Cell Division – Mitosis & Meiosis

1. Overview of Topic

The first single cellular organisms appeared about 3.5 billion years ago, roughly about a billion years after Earth was formed. It took a longer time for more complex life forms to evolve, with the first multicellular organisms only appearing about 600-800 million years ago. As life on earth progressed from single-cellularity to multi-cellularity, there was a need for the cell cycle to be more systemic and precise. Nuclear division is a stage of the cell cycle. Following nuclear division, the genetic information stored in the form of DNA, on chromosomes, is appropriately passed on to daughter cells from the parent cells. In mitosis, the daughter nuclei would possess the same type and number of chromosomes as the parent nuclei. Meiosis occurs only in the sexually reproducing organisms. In meiosis, the daughter nuclei (haploid) end up with half the number of chromosomes as the parent cell (diploid). The daughter chromosomes may also have different allelic combinations due to allelic exchanges between the maternal and paternal chromosomes. Mitosis and Meiosis bring about genetic stability and genetic variation in the organisms. In this chapter, we will be examining these nuclear division processes.

2. Learning Outcomes

a. Describe the events that occur during the mitotic cell cycle and the main stages of mitosis (including the behaviour of chromosomes, nuclear envelope, cell membrane and centrioles).
b. Explain the significance of the mitotic cell cycle (including growth, repair and asexual reproduction) and the need to regulate it tightly. (Knowledge that dysregulation of checkpoints of cell division can result in uncontrolled cell division and cancer is required, but detail of the mechanism is not required.)
c. Describe the events that occur during the meiotic cell cycle and the main stages of meiosis (including the behaviour of chromosomes, nuclear envelope, cell membrane and centrioles). (Names of the main stages are expected, but no the sub-divisions of prophase.)
d. Explain the significance of the meiotic cell cycle (including how meiosis and random fertilisation can lead to variation).

3. References

Campbell, N.A. and Reece, J.B. (2008). Biology, 9th edition. Pearson.
Jones & Jones. (1997). Advanced Biology.
Hoh Yin Kiong (2003). Longman A-Level Course in Biology, Vol. 1. Longman
Green, Stout and Soper (1990). Biological Sciences, Vol 1. Cambridge
Raven, Johnson, Losos, Mason & Singer (2008). Biology, 8th edition. McGraw-Hill.

Contents

4. Introduction

Notes to self

The modern cell theory states that all new cells are derived from other cells. Many cells in a multi-cellular organism undergo a well-defined sequence of stages culminating in the division and formation of new cells. The processes involved are collectively grouped under the term **cell division**.

There are some types of cells that are continuously dividing throughout the lifetime of the organism (e.g. bone marrow cells, epithelial cells of the skin, etc.) whilst others stop dividing upon reaching maturity (e.g. neurones, muscle cells, etc.).

Cell division occurs in 2 main steps:

- **Nuclear division** &
- **Cytokinesis (cytoplasmic division)**

Cell division = Nuclear division + Cytokinesis

1) **Nuclear Division** (= division of the nucleus):

- There are **2 types** of **nuclear division**: **Mitosis** & **Meiosis**

2) **Cytokinesis** (= division of the cytoplasm)

- Cytokinesis is the division of the cytoplasm to form 2 separate daughter cells immediately after mitosis, meiosis I or meiosis II.

⚠ Please note that mitosis and meiosis are nuclear divisions and only occur in eukaryotic cells and not prokaryotic cells.

5. Structure of Chromosomes

Chromosomes carry the hereditary material (DNA) in cells. The hereditary material is passed on to the next generation through cell division.

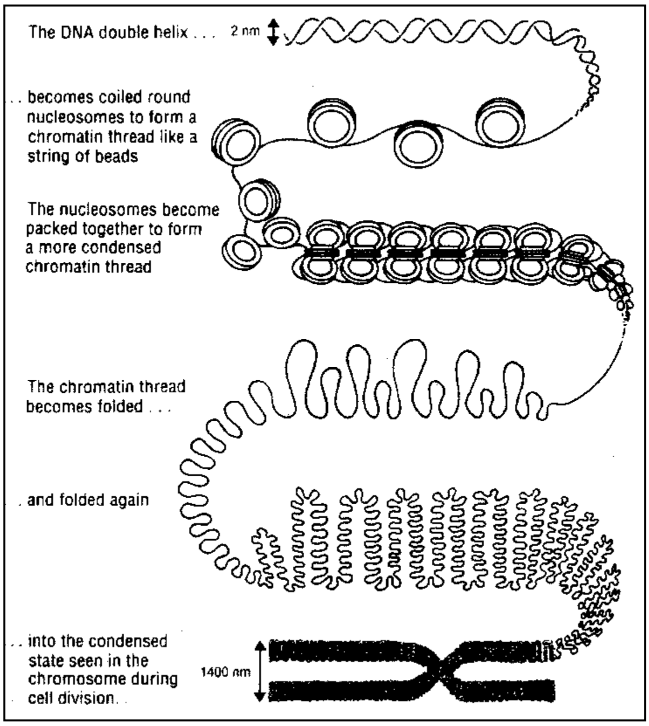
The structure of the eukaryotic chromosome:

- DNA (deoxyribonucleic acid) is the double-stranded, helical molecule found within the nucleus of each cell. DNA carries the genetic information that encodes the proteins necessary for cells to reproduce and to perform their functions.
- When a cell is not dividing, chromosomes exist in their dispersed, uncondensed form, as a mass of long, thin, thread-like fibres known as chromatin.
- **Chromatin** is a complex of **DNA and histone proteins**. The DNA winds around an **octamer** formed by **8 histone proteins** forming **nucleosomes.**

Notes to self

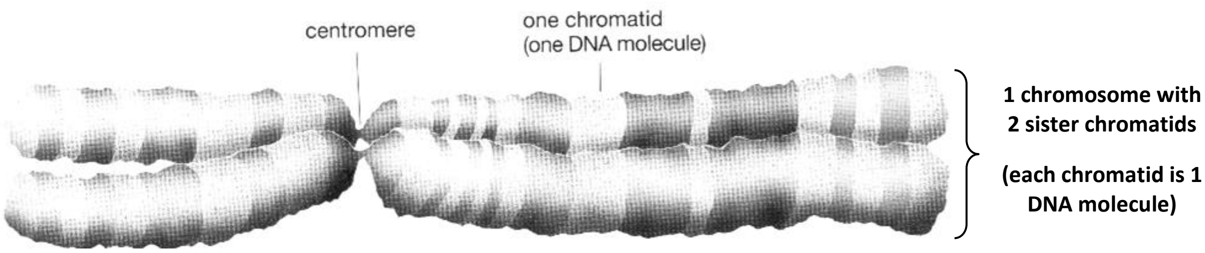
- Chromatin that has been condensed by coiling/folding many times upon itself results in a chromosome which appears as a thicker, shorter and more visible structure.

Level of chromatin packing in a chromosome



- **Condensed chromosomes** are found in the nucleus of dividing cells during some stages of mitosis and meiosis, such as late prophase, metaphase, anaphase, early telophase etc. During these stages, the chromatin is condensed and more tightly coiled and folded such that the chromosome appears thicker and shorter and more visible.
- **Sister chromatids** contain **identical DNA molecules** as they are **replicated from the same DNA molecule**.

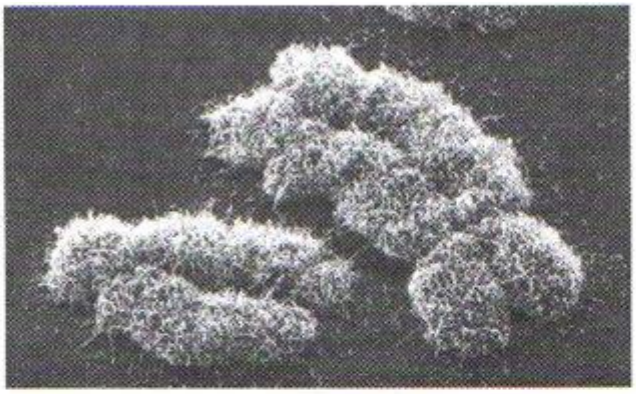
  After DNA has replicated during interphase, the chromatin condenses during prophase to form two sister chromatids held together at the **centromere**.



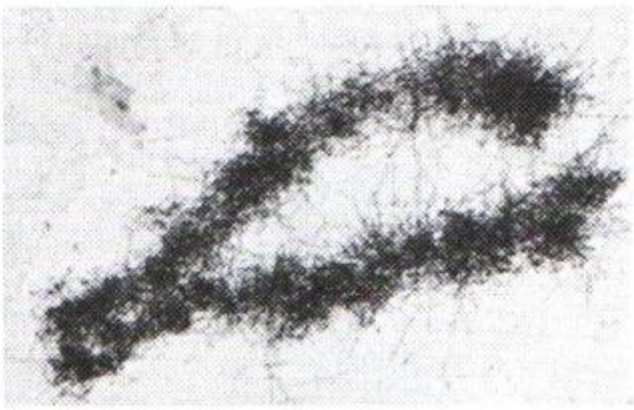
Structures of chromosome during metaphase and anaphase

Notes to self

Scanning electron micrograph of chromosome



Chromosome, with 2 sister chromatids, at metaphase (transmission electron micrograph)



6. Diploidy & Haploidy

The term diploid is used to describe a nucleus, cell or organism with two complete sets of chromosomes, where **chromosomes exist as homologous pairs with each chromosome of the pair come from either parent** (maternal & paternal). Most organisms exist in a diploid condition.

The diploid condition is represented as **2n**, where n represents 1 complete set of chromosomes.

Somatic (non-gametic) cells are diploid e.g. the diploid number of chromosomes for humans is 46.

The term **haploid** is used to describe a nucleus, cell or organism that contains only **one complete set of chromosomes** that has half the diploid number of chromosomes and contains one homologue of each homologous chromosome pair.

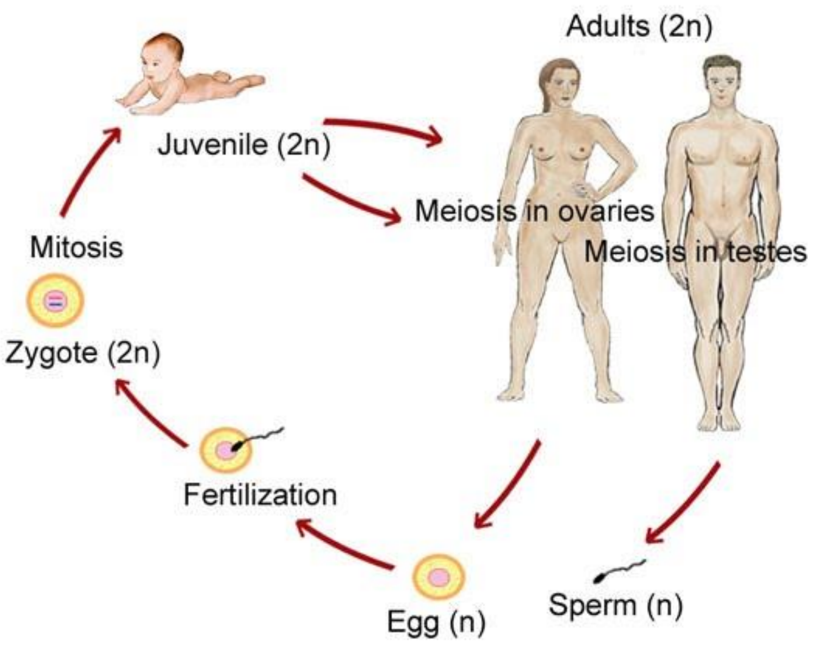
The haploid condition is represented as **n**. e.g. the haploid number of chromosomes for the gametes in human is 23.

Gametes are haploid.

Notes to self

Table showing the diploid and haploid chromosome numbers across different species

Organism	Diploid chromosome number	Haploid chromosome number
Fruit fly (*Drosophila melanogaster*)	8	4
Onion (*Allium cepa*)	6	3
Maize (*Zea mays*)	20	10
Locust (*Locusta migratoria*)	24	12
Lily (*Lilium longiflorum*)	24	12
Tomato (*Solanum lycopersicum*)	4	2
Mouse (*Mus musculus*)	40	20
Human (*Homo sapiens*)	46	23
Potato (*Solanum tuberosum*)	48	24

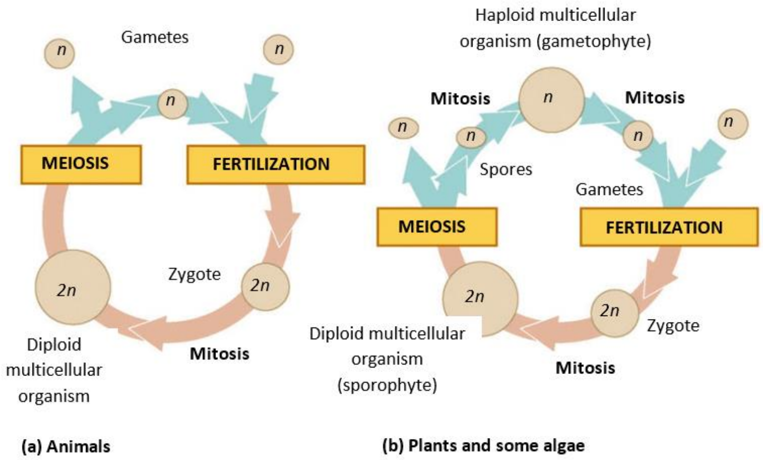


Human Life Cycle

Notes to self

The **fusion** of a **haploid** sperm and **haploid** egg during **fertilisation** results in the formation of a **diploid zygote**. This new cell is "diploid" because it contains the two haploid sets of chromosomes, one set supplied by the mother and one by the father. These chromosomes bear the ancestral genes that represent the maternal and paternal family lines.

After fertilisation, the zygote undergoes a process of nuclear division called **mitosis**. This generates cells that are **genetically identical** to the original zygote. These cells are then stimulated to differentiate into specialised cells that form the organism.



<u>**Sexual reproduction in animals and plants**</u>

7. Homologous chromosomes

In a **diploid** cell, two chromosomes having the same **size**, **shape**, **centromere position**, **staining pattern**, and **position of genes** are known as **homologous chromosomes**.

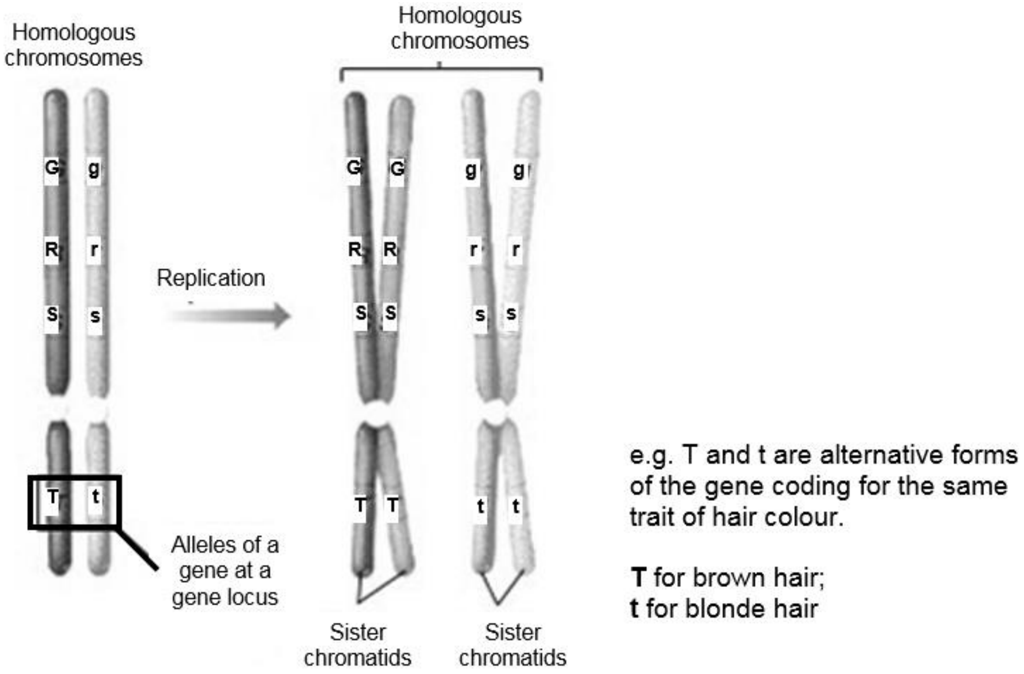
Each member of such a pair is called a **homologue**.

Characteristics of homologous chromosomes:

- They are similar in **size**, **shape**, **centromere position** and **staining pattern**.
- One homologue originates from the **male** parent and the other from the **female** parent.
- They have the **same genes** (that determine the same characters) at corresponding loci. e.g. blood group, hair colour. *Note: Locus (singular)/ loci (plural) – is the fixed position of a gene in a chromosome*
- However they may not be identical in what they code for, thus they may have **different alleles** at the same locus.

Alleles are **alternative forms of a gene** and hence occupy the same loci on a pair of homologous chromosomes. e.g. for the gene that controls the hair colour character, one homologue may carry an allele that codes for brown hair and the other homologue may carry the allele for blonde hair.

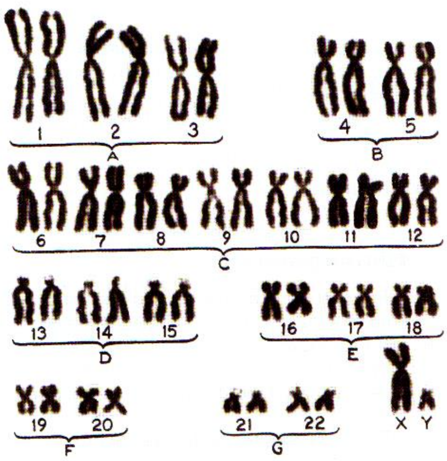
Notes to self



Formation of sister chromatids, with identical allelic combinations, in homologous chromosomes following semi-conservative DNA replication.

Sister chromatids, if no crossing over occurs, *always* have the same alleles. While homologous chromosomes have the same genes but may have different alleles as one homologue is from the father while the other is from the mother.

The number of chromosomes varies from one species to another but is always the same for normal individuals of one species. However, some species may share the same chromosome *number*, but the *types* of chromosomes are different. Humans have 46 chromosomes or **23 homologous pairs** of chromosomes.



Male human karyotype showing 23 pairs of chromosomes (22 homologous chromosomes & 1 pair of sex chromosomes)

Question: Are all the chromosome pairs homologous?

No. X and Y chromosomes are not homologous as their size, shape and centromere position are different.

Notes to self

Question: A chicken has 78 chromosomes in its somatic cells.
a) How many chromosomes did the chicken inherit from each parent? ***39***
b) How many chromosomes are in each of the chicken's gametes? ***39***
c) How many chromosomes are in each cell of the embryo? *78*
d) How many chromosomes are in one "set" / haploid? *39*

8. Factors influencing cell division

	Factors	How they affect cell division
1.	**Surface area to volume ratio**	As a cell enlarges, its volume increases faster than its surface area. The cells in a given tissue are stimulated to divide when the ratio of surface are to volume exceeds a critical figure. Why? *When the surface area is not great enough to accommodate the entry of food materials and oxygen at a rate sufficient to supply the cell's demands, the cell divides in order to restore a favourable surface area to volume ratio.*
2.	**Nucleus to cytoplasmic ratio**	When a cell increases beyond a certain size, the cell will divide. Why? *As there is a limit to the amount of cytoplasm which a nucleus can control, the cell will divide so as to restore a more favourable nucleo-cytoplasmic ratio. By doing so, it will enable the nucleus to effectively direct and control the many activities in the cytoplasm.*
3	**Chemical substances**	Growth hormones in plants and animals are required to initiate cell divisions and determine the rate of cell division e.g. auxins in plants and thyroxine in vertebrates. In humans, how is cell growth stimulated in an injured area? *Wounds usually causes the production of chemicals that stimulate cell division to grow over the injured area.*

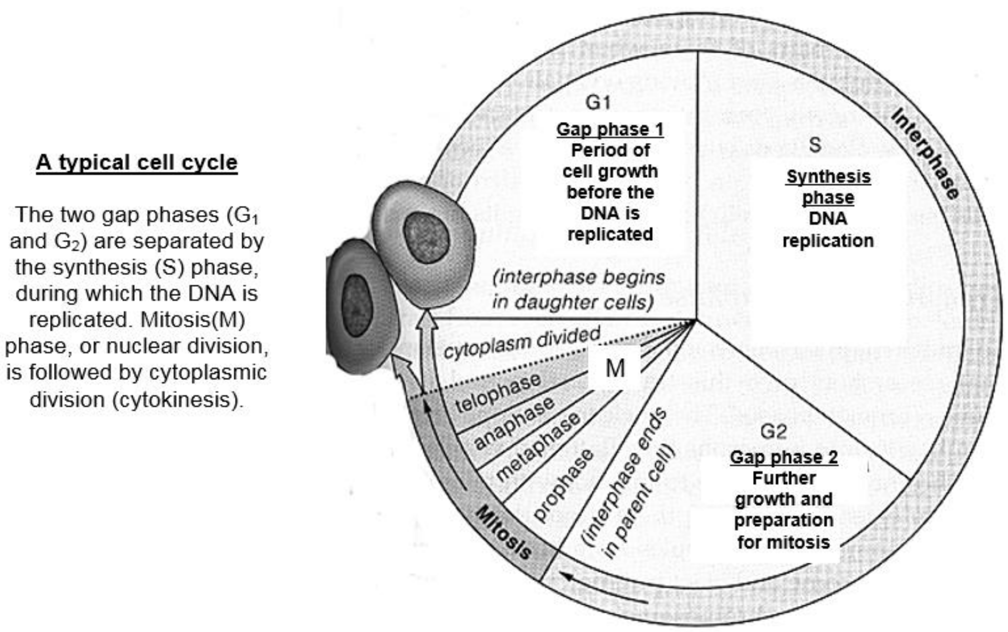
Other factors influencing cell division includes age, temperature and mechanical stimuli.

An example of mechanical factor is abrasion which removes cells from skin surfaces and this stimulates the cells beneath to divide more rapidly.

9. The Cell Cycle

Notes to self

The cell cycle is the sequence of events which occurs between the formation of a cell and its division into daughter cells.



The Cell Cycle

The cell cycle consists of the following 3 main stages:

Stages in cell cycle	**Main events**
Interphase (longest phase, 90% of cell cycle)	- Period of synthesis and growth - Cell produces many materials and organelles required for carrying out all its functions - Cell replicates its DNA (during **S phase of interphase**) to prepare for nuclear division
Nuclear division	- Either mitosis or meiosis
Cytokinesis (cytoplasmic cleavage)	- Division of **cytoplasmic contents** into 2 daughter cells

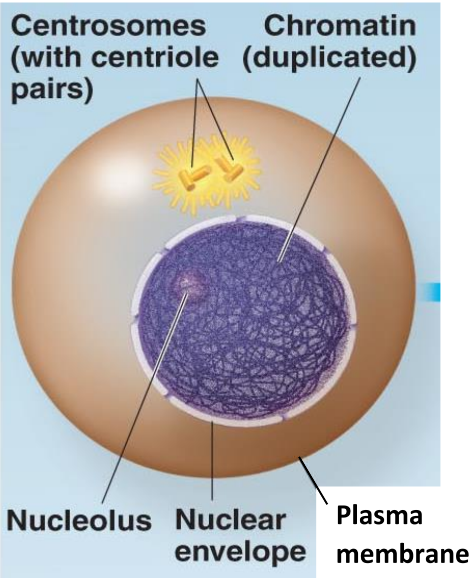
(Note: Cells do not normally divide continuously i.e. a certain period will elapse between two divisions.)

10. Interphase

Notes to self

The interphase is a stage of preparation for mitosis/meiosis. It is non-dividing phase of the cell and is the longest phase of the cell cycle (90% of cell cycle).

Phase	Events within the cell
G_1 (Gap phase 1)	Intensive cellular synthesis: **a)** Organelle synthesis **b)** RNA synthesis **c)** Protein synthesis **d)** ATP synthesis
S (Synthesis phase)	**Semi-conservative DNA replication occurs**: **a)** DNA strands replicate → DNA content of the cell doubles
G_2 (Gap phase 2)	**Intensive cellular synthesis** (in preparation for mitosis): a) Organelle synthesis b) Synthesis of spindle proteins c) ATP synthesis d) Microtubules begins to form **e)** Condensation of chromosomes begins



- The longest part of the cell cycles
- Includes G_1, S and G_2 phases
- By the end of interphase:
  - **DNA duplicated**
  - Nucleus is bound by **nuclear envelope**
  - **Nucleolus** present
  - Single **centrosome replicated** to form two centrosomes, each containing a pair of centrioles in animals
  - Organelles duplicated

⚠ There is no centriole in higher plant cells.

Use the term **microtubule organizing center** instead.

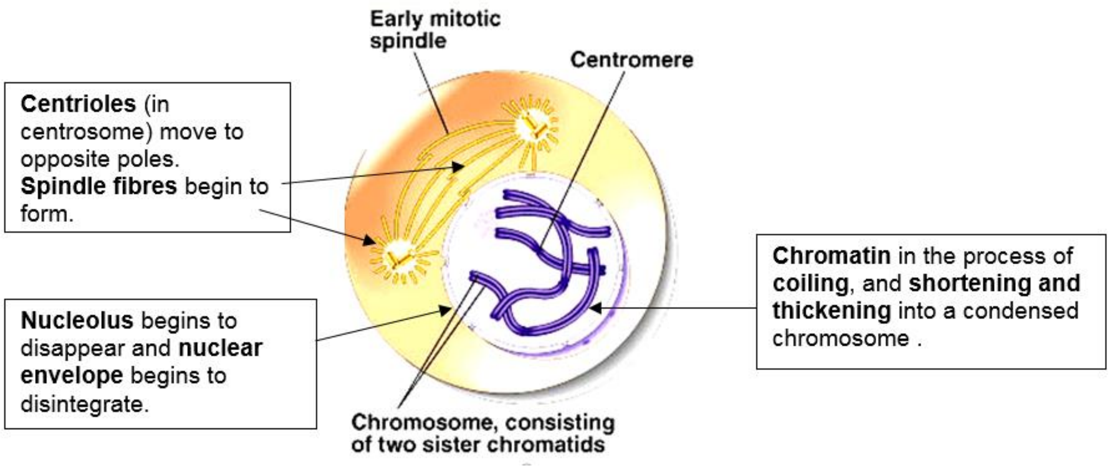
11. Mitosis

Notes to self

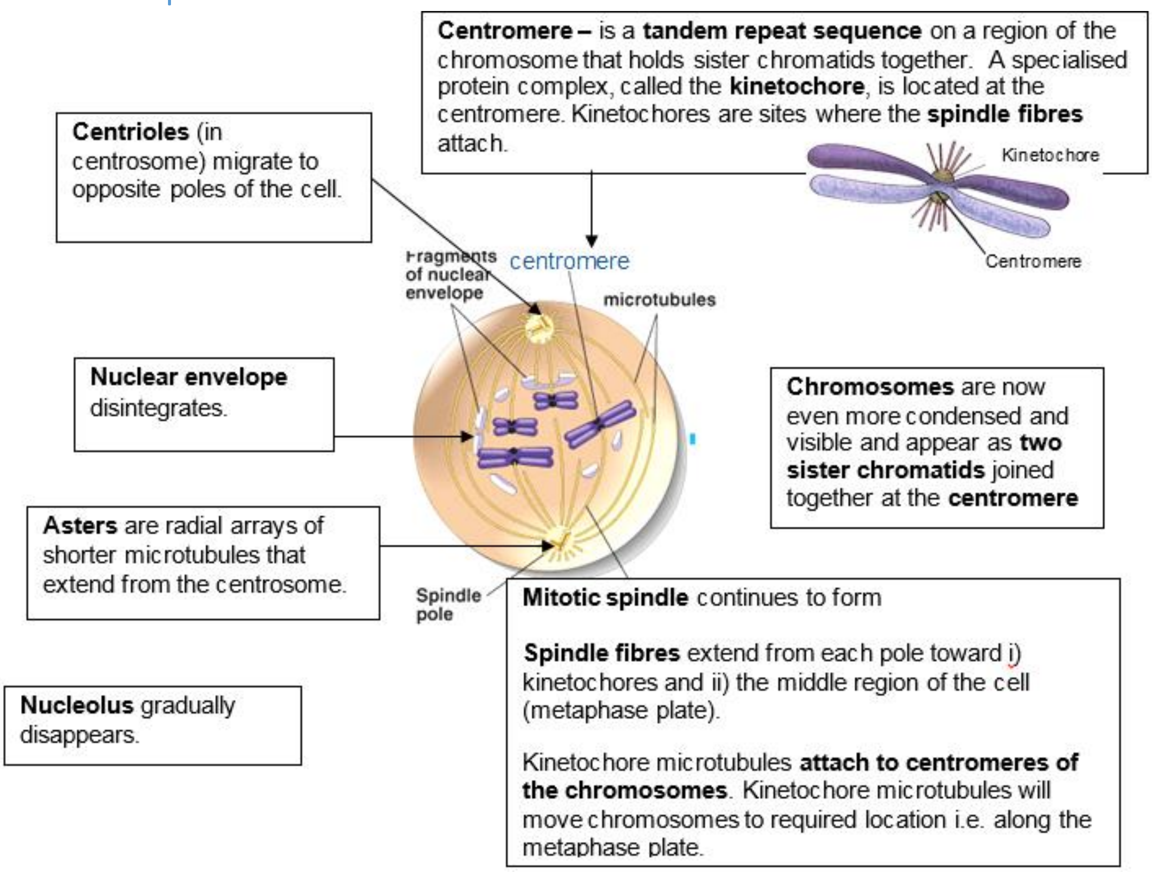
Mitosis is a form of **nuclear division** in eukaryotic cells which produces **two daughter nuclei** containing **identical sets of chromosomes** as the parental cell nucleus. It follows interphase (if the conditions are right). It is usually followed immediately by **cytokinesis**, during which an equal division of the cytoplasm of the parent cell and formation of the cell membrane and cell wall (in plants) results in the formation of two daughter cells.

Mitosis is made up of 4 main stages: **P**rophase, **M**etaphase, **A**naphase, **T**elophase.

a. Early Prophase (Usually the longest phase of mitosis)



b. Late Prophase

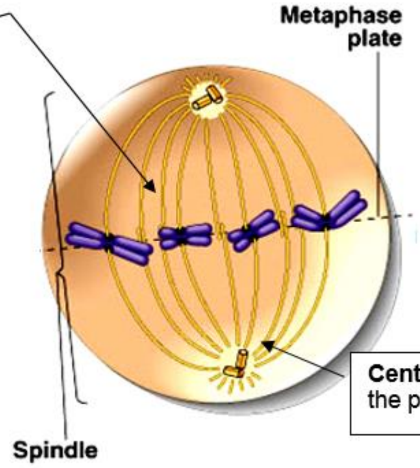


c. Metaphase

Notes to self

Chromosomes are aligned at the equator / metaphase plate

Spindle is **completely formed**.
Kinetochore microtubules are attached to centromeres of the chromosomes.

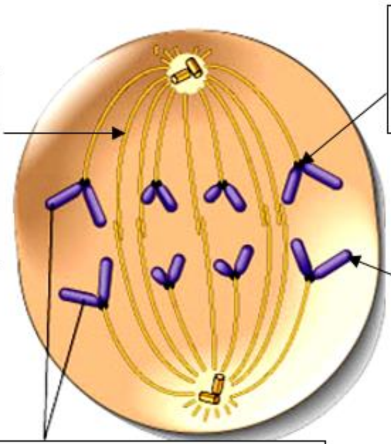


Centrioles located at the poles of the cell.

1. If the cell is diploid, **both** homologous chromosomes are present but are aligned singly and not pair up.
2. Use terms like equator/ metaphase plate and not centre / middle

d. Anaphase (shortest phase in mitosis)

Spindle fibres (**non-kinetochore microtubules**) elongate and slide in opposite direction due to the actions of motor proteins. This cause the two poles to move further apart.



Centromere of the chromosome **divide.**

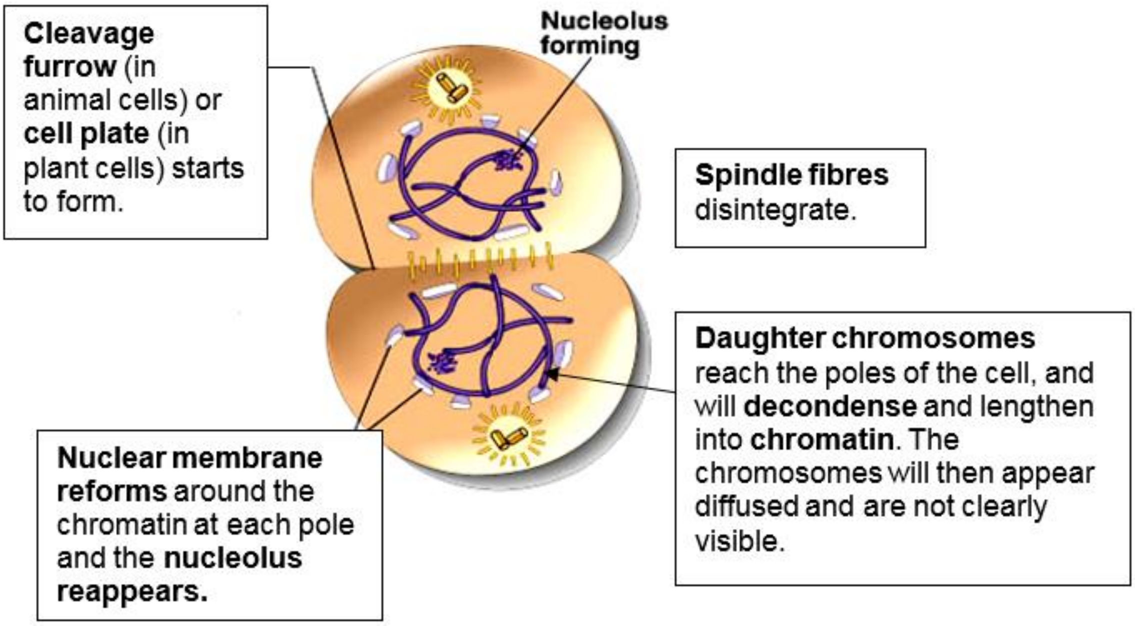
Daughter chromosomes are **<u>led by their</u> <u>centromeres</u>** resulting in the characteristic **'V' shape** of chromosomes seen in anaphase.

Separated sister chromatids, now called **daughter chromosomes** are pulled to **opposite poles** by **shortening** spindle fibres/**kinetochore microtubules**.

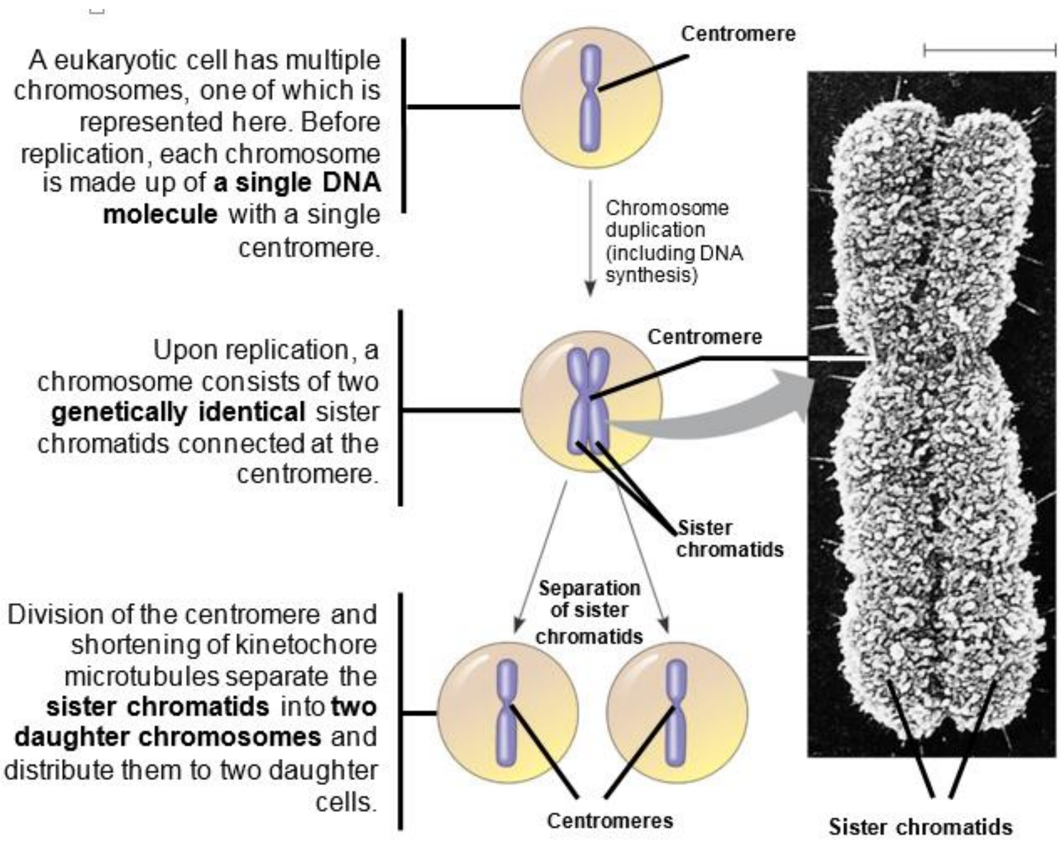
1. Centromere divides/duplicates and <u>not</u> split/replicate
2. Pole is the correct term and <u>not</u> end
3. The shortening of the kinetochore microtubules <u>does NOT</u> cause the division of the centromeres! Centromere divides thus allowing the sister chromatids to be separated
4. Need to mention separated sister chromatids, which now form daughter chromosomes, are pulled to opposite poles instead of just mentioning chromosomes alone.

e. Telophase (2 nuclei forming in one cell)

Notes to self



Review: Chromosomal DNA replication and distribution during cell division



Note: all the chromosomes above are drawn as 'metaphase-stage' chromosomes for ease of viewing, not all of them should look like that – the topmost chromosome should appear in chromatin form because of the stage it is in i.e. before duplication (S phase of interphase)

Notes to self

Question: Fill in the blanks.
where n = no. of chromosomes and X = amount of DNA

	In a cell		
	No. of chromos-omes.	**Amt. of DNA**	**No. of DNA molecules**
G_1 phase	**2n**	**X**	**4**
Prophase	*2n*	*2X*	*8*
Metaphase	*2n*	*2X*	*8*
Anaphase	*4n*	*2X*	*8*
Telophase	*4n*	*2X*	*8*
Cytokinesis	*2n*	*X*	*4*

1 chromatid = 1 DNA molecule; parent chromosome with 2 sister chromatids has 2 DNA molecules. After anaphase, 1 daughter chromosome has 1 chromatid thus 1 DNA molecule.

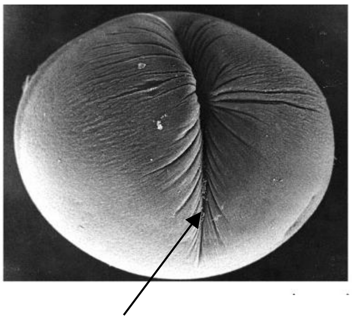
12.Cytokinesis (Cytoplasmic division - not part of mitosis)

Notes to self

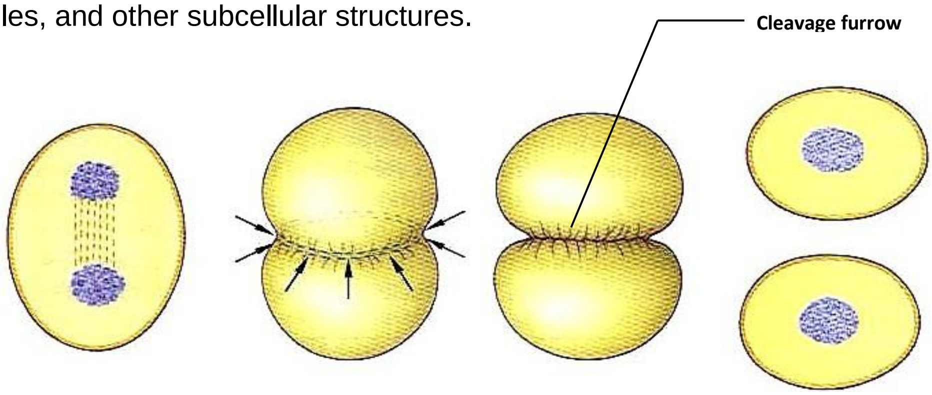
Cytokinesis generally begins at **telophase** during which the cytoplasm and cell organelles of the parent cell are evenly distributed between the resulting daughter cells.

a) In animal cells

- The cell membrane begins to **invaginate** towards the region previously occupied by the equator / metaphase plate, forming a **cleavage furrow** due to the **microfilaments** in the ‘**drawstring’ effect**.
- The cleavage furrow deepens until the parent cell is **pinched** into two, producing two completely separated cells each with its own nucleus and share of cytosol, organelles, and other subcellular structures.



Cleavage furrow



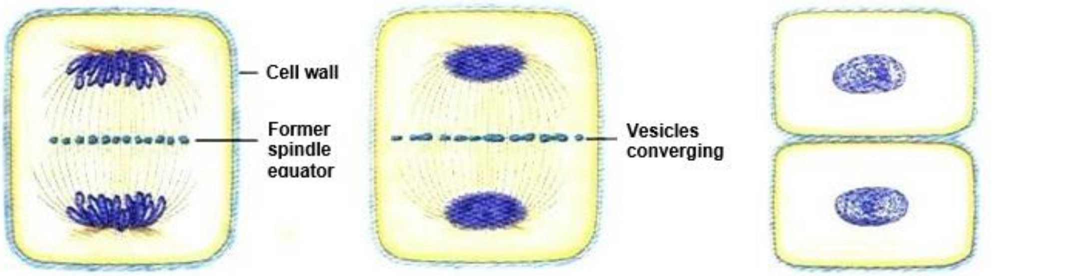
a. Mitosis is over, and the spindle is now disassembling

b. Just beneath the plasma membrane, the cell membrane begins to invaginate forming a **cleavage furrow**

c. The contractions continue, and cut the cell into two, forming two daughter cells

b) In plant cells

- In the cells of the higher plants, a series of **fluid-filled vesicles** (derived from the Golgi apparatus), move to the equator/metaphase plate of the cell and **coalesce** (i.e. fuse) to form **cell plate**.
- The contents of the vesicles will be converted to pectin and cellulose, which contribute to the middle lamella and cell wall matrix respectively, of the daughter cells. The membranes of the vesicles form the cell surface membranes of the daughter cells.
- The cell plate eventually fuses with the parent cell wall and cell membrane, separating the daughter cells.



a. The Golgi apparatus produces a number of small fluid-filled vesicles, which first appear in the centre of the cell.

b. Guided by microtubules, the vesicles coalesce to form a cell plate which grows across the equatorial plane.

c. The contents of the Golgi vesicles contribute to the new cell walls of the daughter cells whilst their membranes form the new cell membranes. The spreading cell plate eventually fuses with the parent cell wall and separates the two daughter cells.

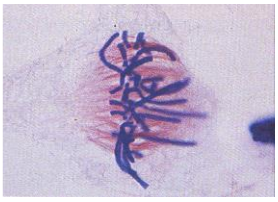
Notes to self

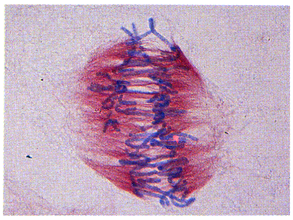
Strengthen Your Synapses

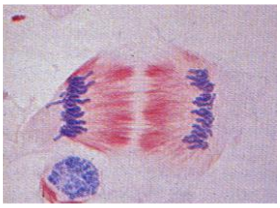
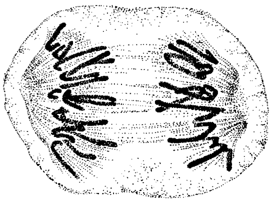
Review questions

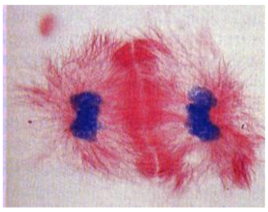
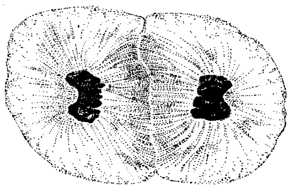
1. Use annotated diagrams to describe the behaviour of chromosomes during mitosis. (Answer in a separate paper)

2. Identify the different stages of mitosis in the pictures shown below.



13. Significance of mitosis

Notes to self

a) Maintaining genetic stability

Mitosis produces 2 daughter nuclei, each of which will have **the same number and same types of chromosomes** as the parent cell.

Each daughter nucleus eventually becomes part of one daughter cell.

Since the chromosomes in both nuclei were derived from the parental chromosomes by exact replication of their DNA and subsequently their even distribution, the chromosomes in the two daughter cells are **genetically identical**.

Thus, mitosis produces daughter cells that are genetically identical to their parent cell.

Mitosis **does not introduce genetic variation**, thus maintaining **genetic stability** within the populations of cells derived from the same parental cells.

In animal, it **will not result in rejection by the body immune system** as the daughter cells produced are genetically identical to the parent cell, thus helping in recognizing **self versus non-self cells**.

b) Growth

Mitosis takes place during growth of an organism. Growth is defined as an increase in number of cells or size of cells.

The **number of cells** within the organism **increases** and the new cells produced are **genetically identical to the existing cells.**

c) Regeneration and cell replacement

Mitosis ensures that when damaged tissues are repaired, the **damaged cells** are replaced by cells that are **genetically identical** to the original cells.

Mitosis helps in cell replacement and regeneration of missing parts, to varying degrees, in multi-cellular organisms.

Examples of regeneration include regeneration of tails in lizards and arms in starfish.

d) Asexual reproduction

A type of reproduction where an organism replicates itself without the production of eggs or without fertilisation. Thus asexual reproduction takes place when a single parent **produces offspring genetically identical** to itself.

Many animal and plant species propagate by asexual means involving mitotic divisions of cells.

Asexual reproduction is an advantage in stable environments where the offspring receive a set of genes from the parent who has survived and reproduced under the same conditions. With this set of genes, the offspring will be suitably adapted to the same conditions that have allowed the parent to thrive. In these ideal conditions, the population can reproduce very rapidly.

e.g. vegetative reproduction in plants (e.g. strawberry)

14. Meiosis – 'Reduction division'

Notes to self

Most organisms produce offspring by a process of sexual reproduction. During this process, a haploid(n) gamete from one parent fuses with another haploid (n) gamete from the other parent to form a diploid (2n) **zygote** (or fertilized egg). This process results in offspring that have 2 sets of chromosomes, one set from each parent.

Most organisms contain diploid (2n) chromosome numbers in their somatic (non-sex, non-gametic) cells. In order to ensure that the offspring have the same number of chromosomes (diploid) as the parents, the two **gametes** must have only **half the number of chromosomes (haploid)** as the parents.

Hence, meiosis is also known as "**reduction division**" because resultant daughter cells have **half** as many chromosomes as their parent cells. The nucleus of each daughter cell will have one set of chromosomes i.e. no homologous pairs. The daughter cells would be **haploid** (**n**) while the parent cells would be **diploid** (**2n**).

Meiosis is a form of nuclear division in sexually reproducing organisms that produces **four haploid daughter nuclei**, each containing half the chromosome number of the parent cell.

Meiosis produces daughter cells that are **genetically different** from the parent and this is important because it contributes to **variation**.

Meiosis involves **two nuclear divisions**:

Meiosis I (the first meiotic division) Involves the **pairing** of **homologous chromosomes** and their subsequent **separation** into 2 daughter cells (which **reduces the chromosome number by half**).	**Meiosis II** (the second meiotic division) Involves the **separation of the 2 sister chromatids**
prophase I metaphase I anaphase I telophase I	prophase II metaphase II anaphase II telophase II

a. Interphase (not part of meiosis)

The events during interphase, preceding meiosis, are similar to those which occur before mitosis. The chromosomes undergo semi-conservative DNA replication and sister chromatids are formed during the Synthesis (S) phase of Interphase. Intensive cellular synthesis also occurs during the G1 & G2 phases of the cell cycle, in preparation for meiosis.

b. Prophase I (early)

Notes to self

Chromatin coils, shortens and thickens into a condensed chromosome.

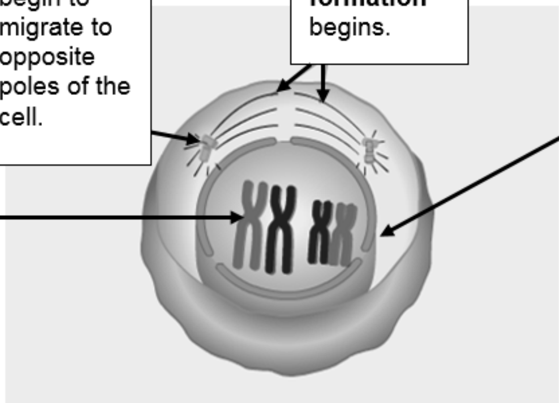
Homologues (homologous chromosomes) **pair up** via the process of **synapsis** to form **bivalents** (this process is independent of spindle fibres)

In every pair, one homologue comes from the **father** and the other homologue from the **mother.**

Centrioles begin to migrate to opposite poles of the cell.

Spindle formation begins.

Nucleolus begins to disappear and **nuclear envelope** begins to disintegrate.



c. Prophase I (late)

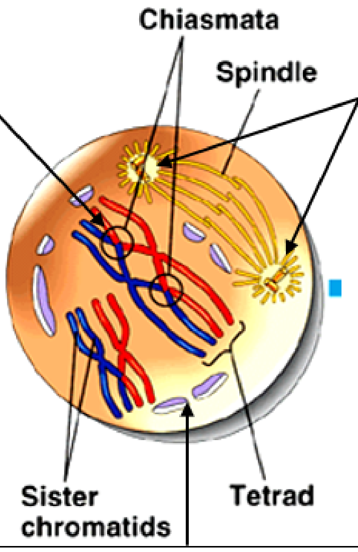
Crossing over occurs between the **non-sister chromatids** of **homologous chromosomes.**

Chiasmata (singular = chiasma)
➔ sites where **non-sister chromatids** of **homologous chromosomes** break and rejoin

Thus crossing over allows **exchange of equivalent portion of genetic material or alleles** between **non-sister chromatids** of **homologous chromosomes.** Crossing over results in **new combination of alleles on the chromosome.** This contributes to **diversity and variation.**

During crossing over, **bivalents** are seen as **tetrads.** (each tetrad = 2 chromosomes each with 2 chromatids)

Recall: Each chromosome consists of **2 sister chromatids** joined at **centromere**



Centrioles
Continue to migrate to opposite poles of the cell.

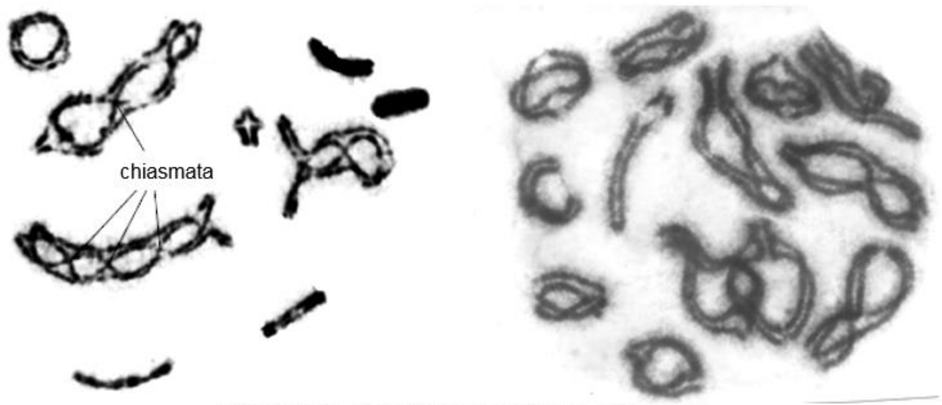
Spindle fibres begin to **attach** to the **kinetochores** of each **homologue.**

Nucleolus disappear and **nuclear envelope** have **disintegrated.**

1. Crossing over occurs at prophase I and not at anaphase I when homologous chromosomes separate.

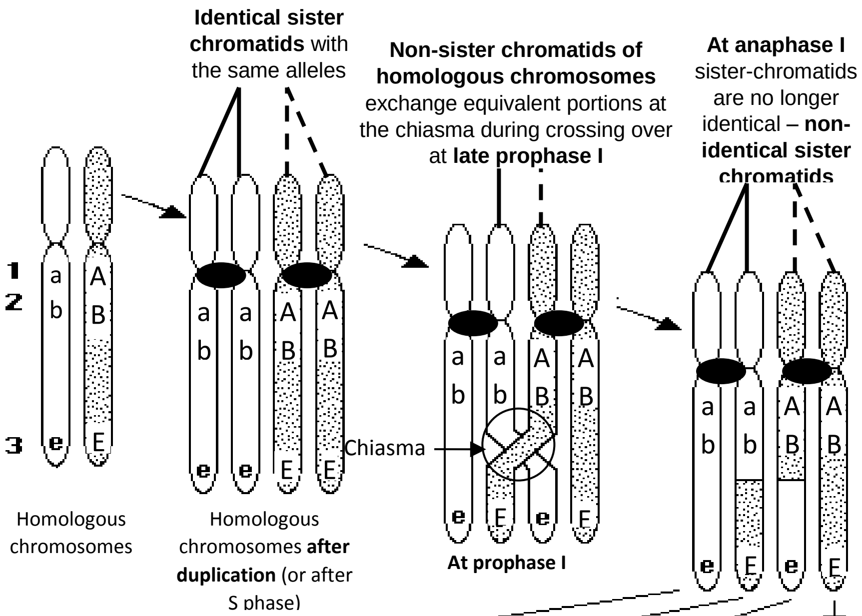
2. Please note that crossing over is between <u>non-sister chromatids</u> of <u>homologous chromosomes</u> and not sister chromatids or just chromatids.

Notes to self



Micrographs showing late prophase I of meiosis I

CROSSING OVER

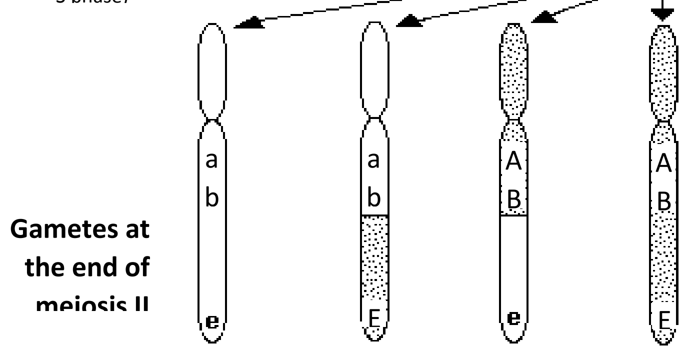


Note:

a and A are alleles of the same gene

b and B are alleles of the same gene

e and E are alleles of the same gene



Recall:

Alleles – alternative forms of a gene.

e.g. the gene for colour of flower may have several alleles, one codes for purple flower colour whereas another allele codes for yellow flower colour.

As a result of crossing over, there is an exchange of genetic material which is the exchange of corresponding alleles between non-sister chromatids of homologous chromosomes.

Genetic variation in populations can arise as a result of crossing over.

d. Metaphase I

Notes to self

Spindle is completely formed

Spindle fibres (**kinetochore microtubules**) attach to the centromere of each homologue

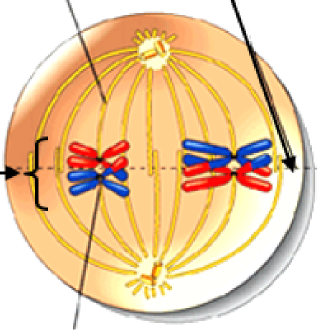
Metaphase plate

Tetrads
Homologous pair of chromosomes align along the **equator/ metaphase plate**

Homologous pairs move to the metaphase plate with the help of the **kinetochore microtubules**

Each homologue is **attached** to the **kinetochore microtubule** from the **pole** it faces

Independent assortment of homologous chromosome occurs at this stage. (refer to Mendel's Law of Independent Assortment) (pg 28)



Kinetochore of centromere
attached to spindle fibres (spindle fibres are made of microtubules)

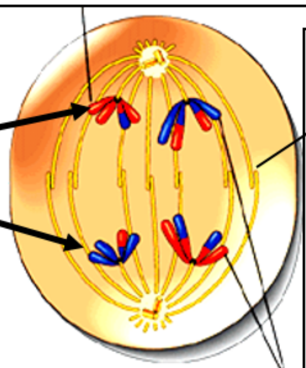
e. Anaphase I

Note: **Sister chromatids** remain **attached** and move together towards the same pole (because the centromeres have not yet separated / divided, this pair of sister chromatids is considered **one chromosome**)

Homologues separate to opposite poles

Each homologue is pulled by a **shortening kinetochore microtubule** (that attaches to the centromere) towards one of the poles

Note: Centromeres do not divide / separate here.

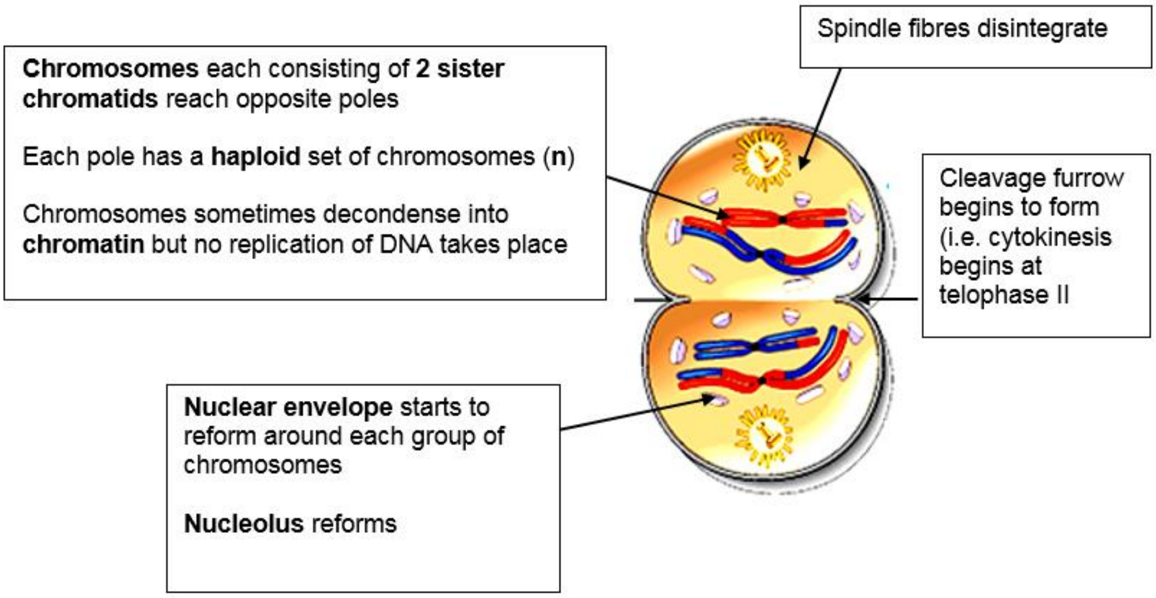


Spindle fibres (**non-kinetochore microtubules**) elongate and slide in opposite direction due to the actions of motor proteins. This cause the two poles to move further apart.

Homologous chromosomes separate

f. Telophase I

<u>Notes to self</u>



⚠ At the end of meiosis I, the nuclei are **haploid**.

g. Cytokinesis

While cytokinesis occurs in some cells after telophase I, in many others, there is **no telophase I** and **no cytokinesis**. Such cells **enter prophase II directly from anaphase I**.

h. Meiosis II

Meiosis II **begins with 2 <u>haploid</u> daughter cells** and involves the separation of sister chromatids, **forming 4 <u>haploid</u> cells**.

1) PROPHASE II
- Chromosomes condense
- Centrioles duplicate and move to opposite poles
- Spindle fibres begin to form
- Nuclear membrane disintegrates, nucleolus disappears

2) METAPHASE II
- Spindle is completely formed
- The centromere of each chromosome is attached to kinetochore microtubules
- Kinetochore microtubules align the chromosomes at the metaphase plate in a single file

3) ANAPHASE II
- Centromeres divide and sister chromatids separate
- **Each chromatid is now called a daughter chromosome**; these are pulled by **shortening** kinetochore microtubules to opposite poles centromeres first (i.e. led by the centromeres)
- Non-kinetochore microtubules lengthen and elongate the cell

Notes to self

4) TELOPHASE II

- Chromosomes reach the poles of the spindle where they decondense and become diffuse/indistinct
- Spindle fibres disintegrate
- Nuclear envelope reforms around each group of chromosomes (now existing in the form of chromatin) and nucleolus reappears in each daughter nucleus

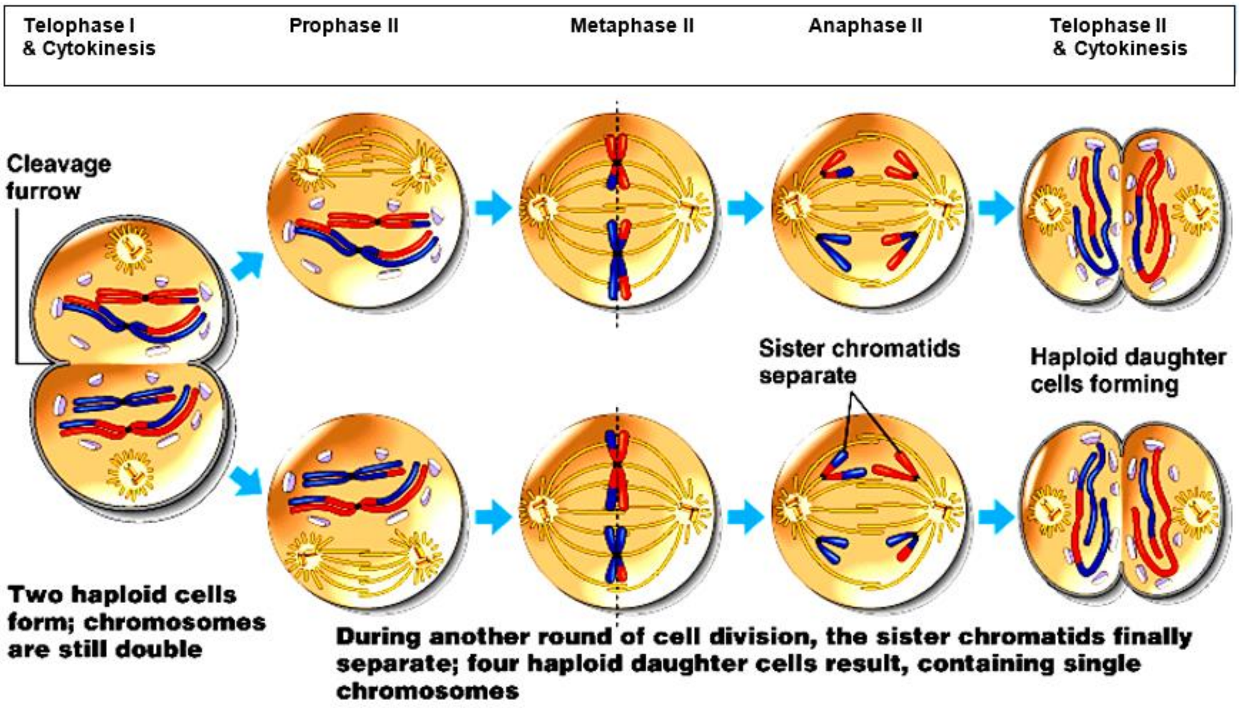
i. Cytokinesis after meiosis II

Cytokinesis follows meiosis II. During cytokinesis, the cells divide to give a total of **4** daughter cells, with each daughter cell (**n**) possessing half the number of chromosomes as the parent cell (**2n**) and half the DNA amount as the parent cell *before S phase* of interphase (or a quarter the DNA amount as the parent cell *after S phase* of interphase).

Cytokinesis begins at telophase II.

Meiosis II is similar to mitosis but starts with haploid cells and sister chromatids may not be genetically identical due to crossing over.

Diagrammatic representation of events which occur during Meiosis II



Notes to self

Question: Fill in the blanks.
Where n = no. of chromosomes and X = amount of DNA

	In a cell			In a cell	
	No. of chromosomes	Amount of DNA		No. of chromosomes	Amount of DNA
G_1 phase	2n	X	***Prophase II***	n	X
Prophase I	2n	2X	***Metaphase II***	n	X
Metaphase I	2n	2X	***Anaphase II***	2n	X
Anaphase I	2n	2X	***Telophase II***	2n	X
Telophase I	2n	2X	***Cytokinesis***	n	½X
Cytokinesis	n	X			

Question: Fill in the blanks.
Where n = no. of chromosomes and X = amount of DNA

	In a nucleus			In a nucleus	
	No. of chromosomes	Amount of DNA		No. of chromosomes	Amount of DNA
G_1 phase		X	***Prophase II***		
Prophase I			***Metaphase II***		
Metaphase I			***Anaphase II***		
Anaphase I			***Telophase II***		
Telophase I			***Cytokinesis***		
Cytokinesis					

15. Significance of Meiosis

Notes to self

1. Formation of haploid gametes in sexual reproduction

Meiosis produces **haploid gametes** (egg and sperm) for **sexual reproduction**. During fertilisation, the haploid nuclei of male and female gametes fuse to produce a zygote with a diploid number of chromosomes. Thus the diploid condition is restored, resulting in the **restoration of ploidy level**.

If meiosis does not occur, fusion of male and female gametes by sexual reproduction will result in the doubling of the number of chromosomes with each successive generation. In order to ensure that the new adult organism has the same number of chromosomes as the parent, the two gametes must have only half the number of chromosomes as the parent.

Meiosis ensures that the **chromosome number in each species is kept constant every generation.**

2. Genetic variation

Meiosis allows for new combinations of alleles in the gametes which leads to genetic variation.

The two important events in **meiosis** that create genetic variation are

a) **crossing over** and
b) **Independent assortment of chromosomes**.

Random fusion of genetically different gametes during **fertilisation** (**after meiosis**) also results in genetic variation.

Why is variation important?

- Due to genetic variation, individuals in a population will have different characteristics.

- When environmental conditions change, certain individuals in the population will be better adapted to the change than others. These individuals will be selected for as they have favourable characteristics that allow them to survive in the new environment. Individuals without the favourable characteristics will be selected against and will die off.

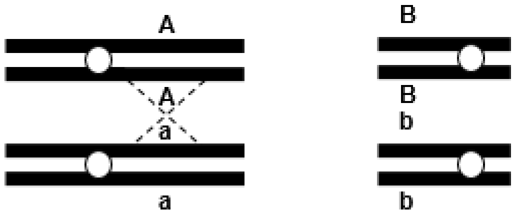
- If there is no variation, when a catastrophic event occurs, the whole population (with same characteristics or without variation) maybe wiped out.

(a) Crossing over

Notes to self

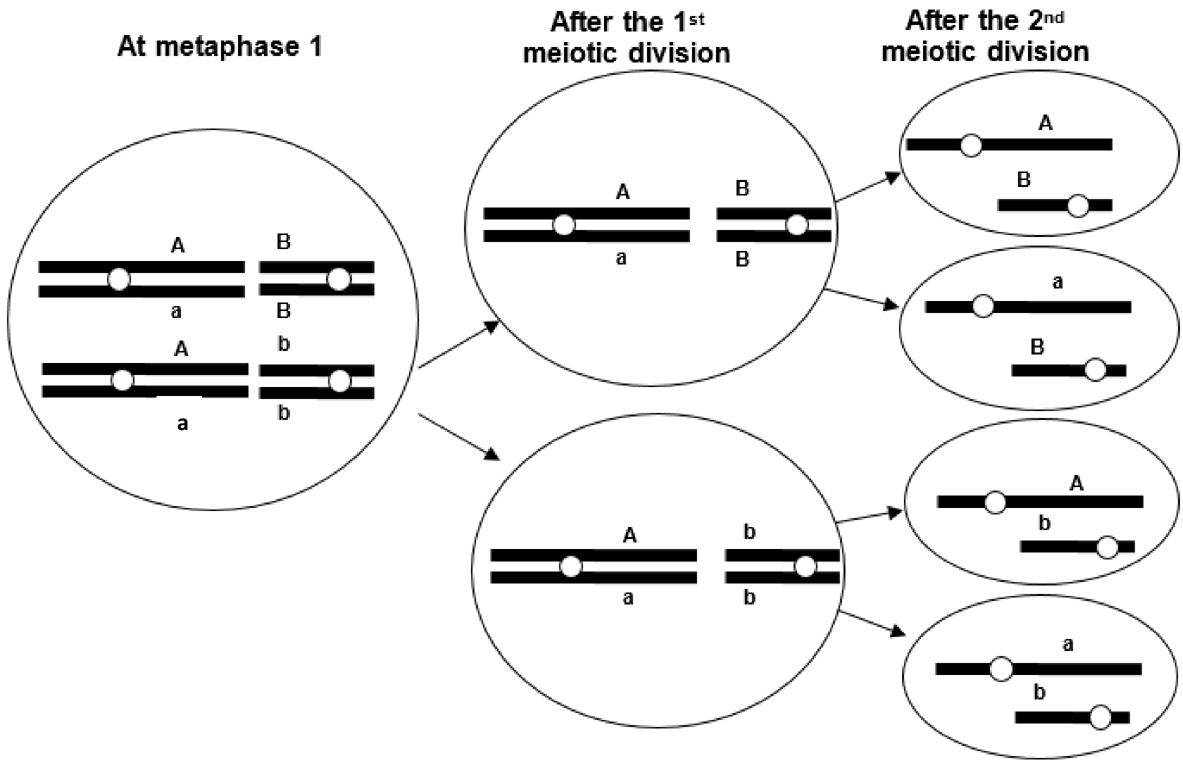
Crossing over of segments of non-sister chromatids of homologous chromosomes at prophase I of meiosis I.

This leads to new combinations of alleles on chromosomes of the gametes.



Crossing over and Chiasma formation

These are 2 pairs of homologous chromosomes in a cell during meiosis. If crossing over occurs at point X, show the possible combinations of gametes that arise.

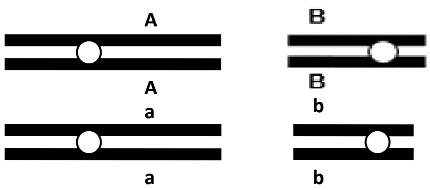


(b)Mendel's Law of Independent Assortment

During **metaphase I**, **arrangement of one pair of homologues** at the **metaphase plate** is **independent of the arrangement of the other pairs of homologues**. e.g. In humans, there are 23 pairs of homologues. In every pair, there is one paternal and one maternal chromosome; where the paternal chromosome #1 aligns during metaphase I (e.g. on the left side of the metaphase plate) does not depend on where paternal chromosome #12 aligns (e.g. it can also be on the left side of the plate or on the right side of the plate)

During **anaphase I**, the chromosomes of one homologous pair will **separate independently** of the other pairs to form daughter cells.

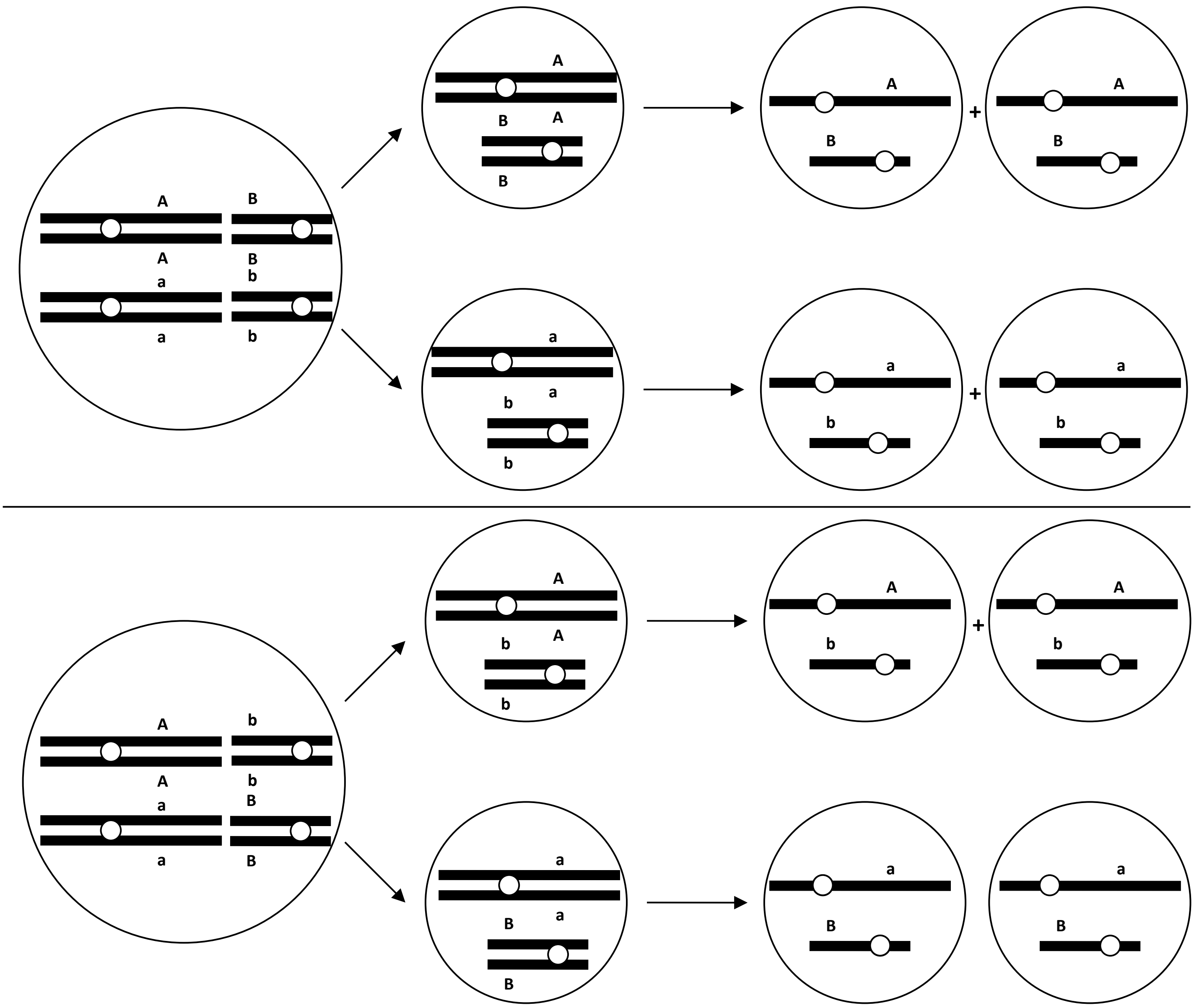
This results in **different combinations** of maternal and paternal chromosomes in the daughter cells at the end of meiosis I and meiosis II.



Independent assortment of chromosomes

These are 2 pairs of homologous chromosomes in a cell during meiosis. Show how the chromosomes align at the metaphase plate in metaphase 1 and the possible combinations of gametes that arise at the end of meiosis II, assuming crossing over does not occur.

Metaphase 1 | **After the 1st meiotic division** | **After the 2nd meiotic division**



When there are two pairs of homologous chromosomes in a diploid cell, __4___ different types of gametes will result at the end of meiosis.

- Due to independent assortment of chromosomes, there are $\mathbf{2^n}$ **possible combinations <u>of chromosomes</u> in gametes** where **n is number of homologous pairs**.

Since 2 pairs of chromosomes results in $\mathbf{2^n}$ = 2^2 = 4 possible combinations of chromosomes in gametes, humans with 23 pairs of chromosomes will have 2^{23} = about 8 millions possible combinations of chromosomes in gametes.

(c) Random fusion of gametes during fertilisation

Meiosis results in haploid gametes being formed. Random fusion of the gametes results in genetic variation. e.g.Humans = 2^{23} = 8,388,608 possible gametes. Possible zygotes (after fertilization) = 8 million x 8 million = 64 trillion.

Comparison between mitosis & meiosis

Notes to self

Feature	**Mitosis**	**Meiosis**
Location	Somatic cells in all parts of the body	Precursor sex cells in reproductive organs (that ultimately give rise to gametes)
Occurs in	Haploid or diploid cells	Only diploid cells
No of nuclear divisions	One	Two
Prophase	No synapsis/ Homologues do not pair up; No chiasma formation; No crossing over of corresponding segments of non-sister chromatids;	PROPHASE I Synapsis occurs / Homologues pair up to form bivalents (tetrads); Chiasma formation; Crossing over of corresponding segments of non-sister chromatids (results in non-identical sister chromatids with new combinations of alleles); PROPHASE II *No difference from prophase of mitosis*
Metaphase	Chromosomes align individually on equator/metaphase plate (i.e. form a single row); Each centromere attaches to spindle fibres from both poles;	METAPHASE I Homologues align in pairs along equator/metaphase plate (i.e. form 2 rows); Centromere of each chromosome attaches to spindle fibre from only one pole (Each member of a homologous pair attaches to spindle fibres from different poles); Independent assortment of homologues occurs (results in gametes with new combinations of alleles, that differ from parental combination of alleles); METAPHASE II *similar to metaphase of mitosis, except that:* chromosomes, consisting of non-identical sister chromatids, align in a random arrangement along the equator/metaphase plate
Anaphase	Division of centromere; Separation of identical sister chromatids to opposite poles; Once separate, chromatids are called daughter chromosomes;	ANAPHASE I No separation of centromere; Separation of homologues (i.e. pair of sister chromatids move to same pole); ANAPHASE II *similar to anaphase of mitosis, except that:*non-identical sister chromatids separate to opposite poles. They are now called daughter chromosomes.

Telophase	2 daughter nuclei which are genetically identical & have the same chromosome number as parental cells (hence can be 2n or n)	<u>TELOPHASE I</u> 2 daughter nuclei which are genetically different & each has half the chromosome number as parental cells (n) (i.e. cells are haploid at the end of meiosis I) <u>TELOPHASE II</u> 4 daughter nuclei which are genetically different & each has half the chromosome number as parental cells (n)
Result of nuclear division	2 genetically identical daughter cells; No variation occurs (in the absence of mutation); Daughter cells have the same number of chromosomes as parent cells, hence mitosis is called replicative division;	4 genetically different daughter cells; Genetic variation has occurred (even in the absence of mutation); Daughter cells have half the chromosome number as parent cells, hence meiosis is called reductive division;

<u>Notes to self</u>