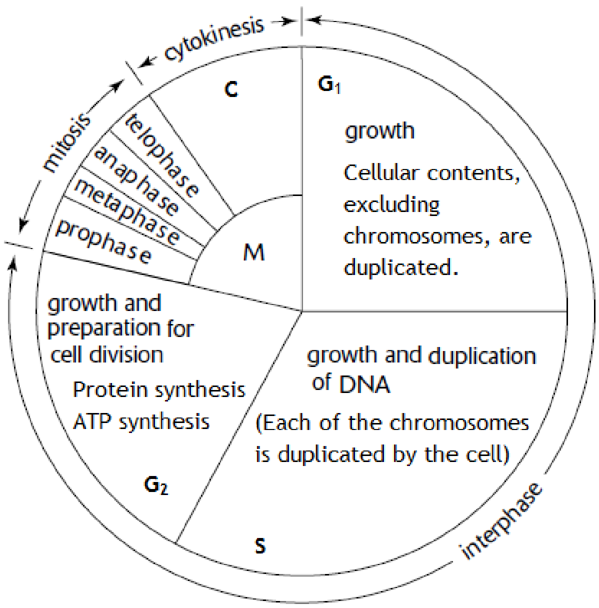
THE CELL CYCLE

The complex sequence of events by which cells grow and divide into daughter cells.
The main phases of the cell cycle:
1. Interphase, which is divided into: **Gap $_1$ phase (G $_1$), Synthesis phase (S), and Gap $_2$ phase (G $_2$)**.
2. Mitosis phase (M), which is sequenced as **Prophase, Metaphase, Anaphase and Telophase.**
Non-dividing cells e.g. most **neurons,** mature **muscle cells** and **brain cells** are in G_0 stage (not in cell cycle).

DEFINITIONS

Interphase: The interval between the end of one mitotic or meiotic division and the beginning of another
Karyokinesis: The actual division of the cell nucleus into two daughter nuclei during mitosis or meiosis.
Cytokinesis: Cleavage of the cytoplasm into daughter cells following nuclear division.
Ploidy: The number of homologous sets of chromosomes in a cell.



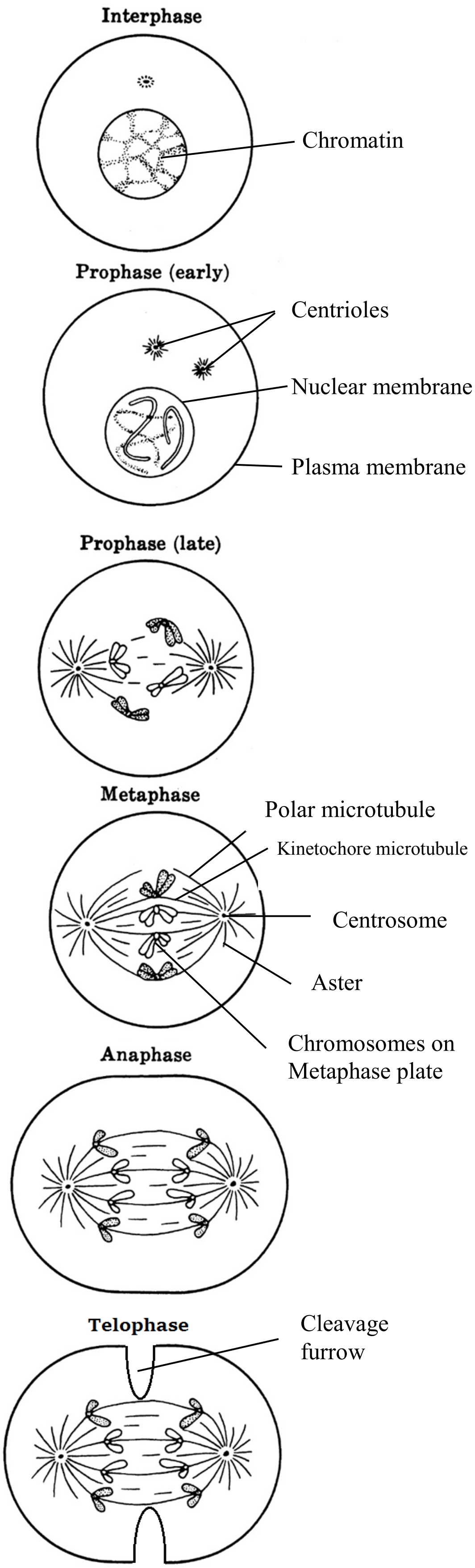
INTERPHASE
A dividing cell spends about 90-95 % of time in interphase.
G1 phase:
Occurs prior to DNA synthesis.
Cell increases in mass and organelle number.
Cell makes enough mitochondria, cytoskeletal elements, endoplasmic reticula, ribosomes, Golgi apparatus, cytosol.
Centriole replication starts but is completed in G_2.
All chromosomes exist in single-chromatid form as they are uncoiled.
S phase:
DNA replicates (during which **gene mutations** may occur).
Chromosome content doubles.
Each chromosome replicates into two identical sister chromosomes (**chromatids**) joined at kinetochores.
Histones and other nuclear proteins are synthesised.
G2 phase:
Occurs after DNA synthesis, prior to start of mitosis.
Additional protein synthesis
Completion of centriole replication
ATP synthesis occurs
Cell size increases
Repairs errors in replicated chromosomes are corrected.

MITOSIS

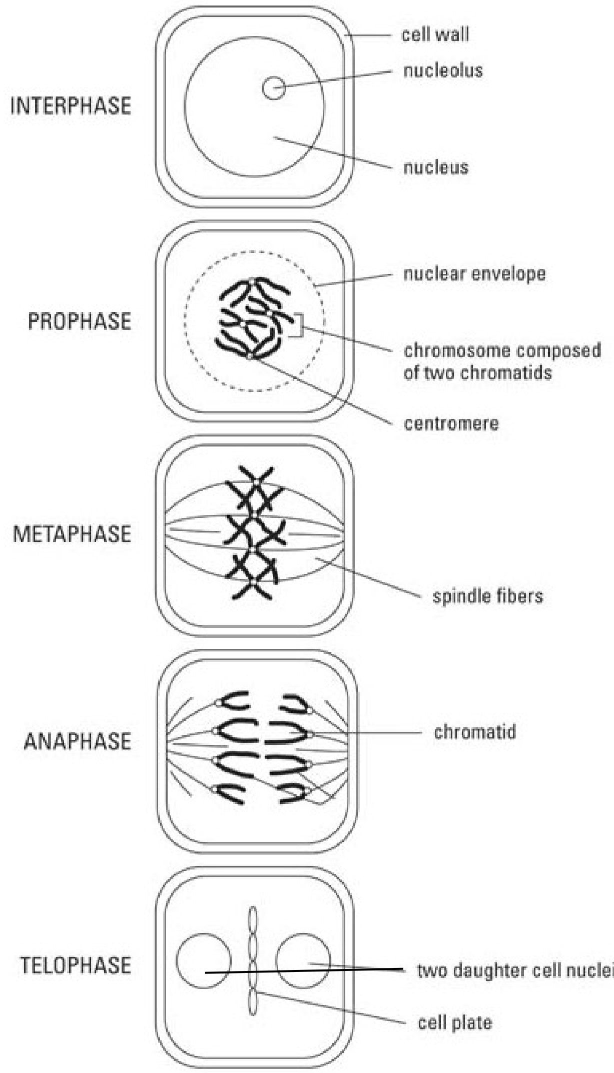
Type of nuclear division whereby one **diploid** or **haploid** parent cell produces two **genetically identical** daughter cells each with **same chromosome number** like the parent cell.

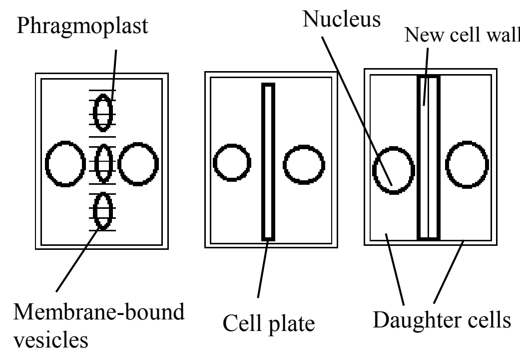
1. Prophase:	***2. Metaphase:***
Changes occur in both the **cytoplasm** and **nucleus** Chromatin **condenses** into discrete chromosomes. Centrioles move towards poles. Chromosomes begin to migrate toward the cell centre. Nuclear envelope breaks down Spindle fibers begin to form at opposite poles of the cell. Nucleolus fades.	Nuclear membrane disappears completely. Centriole pairs reach the poles Spindle fully develops Chromosomes condense further Chromosomes align at the metaphase plate
3. Anaphase:	***4. Telophase:***
Sister chromatids separate and orient towards opposite poles. Chromatids make a "V" shape as the arms of the chromatid drag behind the centromere, which leads towards its pole. Polar microtubule – which run from one centriole to another (without attachment to chromosomes) pull and lengthen the cell. Therefore, the shape of animal cell changes.	Sister chromatids (now called Chromosomes) reach opposite poles. Chromosomes de-condense Nucleolus begins to appear Nuclear envelope appears. Spindle disappears. Cell surface membrane folds in (invaginates) to divide the genetic content of the cell equally into two parts. Cytokinesis begins prior to the end of mitosis and completes shortly after telophase.

MITOSIS IN AN ANIMAL CELL



MITOSIS IN A PLANT CELL



CYTOKINESIS IN PLANTS	Stages of Cytokinesis in a plant cell
●Cell wall forms during telophase stage of cell division when the **cell plate** forms between daughter cell nuclei. ●Cell plate forms from a series of vesicles produced by **Golgi** (**Dictyosomes)**. ●Vesicles migrate along the microtubules and actin filaments within the **phragmoplast** and move to the cell equator. ●**Phragmoplast** contains mitotic spindles, microtubules, microfilaments, and endoplasmic reticulum surrounded by nuclear envelopes. ●Vesicles join up their contents, and the membranes of the vesicle become the new cell membrane. ● Dictyosomes synthesize the non-cellulosic polysaccharides like **pectins** and transported to build the middle lamella. ●**Cellulose** is made at the cell surface, catalyzed by the enzyme cellulose synthase. ●While the cell plate is growing, segments of smooth endoplasmic reticulum are trapped within it, later forming the **plasmodesmata** connecting the two daughter cells	

COMPARISON OF MITOSIS IN PLANTS AND ANIMALS
Similarities
In both:
(i) Spindle fibres form
(ii) During Prophase, chromosomes condense(iii) Before metaphase, the nuclear envelope breaks down.
(iv) Spindle attaches to chromosomes at centromeres
(v) At metaphase, the chromosomes align at the equator
(vi) At anaphase, chromosomes move towards opposite poles
(vii) At telophase, the nuclear envelope appears again, chromosomes de-condense, and the spindle breaks down

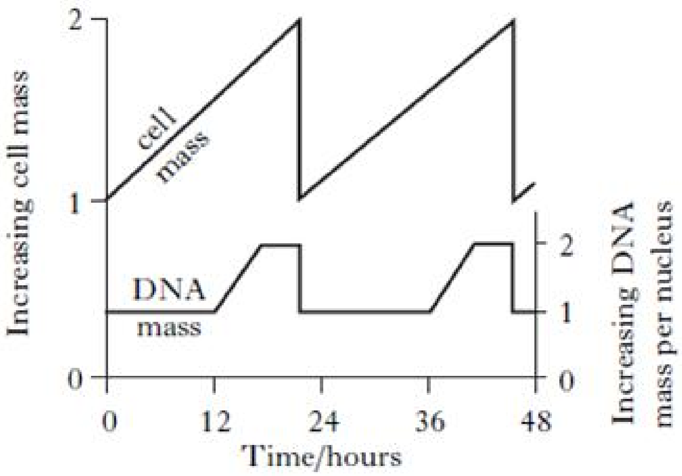
Differences

Mitosis in animal cells	**Mitosis in plant cells**
Occurs almost all over the body	Occurs at apical, lateral and intercalary meristems only.
Centrioles present	Centrioles absent
At telophase a contractile ring of actin and myosin forms halfway between the two nuclei.	At telophase a phragmoplast of actin, myosin, and microtubules, forms at the future site of cell wall.
Cytokinesis occurs by cleavage	Cytokinesis occurs by cell plate method
Cell becomes rounded before division	Cell shape does not change before division
A furrow is formed between two daughter cells	A solid middle lamella forms between two daughter cells
Mitotic apparatus contains asters	Mitotic apparatus lacks asters
Spindle degenerates at cytokinesis	Spindle in form of phragmoplast persists at cytokinesis.
Several hormones induce cell division, not one specifically	It is induced by a specific hormone called cytokinin

SIGNIFICANCE OF MITOSIS
(i) During growth in multicellular organisms, the number of cells within an organism increases by mitosis.
(ii) Enables cell replacement when old cells die or get damaged.
(iii) Maintains genetic properties of new cells when damaged tissues are repaired hence retains normal function of cells.
(iv) Enables regeneration of body parts in some animals e.g. lizard tails.
(v) Produces a clone of offspring (genetically identical to parents) during vegetative reproduction in some plants.

TYPICAL EXAMINATION QUESTION (40 MARKS)

Figure 1 below shows changes in the quantities of nuclear DNA and cell mass during repeated cell cycle.



(a) For one cell cycle only, describe the changes in:

(i) Mass of DNA (2½ marks)

One cell cycle lasts from 0 hour to about 23 hours; DNA mass remains constant from 0 hour to 12 hours; increases rapidly to about 18 hours; remains constant up to about 23 hours; decreases suddenly to original mass at about 23 hours;

(ii) Cell mass (1½ marks)

Cell mass increases rapidly from 0 hour to a peak at about 23 hours; Decreases suddenly; to original mass at about 23 hours;

(b) For one cell cycle only, explain the trend in:

(i) Mass of DNA (8 marks)

From 0 hour to 12 hours is the first growth (**G_1**) phase; cell contents replicate except DNA; from 12 hours to about 18 hours is the synthesis (**S**) phase; DNA replicates to double original mass; from 18 hours to about 23 hours is the second growth (**G_2**) phase and mitosis; no DNA synthesis; at about 23 hours cytokinesis occurs; halving the DNA mass in each new cell to the original mass;

(ii) Cell mass (8 marks)

0 hour to about 23 hours marks the period of interphase and mitosis; during which organelles like mitochondria, cytoskeletal elements, endoplasmic reticula, ribosomes, Golgi apparatus, centriole, etc replicate and increase in number; and the cell grows (***G1 phase***); DNA replicates; and the chromosome content doubles; histones and other nuclear proteins are synthesised (***S phase***); Synthesis of additional proteins that support cell metabolism occurs (***G2 phase***); At about 23 hours cytokinesis divides the parent cell into equal sized daughter cells;

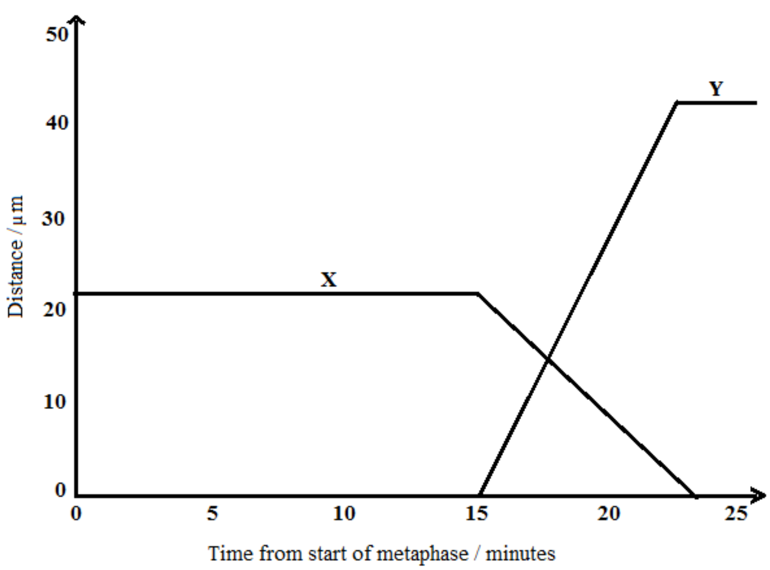
(c) Explain the significance of the observed changes in mass of DNA from 12 hours to about 23 hours. (1 mark)

From 12 hours to about 23 hours the mass of DNA increases rapidly to double the original mass; so that each daughter cell produced by cytokinesis gets a complete genome as it is in the parental cell;

In **figure 2** below, the graphs represent changes during mitosis in the distance between:

(i) Centromeres of chromatids and pole of the cell.

(ii) Centromeres of sister chromatids.



(d) Identify what curves X and Y represent (1 mks)

X – Distance between centromeres of chromatids and cell poles;

Y – Distance between centromeres of sister chromatids;

(e) Explain the trend in distance represented by:

(i) Curve X (8 marks)

From 0 minute to about 15 minutes the distance between centromeres of chromatids and poles of the cell is relatively long; and remains constant; because the cell is in metaphase stage; chromosomes are at metaphase plate; with sister chromatids still held at centromeres;

From about 15 minutes to about 23 minutes the distance between centromeres of chromatids and poles of the cell decreases rapidly to 0 µm; because after splitting during anaphase stage; sister chromatids are pulled rapidly towards poles by microtubules (spindle); and eventually arrive at the poles during telophase stage;

(ii) Curve Y (7 marks)

From 0 minute to about 15 minutes the distance between centromeres of sister chromatids was 0 µm; because sister chromatids were still joined at their centromeres during anaphase;

From about 15 minutes to about 23 minutes the distance between centromeres of sister chromatids increased rapidly to a maximum; because after splitting during anaphase stage; sister chromatids are separated from each other rapidly by the pulling of microtubules (spindle) towards poles;

After about 23 minutes the distance between centromeres of sister chromatids is very long and remains constant; because sister chromatids have arrived at the respective poles during telophase stage;

(f) Explain the variation in the maximum distance achieved in X and Y (3 marks)

The maximum distance for **Y** (between centromeres of sister chromatids) is almost **twice longer** than for **X** (distance between centromeres of chromatids and poles); During metaphase, chromosomes are at metaphase plate which is equidistant from either pole of the cell therefore maximum for X is shorter; Maximum for Y is longer since spindles pull chromatids to the extremes of the cell (poles) which are very distant apart;

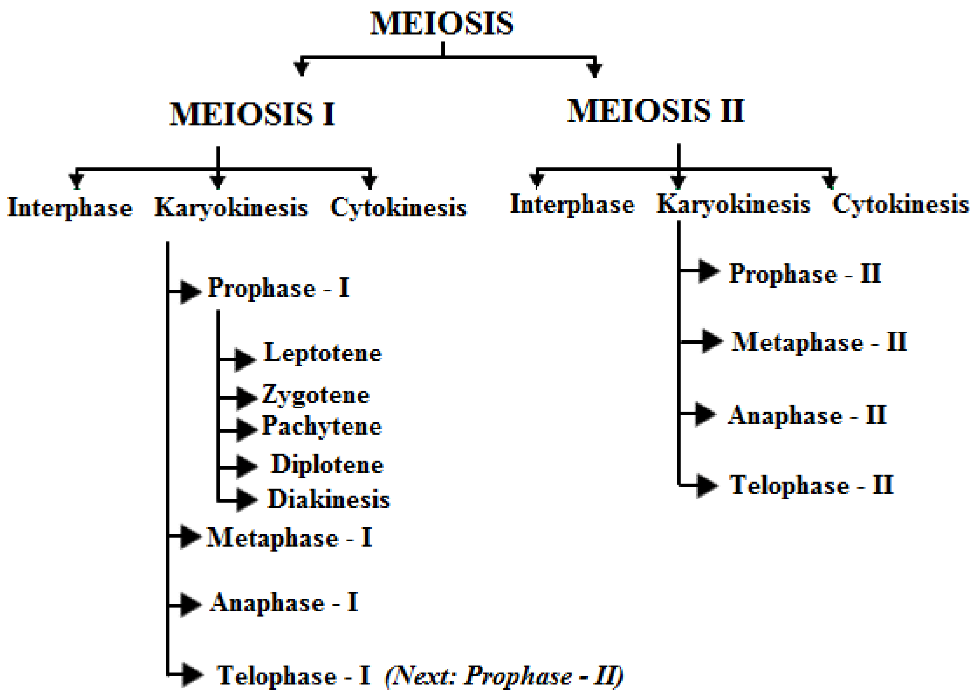
MEIOSIS

Type of nuclear division whereby one **diploid** parent cell produces four **genetically non-identical** daughter cells each with chromosome number **halved** to **haploid**.

SITE OF MEIOSIS

Mammals: **(1)** Seminiferous tubules of testes in males **(2)** Ovaries of females

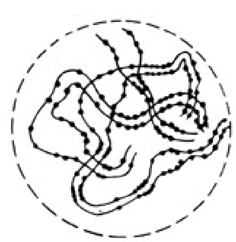
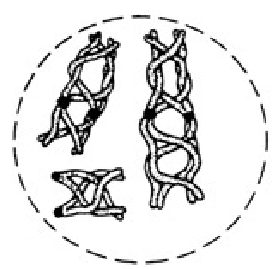
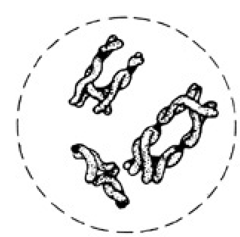
Flowering plants: **(1)** Anthers **(2)** Ovary of flowers



Prophase – I

It is the longest phase, taking 90% of the time for meiosis

Prophase – I is divided into five sub-divisions:

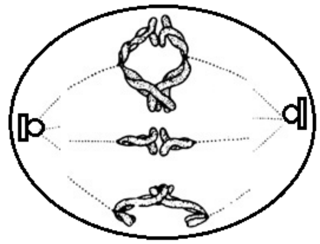
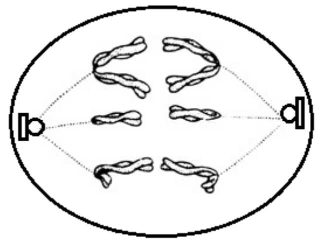
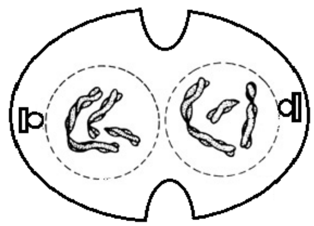
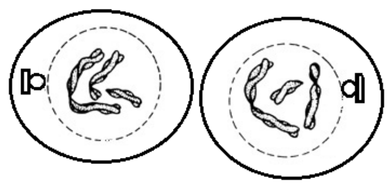
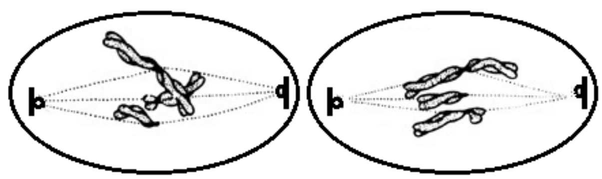
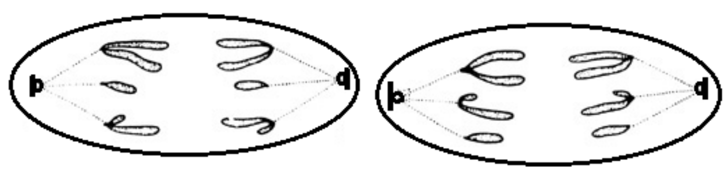
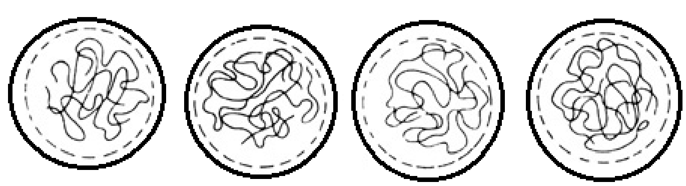
Leptotene	Zygotene	Pachytene	Diplotene	Diakinesis
				
-Chromosomes condense as mass of long coiled threads. -Spindle start to form.	-Nucleolus has disappeared. -Homologous chromosomes pair to form **bivalents**. -This is called **synapsis**	-Homologous chromosomes shorten and thicken.	-Each chromosome now appears as 2 sister chromatids. -Homologous chromosomes begin to repel each other. -Breaks occur in opposing non-sister chromatids to cause crossing-over	-Point of cross-over is called a **chaisma (*plural:* chiasmata).** -Homoogous chromosomes unwind as repulsion continues. -Centromeres are the repulsion centre. -Chromosomes are held together until they alighn on equator. Nuclear envelope breaks down

Crossing-over: The exchange/swapping of genetic material between non-sister homologous chromatids.

Importance of crossing-over: Gives rise to genetic recombination, causing variation which is the basis for evolution.

Chiasma: One point of cross-over between non-sister chromatids.

Importance of chiasmata: **(i)** Hold homologues together while they move into position on the spindle prior to segregation.
(ii) Crossing over exchange of genetic material increases variation, the basis for evolution.

Metaphase I **Tetrads** are dispersed across the metaphase plate, which is the plane equidistant from the poles. Microtubules attach to the kinetochore of each homologous pair. Centrioles are at opposite ends (poles) of the cell.	
Anaphase I Homologous tetrads move to opposite poles by pulling action of the spindle. ***Note:*** A key difference between meiosis and mitosis is that in meiosis during anaphase I, the sister chromatids are still together whereas in mitosis, they separate.	
Telophase I Chromosomes reach their own poles. Nuclear membrane surrounds each chromosome set. Spindle fibre disappears, **cytokinesis** follows. In animal cells, a **cleavage furrow** pinches the cell into two. Daughter nuclei contain **haploid** chromosomes but each chromosome will have **two chromatids**	
Prophase II Nuclear envelope breaks, spindle develops. Centrioles duplicate. Spindle start to form, usually at **right angles** to one formed in meiosis – I. Centrioles go to opposite poles to form **centrosomes**.	
Metaphase II Single chromosomes align on metaphase plate, not as tetrads. Spindle apparatus for both daughter cells are formed. **Kinetochore microtubules** attach to kinetochores of each sister chromatid.	
Anaphase II Chromosomes are pulled apart into two chromatids towards opposite ends by the microtubules of spindle apparatus. The centromeres separate.	
Telophase II Nuclear envelope surround each chromosome set. Nucleolus reform. Cytokinesis occurs, forming 4 **haploid daughter** cells which are **genetically non-identical** due to crossing-over during Prophase I.	

SIGNIFICANCE OF MEIOSIS

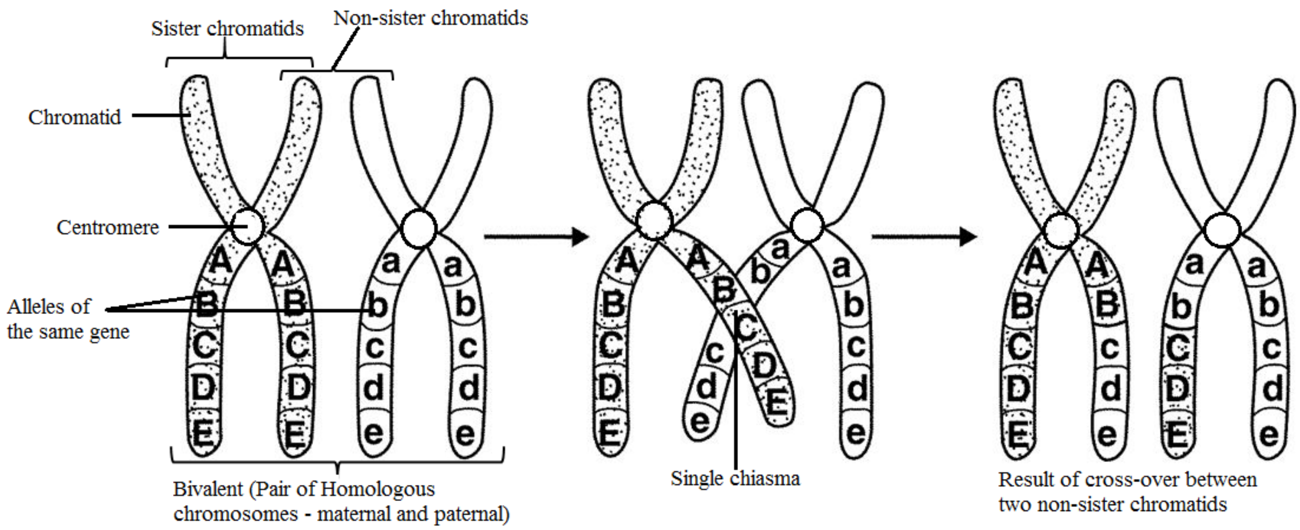
(i) Meiosis preserves the genome size of sexually reproducing eukaryotes by **halving** the **diploid** chromosome number to **haploid** ($2n \rightarrow n$). The **diploid** state is restored during fertilisation.

(ii) Meiosis leads to increased genetic variation, which is the basis for evolution.

HOW MEIOSIS CAUSES ALMOST INFINITE GENETIC VARIATION / DIVERSITY

1. Meiosis produces **haploid** ♂ and ♀ gametes which fuse during **fertilisation** to create new combinations of parental genes.

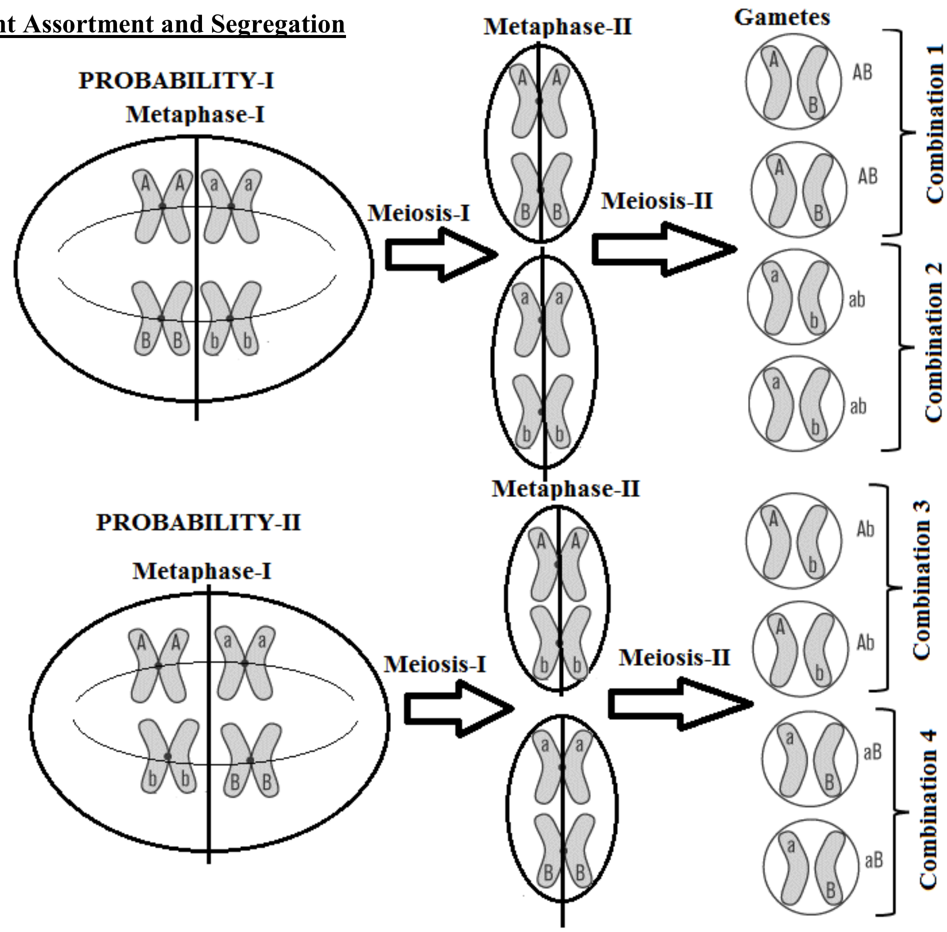
2. Crossing over during **prophase I** of meiosis can separate and rearrange genes located on the same chromosome to form genetically non-identical gametes.



3. Independent assortment of homologous chromosomes on metaphase plate during **metaphase – I** with respect to which paternal and maternal homologue is on either side forms different combinations of parental chromosomes in gametes. The number of possible combinations of maternal and paternal homologues is **2^n**, where **n** = the haploid number of chromosomes. In humans it produces **2^{23} (8,388,608 - over 8 million)** different combinations of chromosomes!

4. During **Segregation** / **separation** of homologues in **anaphase - I** and sister chromatids at **anaphase II**, alleles for dominant / recessive traits go to **opposite poles** whereby only one of a pair of alleles goes into a single gamete.

<u>Independent Assortment and Segregation</u>



RELATIONSHIP BETWEEN MEIOSIS AND MENDELIAN INHERITANCE

The laws of genetic inheritance are based on **unique features of meiosis**, which are: (a) Synapsis (b) homologous recombination (c) reduction division

MENDEL'S GENETIC LAWS

1. Law of Segregation: During gamete formation, the alleles for each gene segregate from each other so that each gamete carries only one allele for each gene

2. Law of Independent Assortment: During the formation of gametes, alleles of gene segregation /separate independently without affecting/being affected by alleles of any other gene on a separate chromosome.

HOW THE LAW OF SEGREGATION OPERATES

Synapsis of homologues (**prophase – I**) and separation of homologous pairs (**anaphase I**) cause **segregation** of alleles.

Assuming a **diploid individual** has two alleles for a particular gene, carried on two separate chromosomes (maternal and paternal), the allele on maternal chromosome segregates / separates from the allele on paternal chromosome (**Anaphase – I**) so that each allele is passed on to different gamete (offspring).

HOW THE LAW OF INDEPENDENT ASSORTMENT OPERATES

Crossing over and the **random separation** of chromosomes cause **independent assortment**.

Assuming an organism has 23 pairs of homologous chromosomes, the maternal and paternal chromosomes of pair – 1 separate randomly during anaphase – I with respect to maternal and paternal chromosomes of pair – 2 or all the other pairs. There is no fixed chance that all the paternal or maternal chromosomes (alleles) will be passed to one gamete.

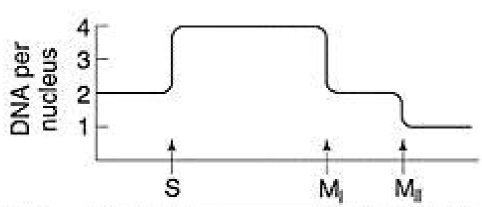
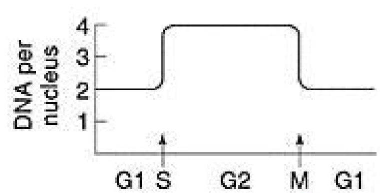
This allows **(1)** independent assortment of genes **(2)** for gametes, and thus offspring, to be much more genetically variable.

COMPARISON OF MEIOSIS AND MITOSIS

Similarities - Both:

(i) Involve cytokinesis to form daughter cells from a parent cell **(ii)** Follow the same fundamental sequence of events i.e. Interphase, prophase, metaphase, anaphase, telophase **(iii)** Include the breakdown of the nuclear membrane during prophase. **(iv)** Involve the separation of genetic material into two groups, followed by cell division **(v)** Involve the reformation of the nuclear membrane in each cell during telophase **(vi)** Involve alignment of chromosomes on metaphase plate

Differences

MEIOSIS	MITOSIS
Occurs in cells involved in sexual cycle	Occurs in somatic cells
Cells involved in meiosis are always diploid	Cells involved can be diploid or haploid
Daughter cells are genetically different	Daughter cells are genetically identical
Crossing over occurs	No crossing over
Homologous chromosomes pair up	No pairing of homologous chromosomes
Two divisions; meiosis –I and meiosis – II ***Meiosis 1***: Prophase I, Metaphase I, Anaphase I, Telophase I; ***Meiosis 2:*** Prophase II, Metaphase II, Anaphase II and Telophase II.	One division involving Prophase, Metaphase, Anaphase, Telophase.
4 haploid cells are formed	2 diploid cells are formed
Chromosome number is reduced by half.	Chromosome number remains the same.
Homologous chromosomes line up along metaphase plate in tetrads	Chromosomes line up singly on metaphase plate
Cytokinesis occurs twice i.e. in Telophase I and in Telophase II.	Cytokinesis occurs once i.e. in Telophase.
Centromeres do not separate during anaphase I, but during anaphase II.	Centromeres split during anaphase.
Karyokinesis occurs in **interphase – I** i.e. one pre-meiotic **S** phase for both meiosis – I and meiosis – II 	**Karyokinesis** occurs in **interphase** i.e. one pre-mitotic **S** phase per cell division. 

NOTE:

1. Meiosis – II and **mitosis** are **not reduction division** because the number of chromosomes remains the same; therefore, **meiosis - II** is referred to as **equatorial division**.

2. Meiosis – I is referred to as a **reduction division** because it reduces the **ploidy** level from **two** to **one**.

<u>MITOTIC PROPHASE AND MEIOTIC PROPHASE-I COMPARED</u>

<u>Similarities:</u> In both: **(1)** chromatins condense to become visible chromosomes **(2)** spindle begin to form **(3)** nucleolus shrinks and disappears **(4)** nuclear envelope breaks down **(5)** centrioles migrate to opposite poles **(6)** sister chromatids are held together at the centromere.

<u>Differences:</u> **(1)** In mitotic prophase, no crossing over while it occurs in meiotic prophase-I **(2)** In mitotic prophase, no chiasmata formation while it occurs in meiotic prophase-I **(3)** In mitotic prophase, no synapsis while it occurs in meiotic prophase-I **(4)** In mitotic prophase, no exchange/swapping of genetic material between non-sister chromatids while it occurs in meiotic prophase-I

<u>TASK</u>: State other comparisons between metaphase, anaphase and telophase stages mitosis and meiosis-I.