The genetic material is found primarily in the nucleus of the cell and that it is organized in the form of chromosomes. We will explore how the genetic material is inherited from generation to generation and the changes in the organization of the genetic material that occur between generations. This subdiscipline of genetics is called Mendelian Genetics after Gregor Mendel who discovered the laws of inheritance with his experiments on garden peas.

HERITAGE FROM MENDEL

Mendel's Crossing Experiments with Peas

In 1865, the Austrian monk Gregor Mendel began his series of crossing experiments with garden peas. By any standard, Mendel was a very gifted scientist who appreciated the importance of carefully designing and interpreting his experiments. Mendel sought to understand the patterns of inheritance of seven different characters in peas (table below) by crossing plants with identifiably different **phenotypes** of a particular character, and then following the presence or absence of the character in successive generations. The traits Mendel studied were morphological attributes of the seed, pod, flower and stem (table below).

Table. Seven Pea-Plant characters studied by Mendel

| Character	Dominant Trait	×	Recessive Trait
Flower color	Purple	×	White
Flower position	Axial	×	Terminal
Seed color	Yellow	×	Green
Seed shape	Round	×	Wrinkled
Pod shape	Inflated	×	Constricted
Pod color	Green	×	Yellow
Stem length	Tall	×	Dwarf

The types of crosses Mendel made are still widely used in genetics today. Unfortunately, Mendel's discoveries were largely ignored during his lifetime, and it was not until 1900 that his work was rediscovered by three European scientists, Hugo de Vries, Carl Correns, and Erich von Tschermak and its importance finally appreciated. Mendel's findings allowed other scientists to predict the expression of traits on the basis of mathematical probabilities.

Why peas?

· Can be grown in a small area

· Produce lots of offspring

· Available in many varieties with distinct heritable features with different variations: flower color, seed color, seed shape, etc.

· Produce pure plants when allowed to self-pollinate (*Self-fertilization* can occur in the same flower) for several generations
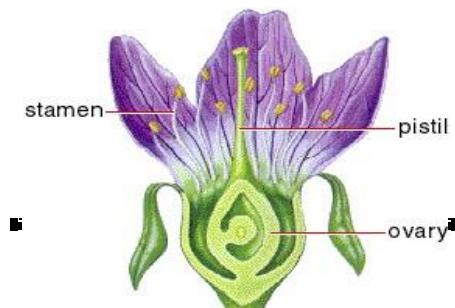
· Can be artificially cross-pollinated   (*Cross-fertilization* can occur between different flowers)
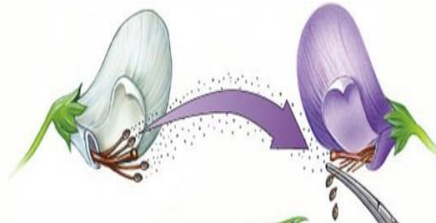
· Mendel had <u>strict control</u> over which plants mated with which:

1. Peas contain both gametes (♀/♂) in the same flower

2. Pollen contains sperm produced by the stamen (♂)

3. Ovary contains eggs inside the flower (♀)

4. Pollen carries sperm to the eggs for fertilization

MENDELIAN TERMS

Gene: A part of the genetic material that carries information about a specific character. Genes are found on chromosomes and each gene has a designated place on every chromosome, called a locus. Each gene is signed by at least 2 alleles.

Character: Heritable feature that varies among individuals (eg. flower color).

Trait: A variant for character, such as white or purple colors for flowers.

Alleles- alternative form or version of a single gene passed from generation to generation. Each allele is at specific locus responsible for a trait of the character which the gene controls (photo below). They are referred to by letters (capital and small).
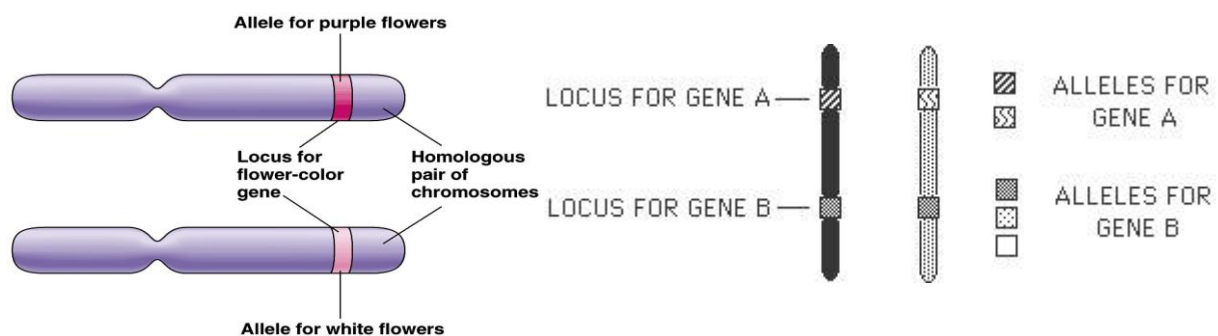

Phenotype - the way an organism looks and behaves (tall or short or color,…)

Genotype - it is the genetic make-up and can give the information about the gene combination an organism contains either homozygous or heterozygous alleles (TT, Tt, tt). If they can't determine the second allele in any dominant pair they can again use "_" to signify that the allele could be Dominant or recessive, and that there isn't enough information to determine which it is or that don't matter.

Homozygous: The individual is called homozygous for certain character If the two alleles controlling such character are similar (TT or tt).

Heterozygous: The individual is called heterozygous for certain character If the two alleles controlling such character are Different (Tt).

purple   PP   homozygous dominant

purple   P*p*   heterozygous
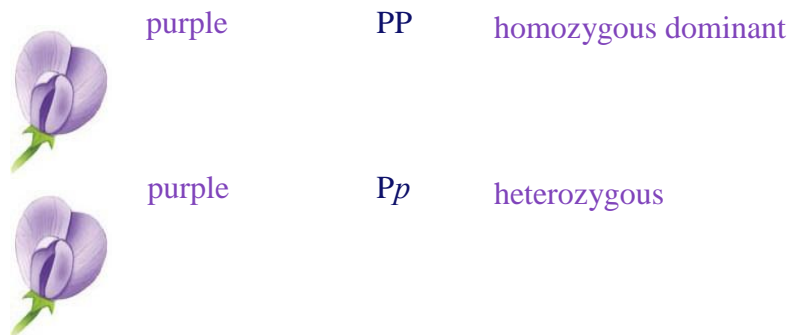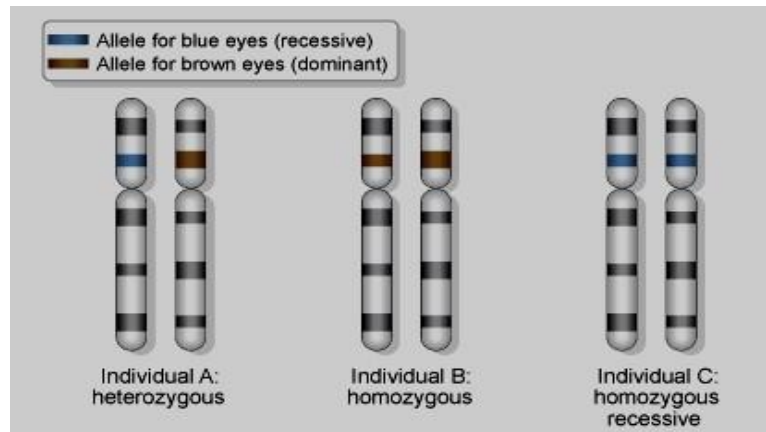
Dominant and Recessive in genetics is a relationship between alleles of a single gene. In heterozygous individual one allele is expressed (the trait it controlled appears) and the other allele is not expressed or masked (the trait it controlled does not appear). The expressed allele and its trait are dominant (sign by capital letter), while the not expressed or masked allele and its trait is recessive (sign by small letter).

Dominant gene that produces the same phenotype in the organism whether or not its allele identical.

Recessive gene is an allele that causes a phenotype (visible or detectable characteristic) that is only seen in a homozygous genotype (an organism that has two copies of the same allele) and never in a heterozygous genotype.
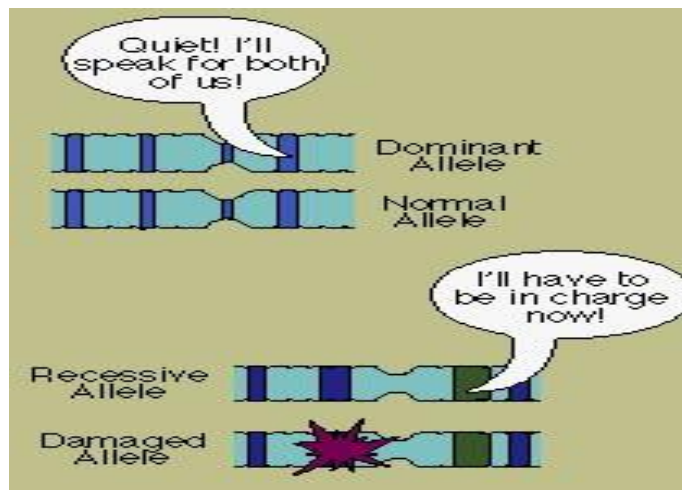
Genetic cross -breeding or mating of two different individuals resulting in offspring that carries a portion of the genetic material of both the parent individuals.

Monohybrid crosses - the two parents differ by a single trait (eg. height).

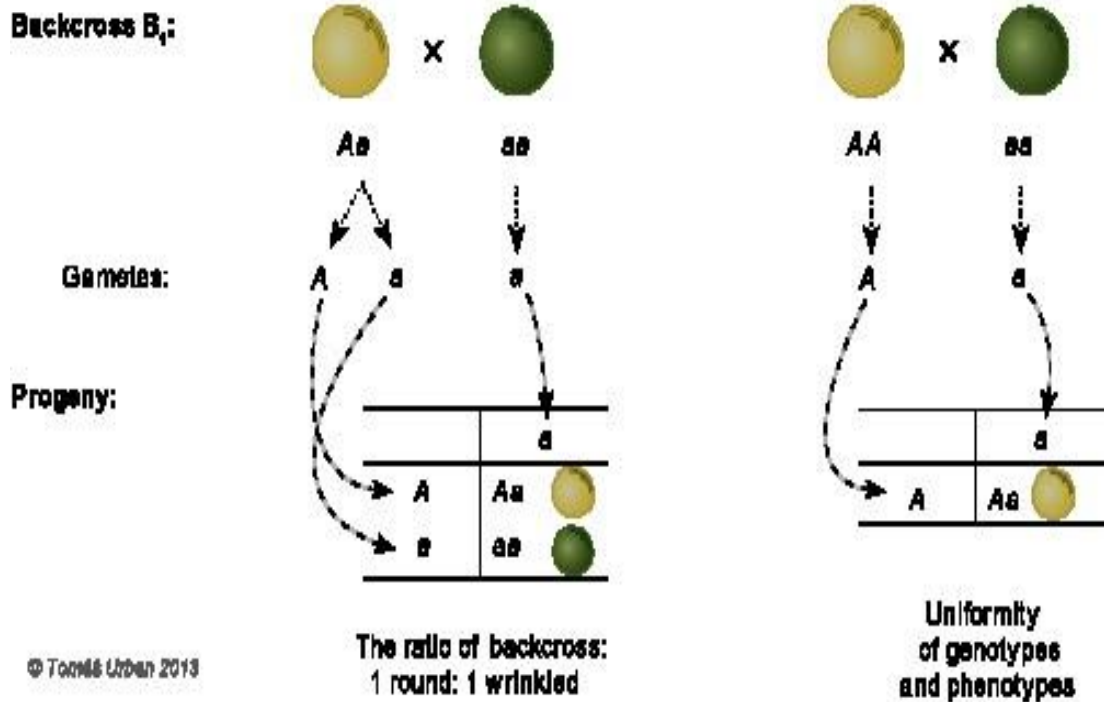**Dihybrid cross -** the two parents differ by two different traits (eg. height and color).

Trihybrid cross- the two parents differ by three different traits (eg. Shape and color of pea seeds and the shape of the pod).

Test cross- is used to determine the unknown genotype of a particular phenotype. If an organism has the dominant phenotype, you can't be sure whether it is homozygous dominant or heterozygous. By crossing it with a homozygous recessive individual (tester), you can infer the genotype by observing the offspring.
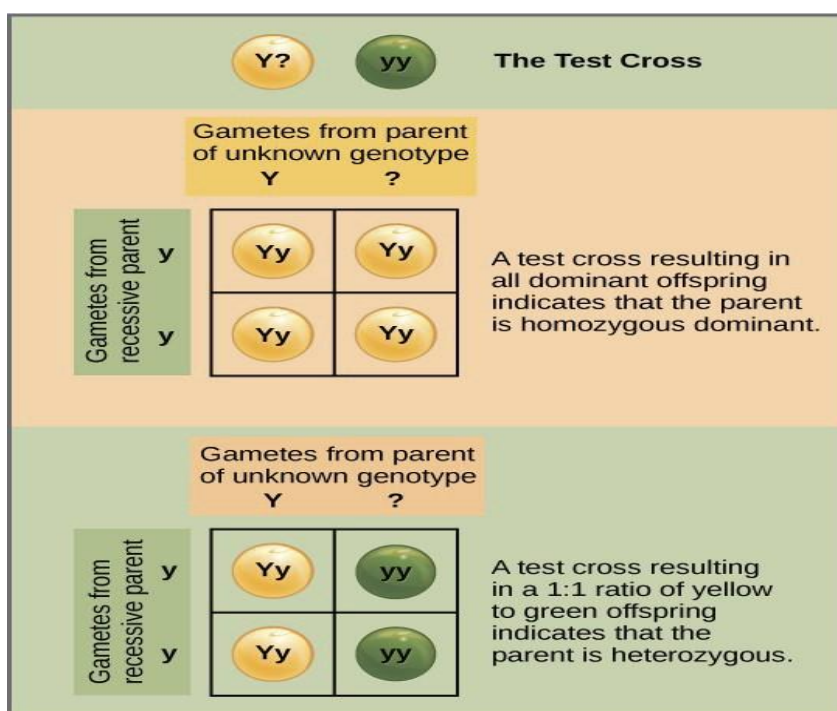
Backcross: The process of crossing a hybrid with its parent or with another individual with genotype similar to its parent.

Backcross of monohybride (evidence of heterozygous genotypes) and cross of homozygous forms

Backcross B₁:

Gametes:

Progeny:

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The ratio of backcross:
1 round: 1 wrinkled

Uniformity
of genotypes
and phenotypes

P₁ generation - "parent" - the original true-breeding parents (♀/♂)

F₁ generation - "filial" (or son or daughter) offspring of the parent plants

F₂ generation or "second filial generation" (or granddaughter or grandson)

Phenotypic ratio- a ratio that shows the different outcomes after a cross based on physical appearance alone.

Genotypic ratio is the proportion of genotypes found in individuals after a cross.

GENOTYPE   PHENOTYPE

PP
(homozygous)   Purple

Pp
(heterozygous)   Purple

Pp
(heterozygous)   Purple

pp
(homozygous)   White

Genotypic ratio (1:2:1) Phenotypic ratio (3:1)

Dept. Biol. Penn State ©2002

Punnett Squares - a shorthand way of finding the expected proportions of possible genotypes in the offspring of a cross invented by an English biologist Reginald Punnett (1905).
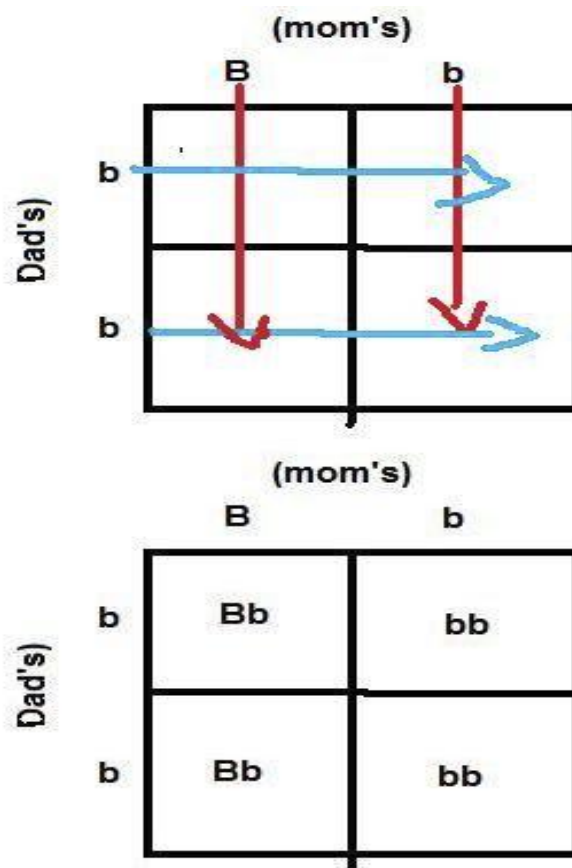
MENDEL RULE AND LAWS

In Mendelian inheritance, the character is controlled by one gene only (**monogenic traits)** and inherited in a simple fashion through the nucleus as follows. Mendel believed that all units of inheritance are passed on to offspring unchanged.

Rule of Dominance

Complete dominance occurs when only one allele (**dominant**) accounts for the phenotypic expression in heterozygotes. In heterozygotes, the unexpressed allele is called **recessive**.

Dominant character is sign either by 2 capital letters (eg TT for homozygous tallness) or 1 capital and one small letter (eg Tt for heterozygous tallness) and recessive character appear when signed by 2 small letters (eg tt for homozygous shortness).

For example (figure below):

Pea plants have 2 genes that control each trait located on the chromosomes.

Pea plants (P generation) that have at least 1 allele for tallness (TT or Tt) are tall because the allele for tallness is dominant over the allele for shortness. The only way a plant can be short is if both height alleles are for a short plant (tt). Dominant trait appears in the F_1 generation, while recessive trait disappears in the F_1 generation. The 2 alleles are located on different copies of a chromosome - one copy inherited from the female parent and one from the male parent.
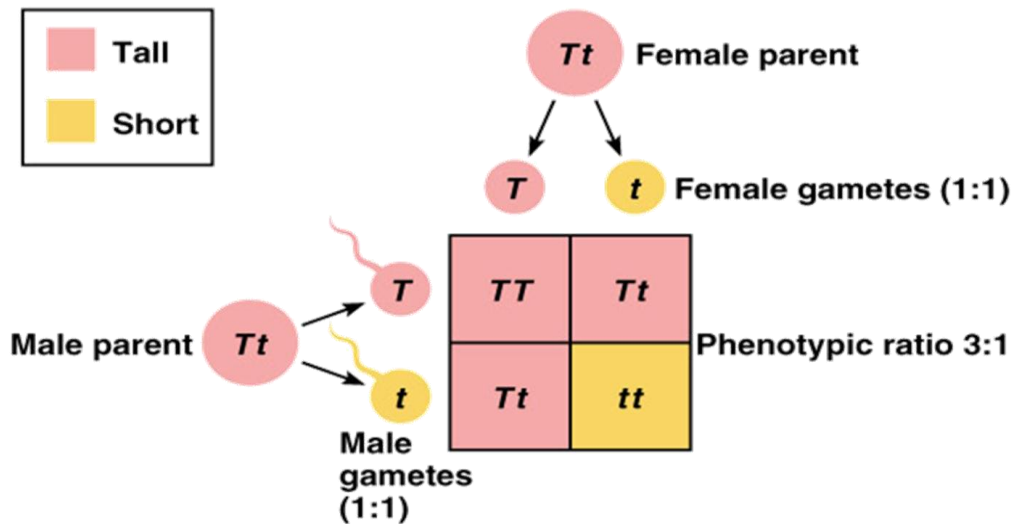
Some human facial characters showing the dominant and receive phenotype:

Human Variations			
Trait	Dominant (both heads)	Hybrid (one head, one tail)	Recessive (both tails)
Shape of Face	Round (RR)	Round (Rr)	Square (rr)
Cleft in Chin	Absent (CC)	Absent (Cc)	Present (cc)
Hair	Curly (HH)	Wavy (Hh)	Straight (hh)
Widow's Peak	Present (WW)	Present (Ww)	Absent (ww)
Spacing of Eyes	Close (EE)	Normal (Ee)	Far (ee)
Shape of Eyes	Almond (AA)	Almond (AA)	Round (aa)
Position of Eyes	Straight (SS)	Straight (Ss)	Slant (ss)
Size of eyes	Large (LL)	Medium (Ll)	Small (ll)

Dominant Gene		Recessive Gene	
Cleft Chin		No Cleft	
Widow's Peak		No Widow's Peak	
Dimples		No Dimples	
Brown/Black Hair		Blonde Hair	
Freckles		No Freckles	
Brown Eyes		Gray/Blue Eyes	
Free Earlobe		Attached Earlobe	

11

Some Bacterial characters showing the dominant and receive phenotype:

Trait:	Dominant:	Recessive
Shape	Cocci (round)	Baccili (rod)
Configuration	Single	Double
Color:	Red	Blue
Flagellum	Double	Single
Capsule	Present	Absent
Pilli	Absent	Present

Bacteria Monster

NOTE: According to Mendel laws, (♀A x ♂B) and (♀B x ♂A) should give same results depending only on dominance.

Symbolism for Dominant and Recessive alleles

According to Mendel: Alphabetical letters were used to symbolize the different alleles so, capital letter for dominant and small letter for recessive.
Example A (dominant purple color) & a (white recessive color) for Pea flower's color.

According to Bateson: The capital letter was derived from the name of the dominant and so, its small letter will represent the recessive.
Example P (dominant purple color) & p (recessive white color) of Pea flower.

According to Wild type System: The word wild type means the dominant natural population (or most common) so, the allele of the recessive will be signed with the letter of its name and that of wild type will be signed + alone or the letter of the recessive with + as superscript. Example + or s^+ (dominant tall plant) and s (recessive short plant).

MENDEL'S FIRST LAW (LAW OF SEGREGATION)

Law 1. states that every individual possesses a pair of alleles for any particular **trait** (assuming diploidy). Each parent passes a <u>randomly</u> <u>selected copy (allele) of only one of these to its offspring</u>. Interactions between alleles at a single locus influence how the offspring expresses that trait according to dominant and recessive rule (previously explained).

Monohybrid Cross

The first crosses Mendel made were between inbred lines of peas that were true **breeding** for opposite types of a character, for example, tall x dwarf, yellow x green seed, round x wrinkled seed coat, etc. These are called **monohybrid crosses** because the peas were inbred lines that differed for a single character (Figure below). In the progeny from the hybrid cross, called the **F1 generation**, he observed that all offspring were always just one of the two alternate types.

Example (1) tall x dwarf plants

Never were both types observed or were offspring of some intermediate type. Mendel then self-pollinated some F1 offspring to create an **F2 generation**, whose plants segregated for both characters found in the inbred parents (Figure below). It was at this point that Mendel was at his scientific best. Not only did he observe the character types in the offspring, but he also counted them and calculated ratios of each type. In the F2 for all seven of the characters he was studying, he observed approximately three times as many plants of one character type as the other. Furthermore, the type observed in the F1 was the one in greater number in the F2.

Mendel interpreted the results of his monohybrid crossing experiments to develop his first three laws of inheritance. He surmised that there must be one factor for tall and one factor for dwarf, and that these factors are somehow paired (**Law 1**). Later this became the basis of the concept of pairs of **homologous chromosomes** with the gene determining a particular character located at the same position (*i.e.* locus) in each homologue. A locus can have different forms of the gene, which are called **alleles**. For example, in Mendel's peas there was one allele coding for tall plants (*D*) and one allele coding for short plants (*d*) and these alleles segregated among the offspring. Plants that have the same allele at a locus on each of the homologous chromosomes

are homozygous (*e.g. DD* and *dd*), whereas those with a different allele on each homologous chromosome are heterozygous (*e.g. Dd*).

Mendel further hypothesized that one unit factor (*i.e.* allele) is **dominant** to the other **recessive** factor (*i.e.* the dominant allele masks the effect of the recessive allele), based on the phenotypes he found in the F1 and F2 (**Law 1**). For example, the allele for tall (*D*) is dominant and the allele for dwarf (*d*) is recessive. This leads to the important distinction between genotype and phenotype. The three possible genotypes are *DD*, *Dd*, and *dd*, although with *D* being dominant to *d*, there are only two phenotypes. The *DD* and *Dd* genotypes are both tall phenotypes and the *dd* genotype is the dwarf phenotype.

A simple method to interpret the results of the monohybrid cross is through the **Punnett Square**, named after its inventor Reginald Punnett (Figure below). It can be seen that when a heterozygous F1 is mated to itself (or crossed to an identical F1), three genotypes (*DD*, *Dd* and *dd*) are found in the 1:2:1 ratio (**genotypic ratio**), respectively. However, only two phenotypes are found, tall and dwarf, in the ratio of 3:1 (**phenotypic ratio**), respectively. Finally, Mendel proposed that the 3:1 ratio observed in the progeny of selfed F1 plants is expected if the *D* and *d* alleles are transmitted from each parent to the offspring at random. The frequencies of the offspring genotypes are the products of the frequencies of the alleles transmitted from each parent. The frequency of the *DD* genotype is 1/4, the frequency of the heterozygous *Dd* class is 1/2, and the frequency of *dd* is 1/4. Because *D* is dominant to *d* and therefore, *DD* and *Dd* have the same phenotype, the expected proportion of tall offspring is 3/4 and the dwarf offspring is 1/4 (or a 3:1 ratio). Mendel confirmed the expectations of random segregation with another type of cross, called a **test cross**. Here he crossed a *Dd* plant with a *dd* plant and found that approximately half of the offspring were tall and half were dwarf.
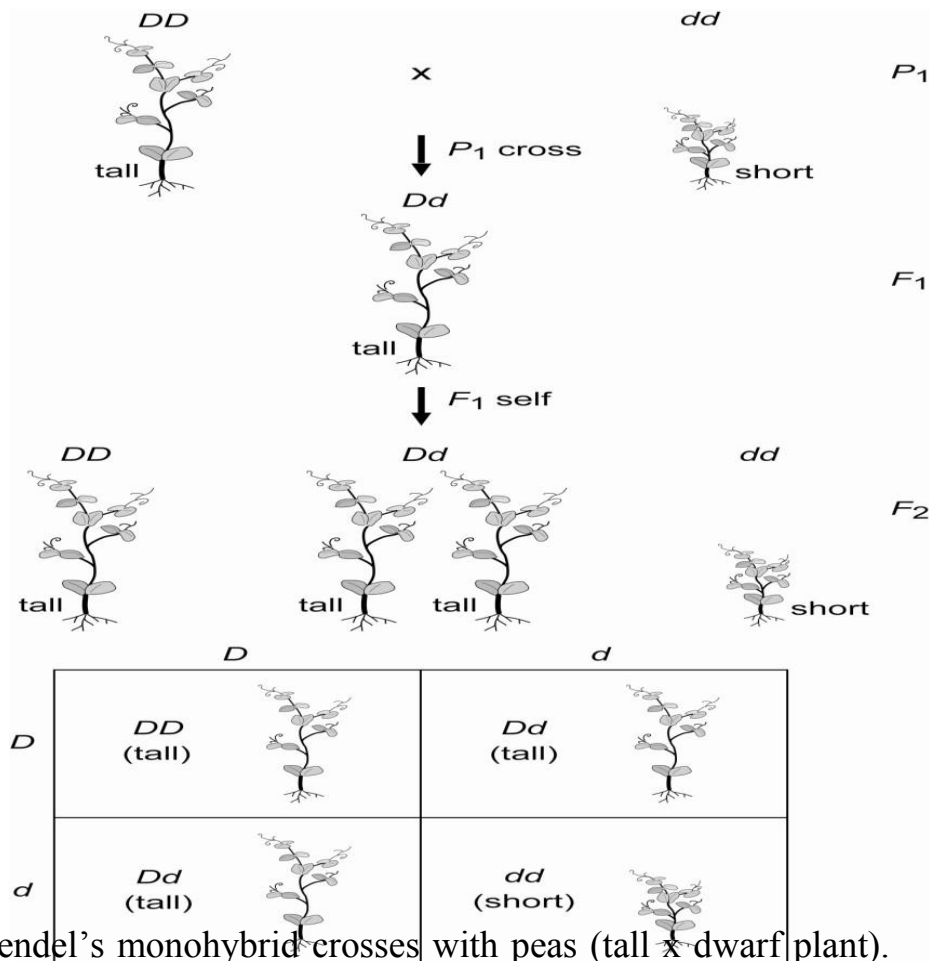
Fig. Mendel's monohybrid crosses with peas (tall x dwarf plant).

Example (2) yellow x green seed

Mendel grew seeds from a cross between green-seed and yellow-seed plants (figure below). All of the offspring in F1 generation had yellow seeds. Mendel allowed the plants in F1 generation to self pollinate. ¾ of the plants had yellow seeds and ¼ had green forming **phenotypic ratio** of 3:1 (3 yellow to 1 green) and genotypic ratio 1 (homozygous dominant) : 2 (heterozygous) : 1 (homozygous receissive).
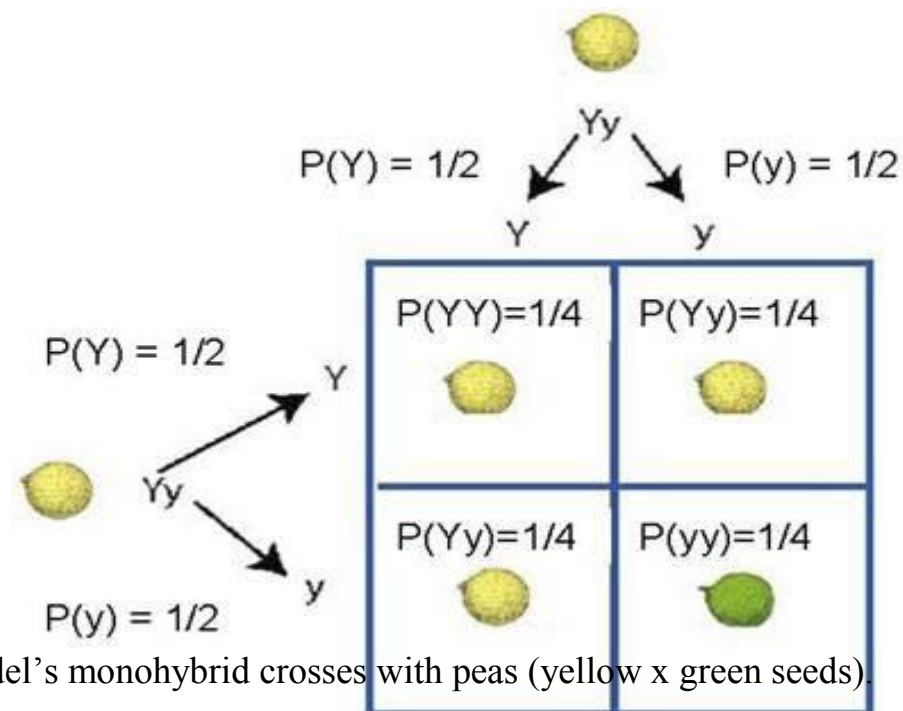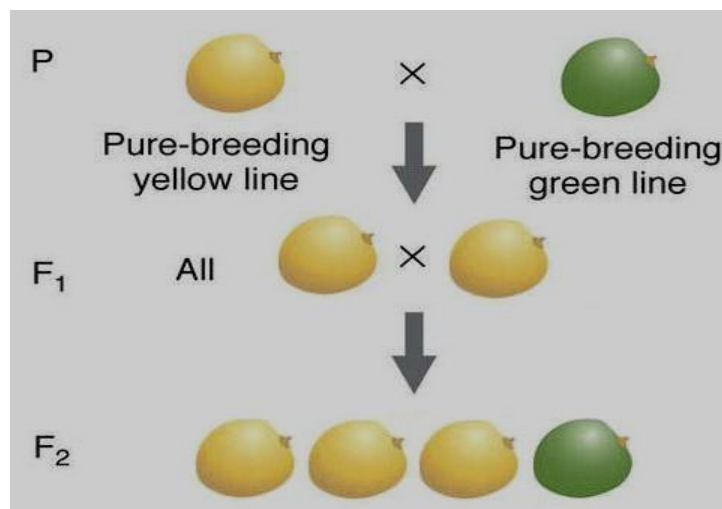
Fig. Mendel's monohybrid crosses with peas (yellow x green seeds).

NOTE: Traits come in alternative versions. For each trait, an organism inherits 2 alleles, 1 from each parent. Eg: purple vs. white flower color, purple-flower allele &

white-flower allele are two DNA variations at flower-color locus i.e. different versions of gene at same location on homologous chromosomes.

Modern molecular study's findings that different alleles vary in the sequence of nucleotides at the specific locus of a gene some difference in sequence of A, T, C, G, so differ in their functional proteins.

> **Lecture activity:** Punnett square of the some monohybrid cross (students solving and open discussion).

MENDEL'S SECOND LAW (LAW OF INDEPENDENT ASSORTMENT)

Law 2. states that different separate genes for different separate traits are <u>passed independently of one another</u> from parents to offspring during gamete formation. That is, the biological selection of a particular gene in the gene pair for one trait to be passed to the offspring has <u>nothing to do</u> with the selection of the gene for any other trait.

Dihybrid Cross

A second type of experiment Mendel performed was the **dihybrid cross**, which was an extension of the monohybrid cross to two characters (figure below). Mendel crossed a yellow and round seeded type to a green and wrinkled seeded type. The F1 offspring were all yellow and round and the alternate types of each character were found in 3:1 ratios in the F2, as observed in monohybrid crosses involving the same traits.

Mendel also counted the two-character phenotypes and these were in a 9:3:3:1 ratio in the F2. This is the expected ratio of two-character phenotypes given that both pairs

of traits segregate randomly and completely independently of one another (**Law 2**). Under independent assortment, the expected frequency of any two-character phenotype is the product of the frequencies of each component character. Therefore, the frequency of yellow round offspring is 9/16 and the frequency of yellow wrinkled is 3/16. In this case, the genes controlling color and smoothness of seed coat reside on different chromosomes. The Punnett square shows the offspring resulting from selfing the F1. There are nine possible genotypes (**genotypic ratio** 1:2:2:4:1:2:1:2:1) but only four phenotypes (yellow and round, yellow and wrinkled, green and round, green and wrinkled) which segregate in a 9:3:3:1 ratio (**phenotypic ratio**).
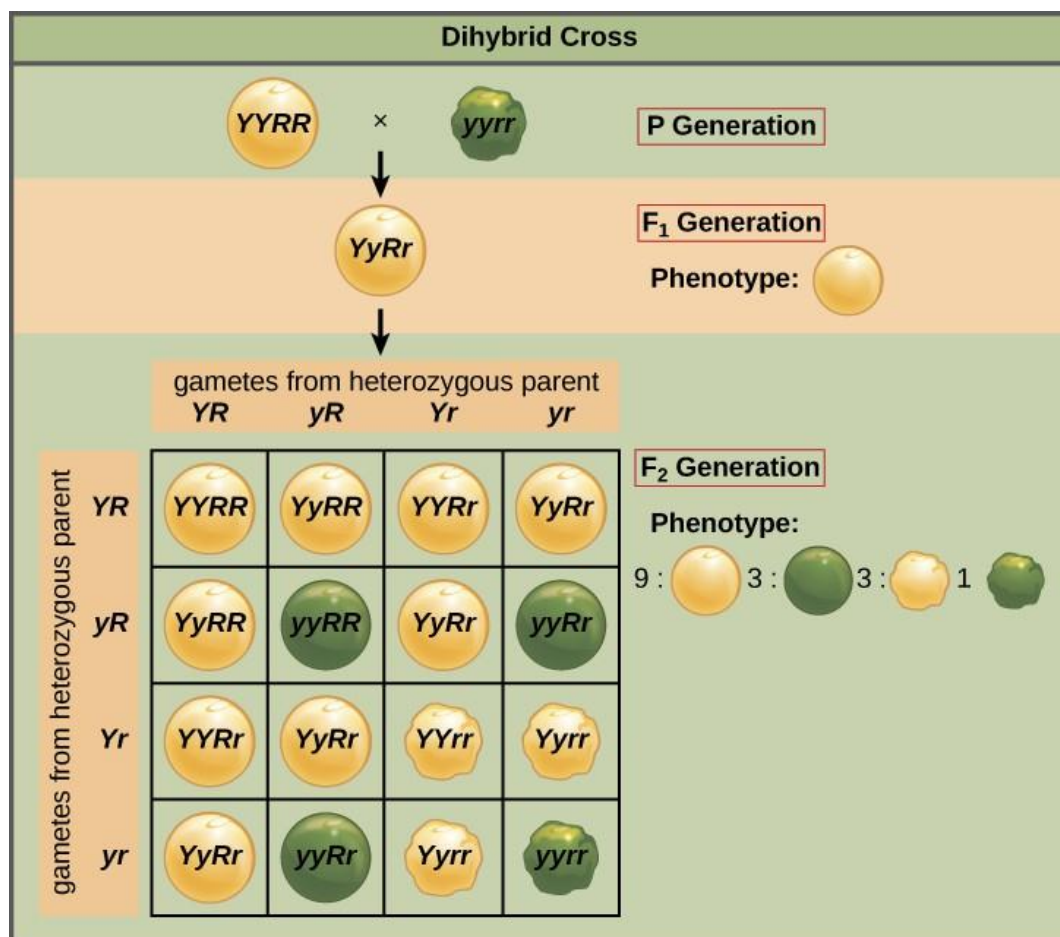
Fig. Mendel's dihybrid crosses with peas (yellow and round x green and wrinkled seeded type).
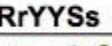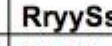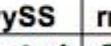
Lecture activity: Punnett square of the some dihybrid cross (students solving and open discussion).

Trihybrid Cross

A trihybrid cross is between two individuals that are heterozygous for three different traits: pea shape and pea color and then a new trait: pod shape. The same rules as before apply for shape and color (round is completely dominant to wrinkled, and green is completely dominant to yellow). Pea pod shape follows similar rules, with smooth pods being completely dominant to constricted pods. Therefore, homozygous-dominant and heterozygous individuals will have smooth pods, while homozygous-recessive individuals will have constricted pea pods.

RrYyCc x RrYyCc is a trihybrid cross, the shape of the pea is controlled by one set of alleles, where round is completely dominant to wrinkled (RR and Rr = round, rr = wrinkled). The second set of alleles is the color of the peas. Green is dominant to yellow (YY and Yy = green, yy = yellow). The third set of alleles is the shape of the pea pod. Smooth is completely dominant to constricted (CC and Cc = smooth, cc = constricted). The gametes for each parent in a trihybrid cross would be RYC, RYc, RyC, Ryc, rYC, rYc, ryC, ryc, with one-eighth of a chance for any of them. The **64 offspring** show a **phenotypic ratio** of 27:9:9:9:3:3:3:1 and a **genotypic ratio** of 1:2:1:2:4:2:1:2:1:2:4:2:4:8:4:2:4:2:1:2:1:2:4:2:1:2:1 .

Example of Trihybrid Punnett

	RYS	RYs	RyS	Rys	rYS	rYs	ryS	rys
RYS	RRYYSS	RRYYSs	RRYySS	RRYySs	RrYYSS	RrYYSs	RrYySS	RrYySs
RYs	RRYYSs	RRYYss	RRYycSs	RRYyss	RrYYSs	RrYYss	RrYySs	RrYyss
RyS	RRYySS	RRYySs	RRyySS	RRyySs	RrYySS	RrYySs	RryySS	RryySs
Rys	RRYySs	RRYyss	RRyySs	RRyyss	RrYySs	RrYyss	RryySs	Rryyss
rYS	RrYYSS	RrYYSs	RrYySs	RrYySs	rrYYSS	rrYYSs	rrYySS	rrYySs
rYs	RrYYSs	RrYYss	RrYySs	RrYyss	rrYYSs	rrYYss	rrYySs	rrYyss
ryS	RrYYSs	RrYySs	RryySS	RryySs	rrYySS	rrYySs	rryySS	rryySs
rys	RrYySs	RrYyss	RryySs	Rryyss	rrYySs	rrYyss	rryySs	rryyss

How to know the number of gametes and the number of offspring in a cross?

gametes (♀ or ♂) = $2^{\text{\#characters}}$

Total # offspring = # ♂ gametes X # ♀ gametes

In Monohybrid: # gametes (♀ or ♂) = 2^1 = 2

Total # offspring = 2 X 2 = 4

In Dihybrid: # gametes (♀ or ♂) = 2^2 = 4

Total # offspring = 4 X 4 = 16

In Trihybrid: # gametes (♀ or ♂) = 2^3 = 8
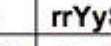
Total # offspring = 8 X 8 = 16

Lecture activity: Punnett square of the some trihybrid cross (students solving and open discussion).

THE RELATION BETWEEN MENDEL LAWS AND CHROMOSOMES IN MEIOSIS

The function of Meiosis I is very different from that of either Mitosis or Meiosis II. In both Mitosis and Meiosis II sister chromatids are separated during anaphase to produce identical daughter cells. In Anaphase I of Meiosis I, members of homologous chromosome pairs are separated. This results <u>accounts for the law of segregation of genes</u> into the two gametes. The principle of segregation is one of two core ideas in genetics proposed by Gregor Mendel.

The alignment of homologous pairs along the metaphase 1 plate accounts for the <u>law of independent assortment</u> (the segregation of any one pair of chromosomes is independent of any other pair). Assortment of chromosomes from each pair to the two daughter cells is random. The number of possible genetic combinations (distribution probability) in the resulting gametes is therefore very large. This model works for genes that are on separate (non-homologous) chromosomes, but not necessarily for genes that are on the same chromosome.

Rr parent

Dominant allele for seed shape — **R** — **r** — Recessive allele for seed shape

Chromosomes replicate

R—**R** **r**—**r**

Meiosis I
Alleles segregate

R—**R** **r**—**r**

Meiosis II

Gametes

R **R** **r** **r**
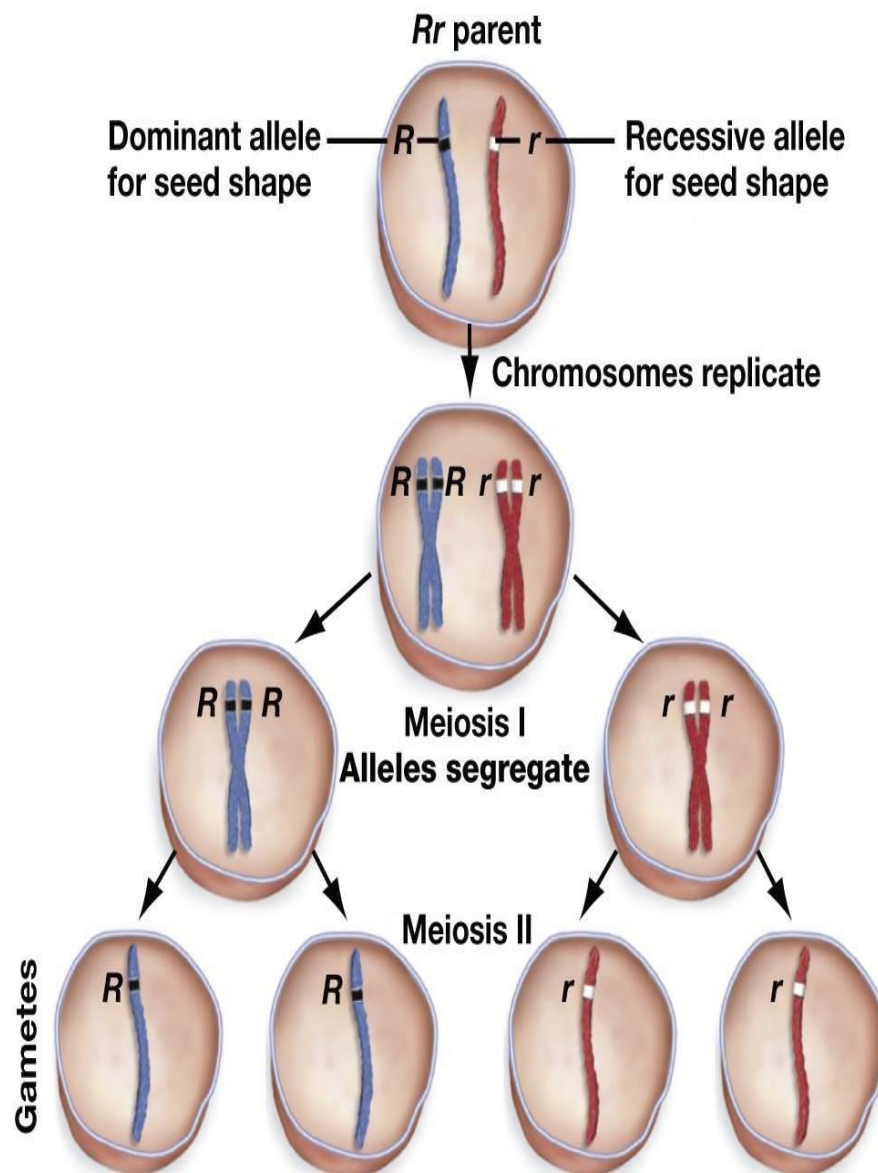
PRINCIPLE OF SEGREGATION: Each gamete carries only one allele for seed shape, because the alleles have segregated during meiosis.

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Figure 8.16 Results of the independent orientation of chromosomes at metaphase I

Possibility 1   **Possibility 2**

Two equally probable
arrangements of
chromosomes at
metaphase I

Metaphase II

Gametes

Combination 1   Combination 2   Combination 3   Combination 4
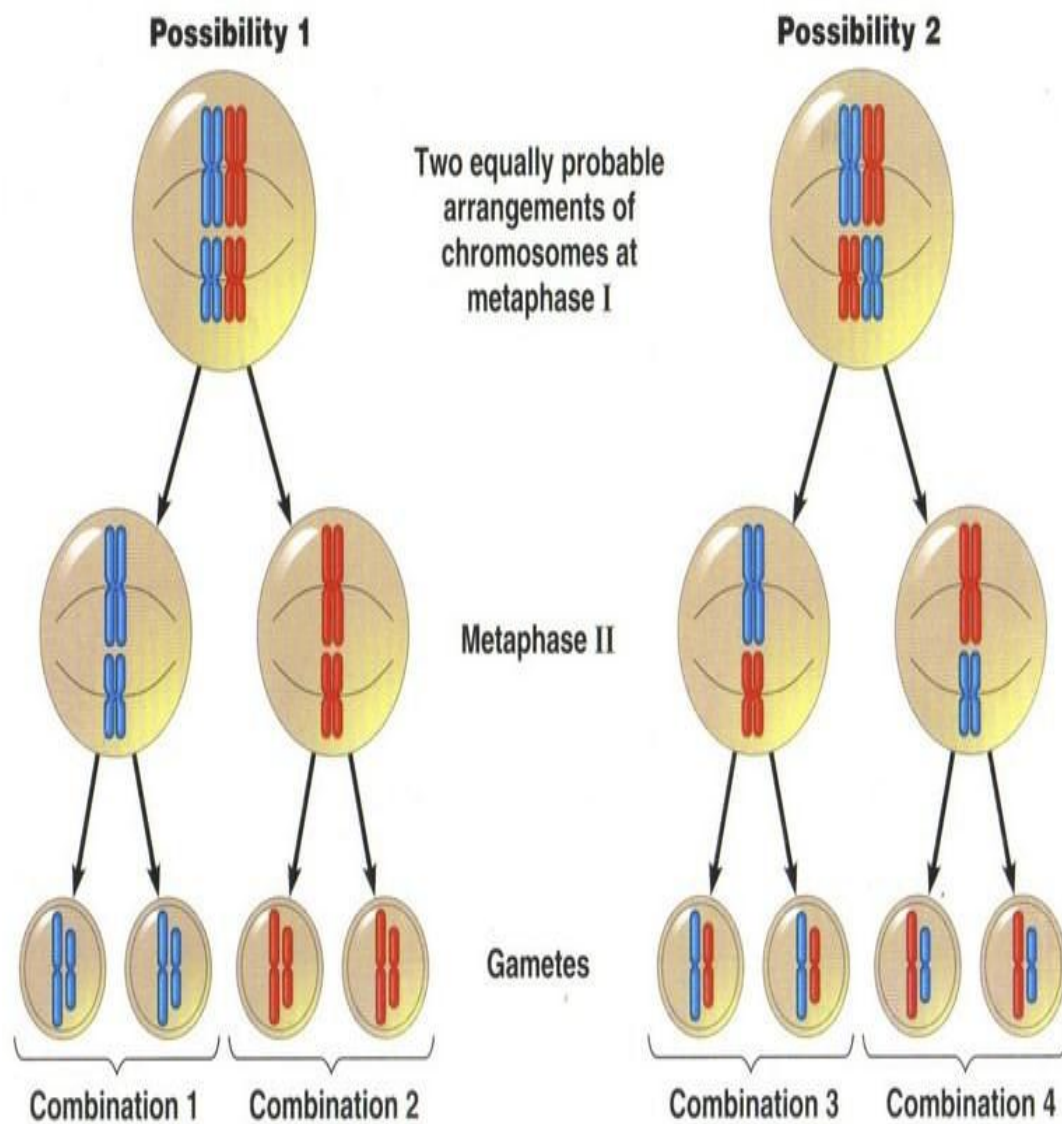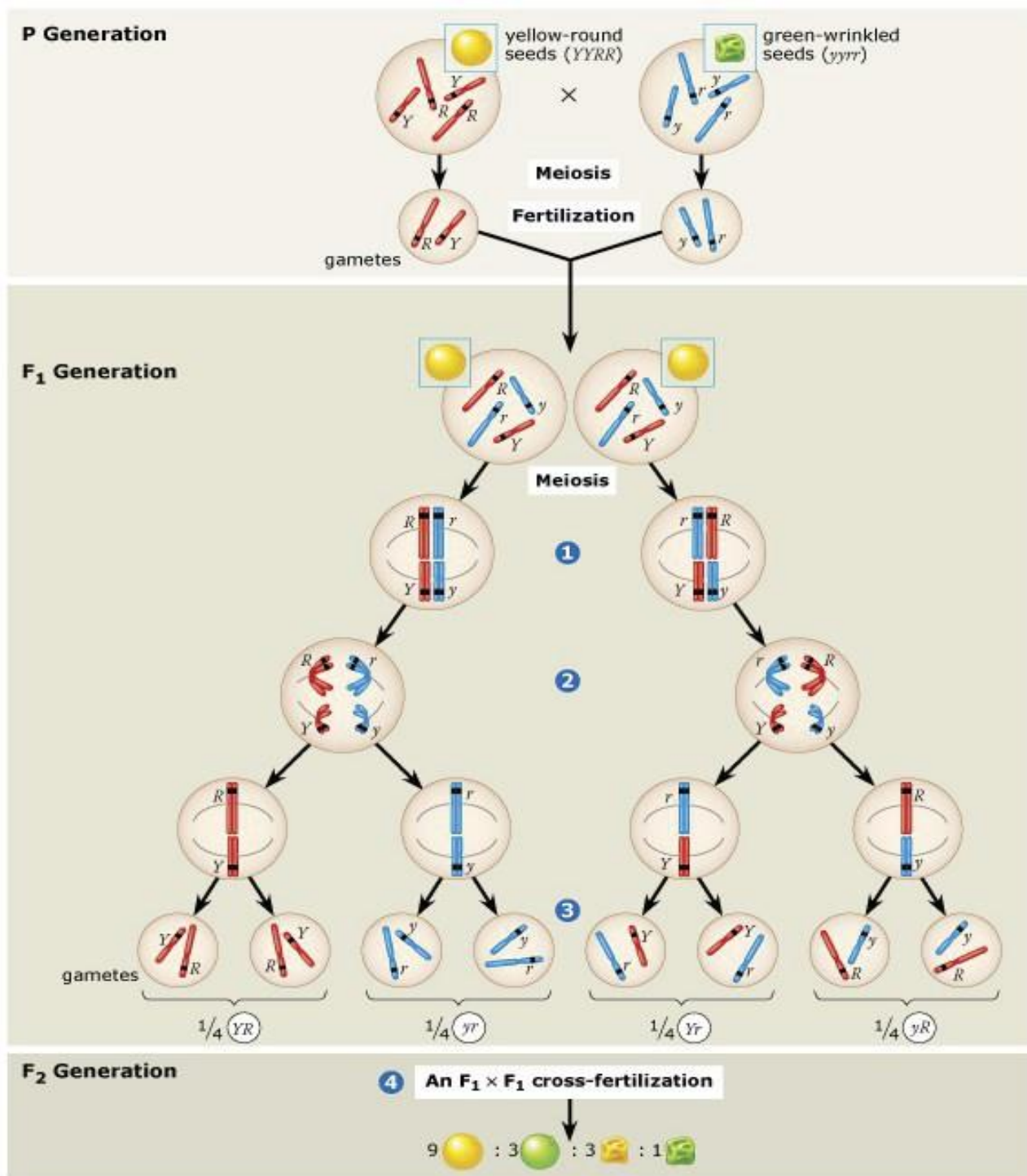
Adapted from *Campbell Biology* by Reece et al. © Pearson Education, Inc.

<u>Animation:</u>

Mendel

https://www.youtube.com/watch?v=3CQqFpKiRhw

http://www.youtube.com/watch?v=Mehz7tCxjSE

https://www.youtube.com/watch?v=GRDKoxNc3MI

For more reading: (in Botany and Microbiology Departmet Library)

1. Study guide and problems workbook: Principles of genetics, Peter Snustad, Simmons and Price (eds), 2nd edition, 2000.

2. Introduction to genetic analysis, Griffiths, Wessler, Lewontin and Carroll, 9th edition, 2008.

3. Concepts of Genetics, William S. Klug, Michael R. Cummings, Charlotte A. Spencer and Michael A. Palladino, 10th edition, 2012, Pearson Education Inc. (also present online)