Education, Inc.
- Solomon E.P & Martin C.E., Martin C.W., Berg, L.R, Biology, 11th ed. (2019) Thomson Learning, Inc.
- Mader S.S & Windelspecht M., Biology, 12th ed. (2016) McGraw-Hill Education
- Raven, P. H., Johnson, G. B. & Mason, K. A. (2018). Biology. (10th ed). McGraw-Hill.

** *Notes: All reference is referred to hardcopy books (including pages)*
A slight difference between paging in e-book and hardcopies

REFERENCES (FIGURE)

- Figure 1 – Solomon (11th ed. pg 233)
- Figure 2 – Adapted from unknown author, licensed under CC BY-SA-NC
- Figure 3 – Campbell (12th ed. page 323)
- Figure 4 – https://images.app.goo.gl/Dg5UEv7CmhE2wT4b7
- Figure 5 – by unknown author, licensed under CC BY-SA-NC
- Figure 6 – https://www.quora.com/What-does-the-term-true-breeding-lineage-mean
- Figure 7 – https://geoffneilsen.wordpress.com/navigation/nineteenth-century/gregor-mendel-1822-84-2/
- Figure 8 – https://quizizz.com/admin/quiz/590085435531151000c9696c?source=quiz_share
- Figure 9 – Mader 12th ed page 187
- Figure 10 – Adapted from Campbell 12th ed page 322
- Figure 11 – https://people.wou.edu/~lemastm/Teaching/BI102/Chapter%2012%20-%20Inheritance%20%282%29.pdf
- Figure 12 - https://www.ck12.org/section/mendel's-investigations-%3a%3aof%3a%3a-gregor-mendel-and-genetics/
- Figure 13 – https://slideplayer.com/slide/8339613/
- Figure 14 – Mader 12th ed page 188
- Figure 15 – Adapted from https://people.wou.edu/~kissanek/Handouts/Handouts/6_Chapter%2012%20-%20Inheritance.pdf
- Figure 16 – Adapted from Copyright © 2009 Pearson Education, Inc.
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- Figure 19 – https://pixels.com/featured/snapdragons-john-kaprielian.html
- Figure 20 – Campbell 12th ed page 329
- Figure 21 – Mader 12th ed page 200
- Figure 22 – https://www.crick.ac.uk/news/2017-01-26-new-insights-into-infertility-causing-sex-chromosome-disorders
- Figure 23 – http://saa.uaic.ro/ancestral-dna-%e2%80%95-an-incontestable-source-of-data-for-archaeology/
- Figure 24 – https://slideplayer.com/slide/12817027/
- Figure 25 – https://www.semanticscholar.org/paper/A-Study-on-the-Coagulation-Profile-and-Its-of-the-Priya/51b8124a887e102844c5cfb391cc8de2952ea975?utm_source=direct_link
- Figure 26 – adapted from https://slideplayer.com/slide/8759359/
- Figure 27 – adapted from https://ib.bioninja.com.au/higher-level/topic-10-genetics/102-dihybrid-crosses-and.html