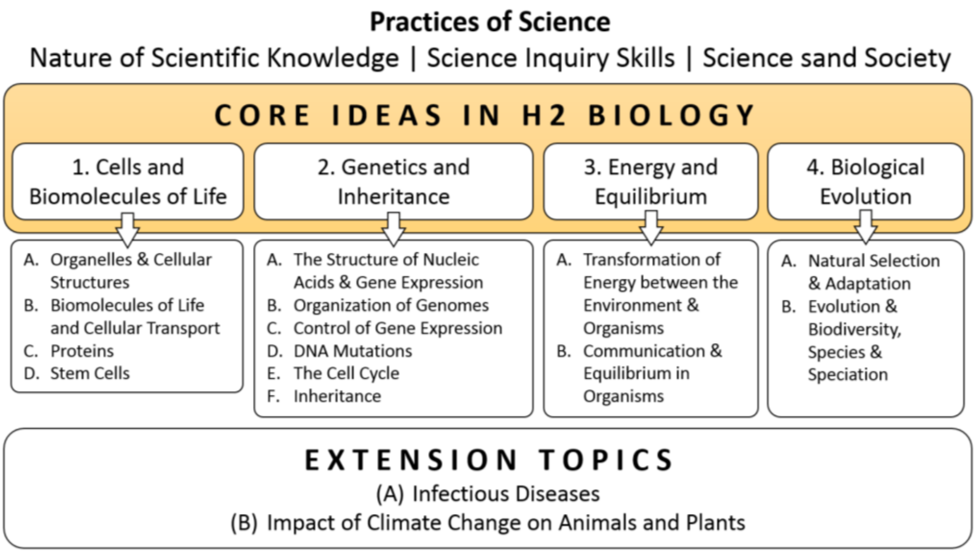
Core Idea 2
4. Genetics & Inheritance (I) – The Cell Cycle



SYLLABUS OVERVIEW		
No.	**Overarching Idea**	**Topics**
1	**Core Idea 1** The Cell and Biomolecules of Life	Cell – The Basic Unit of Life
2		Biomolecules of Life and Cellular Transport
3	**Core Idea 3** Energy and Equilibrium	Transformation of Energy – Photosynthesis and Cellular Respiration
4	**Core Idea 2** Genetics and Inheritance	Genetics and Inheritance (I) – The Cell Cycle
5		Genetics and Inheritance (II) – DNA Replication and Gene Expression
6		Genetics and Inheritance (III) – DNA Mutations and their Consequences
7		Genetics and Inheritance (IV) – Molecular Techniques in DNA Analysis
8		Genetics and Inheritance (V) – Organization of Genome & Control of Gene Expression in Eukaryotes *[Includes Core Idea 1D: Stem Cells]*
9		Genetics and Inheritance (VI) – Organization and Inheritance of Viral Genomes
10		Genetics and Inheritance (VII) – Organization of Genome & Control of Gene Expression in Prokaryotes
11		Genetics and Inheritance (VIII) - Inheritance
12	**Core Idea 3** Energy and Equilibrium	Communication and Equilibrium in Multicellular Organisms
13	**Core Idea 4** Biological Evolution	Biological Evolution
14	**Extension Topic A** Infectious Diseases	Immunity and Infectious Diseases
15	**Extension Topic B** Impact of Climate Change on Animals & Plants	Climate Change – Causes and Impacts on Animals and Plants

NARRATIVES

An understanding of *Genetics and Inheritance* that would help make sense of the transition from molecular to organismal level. *Genetics and Inheritance* provides the molecular basis to the understanding of how variations in populations arise and this is important in the study of biological evolution. At the cellular level, expression of genes involves cellular structures such as the nucleus, endoplasmic reticulum and ribosome. Many essential products of gene expression are enzymes involved in biochemical pathways which control physiological functions. As such, mutation of genes may give rise to dysfunctional proteins which in turn could result in diseases. Sickle cell anemia and cancer are raised as examples of a monogenic and a multi-genic disease respectively.

The following questions should help students frame their learning:
- How does the genetic make-up of an organism influence its appearance, behavior and survival?
- How does the inheritance of genetic information ensure the continuity of humans as a species?

The cell cycle is tightly regulated

The cell cycle comprises interphase, nuclear division and cytokinesis. There are two types of nuclear division: mitosis and meiosis. A cell cycle that involves mitosis will give rise to genetically identical cells and this is important for growth, repair and asexual reproduction of organisms. This cycle is coupled intricately and inexplicably with another important process of the living cell i.e. DNA replication, which occur during synthesis phase of interphase. The mitotic cell cycle is tightly regulated at various checkpoints that control the rate of cell division; uncontrolled cell division could result in cancer.

A cell cycle that involves meiosis occurs in reproductive organs of organisms and is important for sexual reproduction. Meiosis results in sex cells having half the amount of genetic material present in somatic cells. The crossing-over of non-sister chromatids and independent assortment of bivalents in meiosis, together with random fertilisation of male and female gametes, give rise to genetic variation in populations. Genetic variation is necessary for natural selection to occur. Homogeneity of a population can result in the entire population being wiped out by diseases or climatic changes.

LEARNING OUTCOMES

Core Idea 2E: The Cell Cycle
There are two different types of cell cycles: mitotic and meiotic. Cell cycles are tightly regulated at various checkpoints. The mitotic cell cycle is necessary for growth and repair while the meiotic cell cycle is necessary to generate gametes. Meiosis gives rise to genetic variation between gametes through crossing over of homologous chromosomes and independent assortment of bivalents.

Candidates should be able to:

n) Describe the events that occur during the mitotic cell cycle and the main stages of mitosis (including the behavior of chromosomes, nuclear envelope, cell surface membrane and centrioles).

o) 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 are not required.)

s) Describe the events that occur during the meiotic cell cycle and the main stages of meiosis (including the behavior of chromosomes, nuclear envelope, cell surface membrane and centrioles).
(Names of the main stages are expected, but not that sub-divisions of prophase).

t) Explain the significance of the meiotic cell cycle (including how meiosis and random fertilization can lead to variation).

LECTURE OUTLINE

1. Introduction

1.1 Somatic cells, Germ cells and Gametes

- In this topic, we will be mainly talking about cell division in eukaryotic cells and multicellular organisms.

- A **somatic cell** (diploid) is any cell in a multicellular organism **other** than those involved in gamete formation (Fig. 1.1). Examples: muscle cell, liver cell, neurons, blood cells, bone marrow cells, etc.

- A **germ cell** (diploid) is a cell that develops into an egg or a sperm (usually haploid).

- A **gamete** is a sperm or an egg cell (usually haploid). They typically carry **half the amount** of DNA and **half the number** of chromosomes that a somatic cell in the same organism carries.

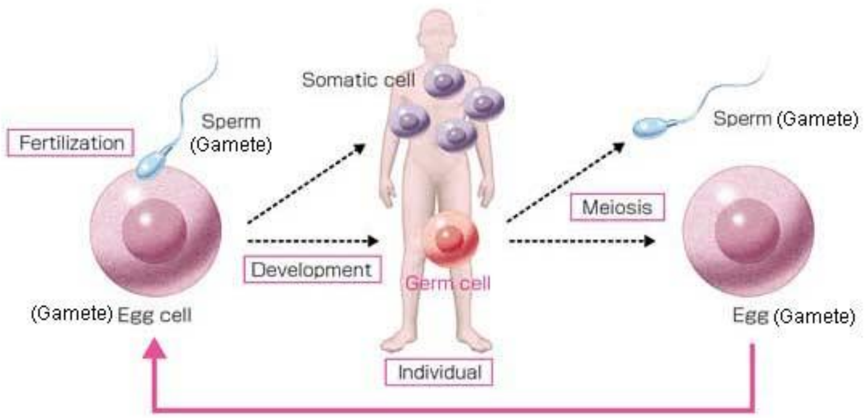


Fig. 1.1: The relationship between somatic cells, germ cells and gametes.

1.2 Gene

- A gene (Fig. 1.2) is an **inheritable and specific sequence of nucleotides** on a **DNA molecule**, which **codes for a RNA** (e.g. tRNA, rRNA, telomerase RNA) or **polypeptide** (e.g. amylase).

- A single chromosome can carry many genes.

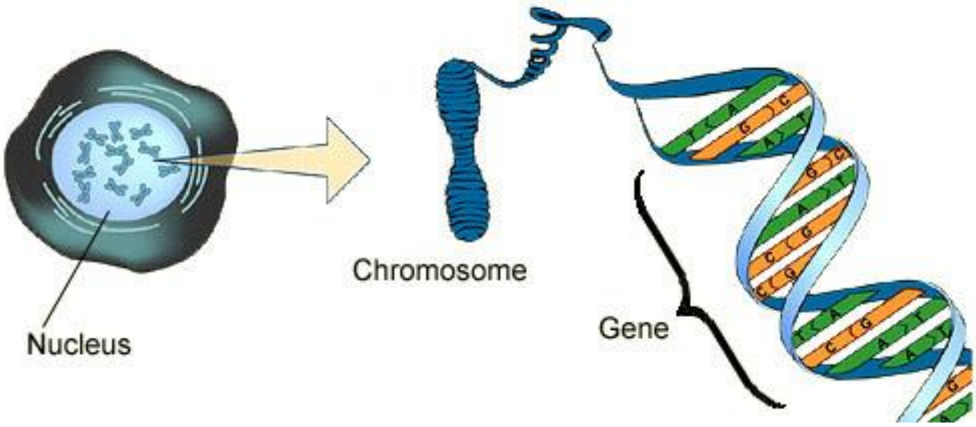


Fig. 1.2: Genes are found on chromosomes. One chromosome contains many genes.

1.3 Alleles

- An **allele** is an **alternative form of a gene**. Alleles of a gene have **different nucleotide sequences** (Fig. 1.3).
  - E.g. the allele for brown eye pigment and the allele for blue eye pigment are alternative forms of the gene that codes for eye color.
  - E.g. the allele for normal haemoglobin and the allele for sickle cell haemoglobin differ by just one base pair (Fig. 1.3).
  - E.g. the gene that codes for flower colour has two alleles, one which codes for purple flowers and the other which codes for white flowers.

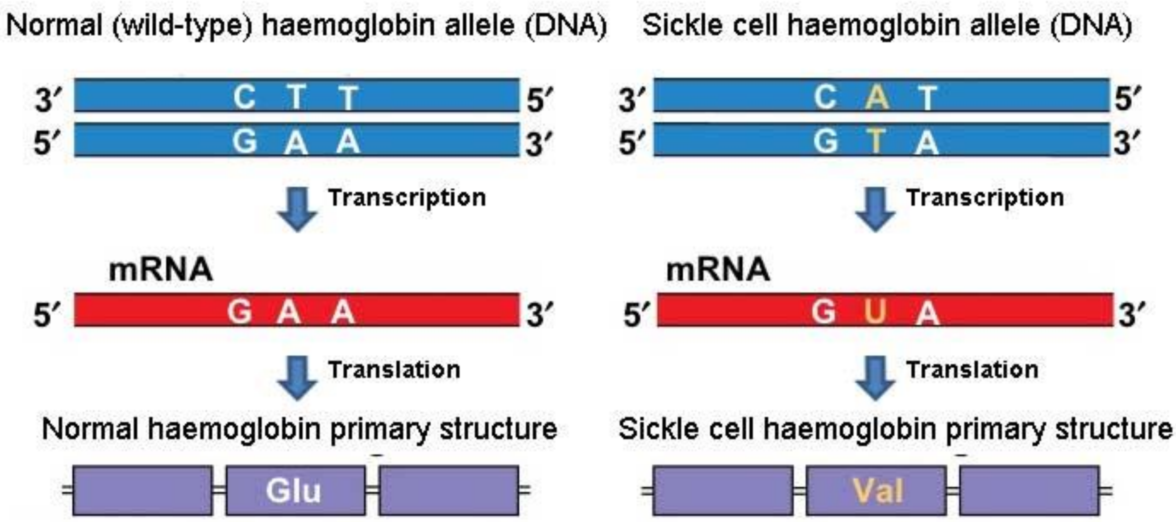


Fig. 1.3: The allele for wild-type haemoglobin (right) differs from the allele for sickle cell haemoglobin (left) by one base pair.

- **Alleles** of a gene **occupy the same locus on a pair of homologous chromosomes** (Fig. 1.4). They occur in **pairs** in a **diploid cell** and only **one of a pair** is present in a **gamete**.

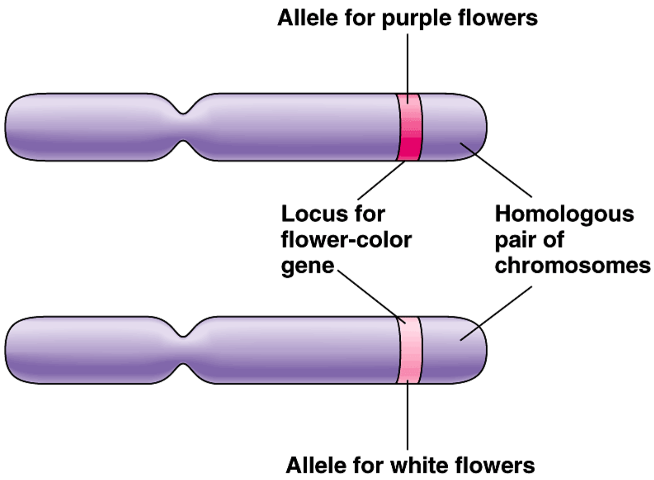


Fig. 1.4: A diagrammatic explanation of gene, allele and locus. A diploid organism usually has two alleles per gene locus.

1.4 Locus / Loci

- Within each species, each gene occupies a fixed position on a particular chromosome. This **fixed position of a gene on a chromosome** is called a **locus** (Fig. 1.4 and Fig. 1.5).

- Alleles of a gene occupy the **same relative position** on **a pair of homologous chromosomes** (Fig. 1.5). They occur in **pairs** in a diploid cell and only one of a homologous pair is present in a gamete (haploid).

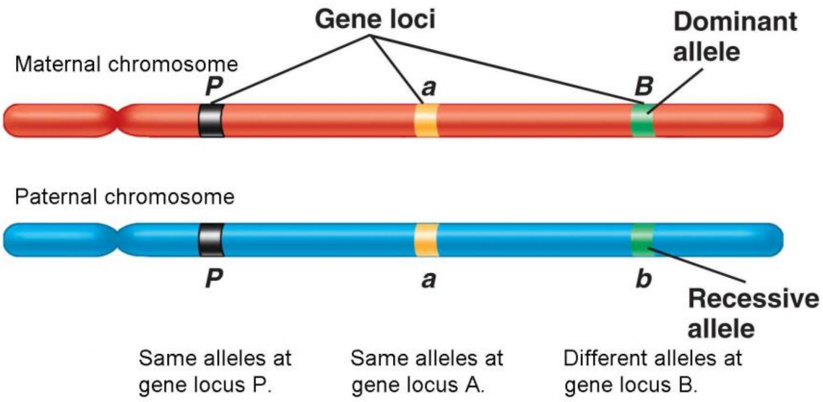


Fig. 1.5: A diagrammatic explanation of a homologous pair of chromosomes, gene loci and their alleles.

1.5 Chromosomes

a) Chromatin

- Chromatin is a complex of DNA and proteins that forms chromosomes within the nucleus of eukaryotic cells.

- **The negatively-charged DNA molecule** is first coiled **around positively-charged histone proteins** to give **nucleosomes**.

- Each histone is made of **eight** protein subunits i.e. a protein **octamer.**

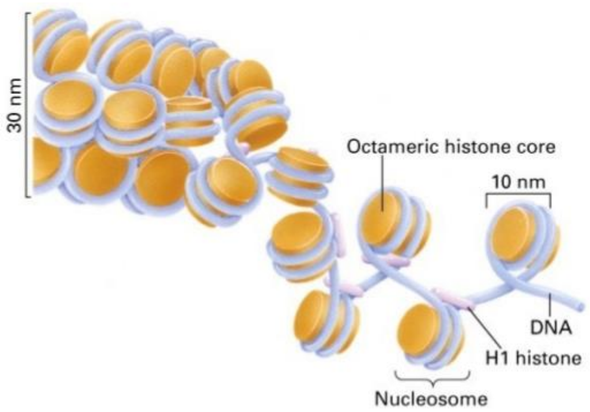


Fig. 1.6a: "Beads-on-a-string" form of chromatin that coils to form the 30nm solenoid.

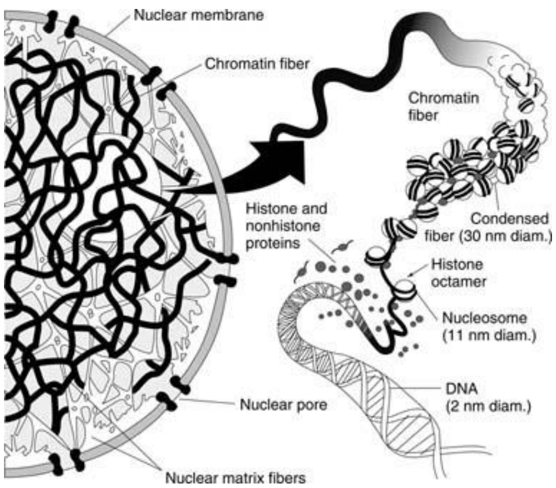


Fig. 1.6b: A diagrammatic representation of chromatin

- The nucleosomes are connected by **linker DNA** to give the "beads-on-a-string" form of chromatin (Fig.1.6a).

- This structure is then coiled to form the **30nm solenoid** (about six nucleosomes per turn) (Fig. 1.6a).

- This forms **chromatin** as seen in **non-dividing cells** (Fig.1.6b).

- **Chromatin** (Fig. 1.6c) is **not visible** under the **light microscope** but regions of **euchromatin** and **heterochromatin** are visible in **electron micrographs**.

- **Individual chromosomes** are **visible only** when the chromatin is **further condensed** during nuclear division (mitosis or meiosis) (Fig. 1.6d).

- One **chromosome** consists of **one DNA molecule**. Most eukaryotic organisms have a certain specific number of chromosomes. (E.g. most humans have 46 chromosomes.)

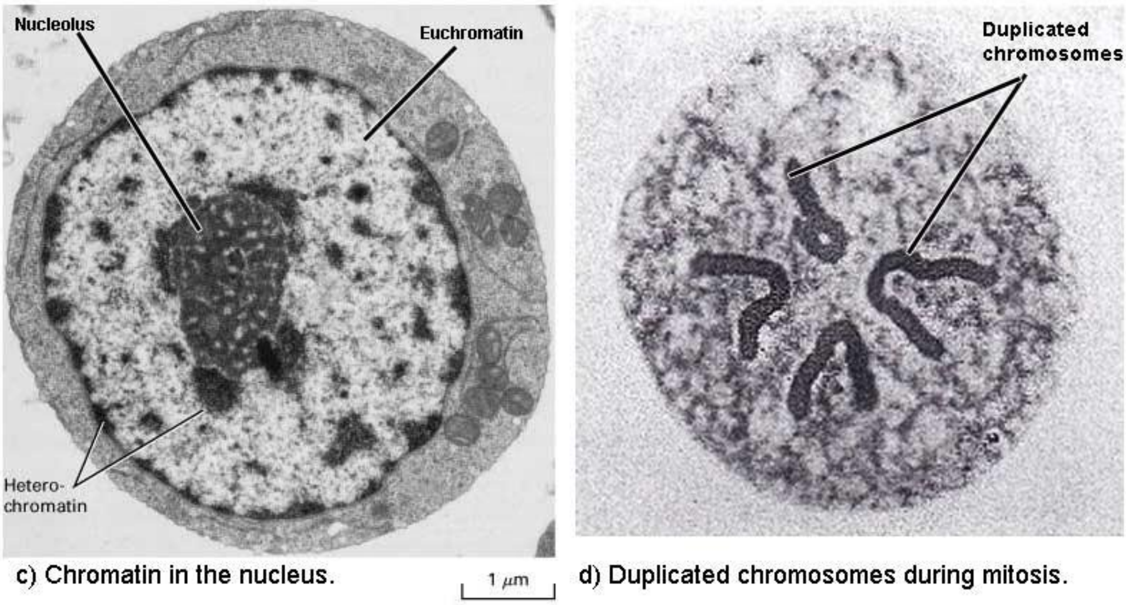


Fig. 1.6 c and d: Chromatin (right) in a non-dividing cell and duplicated chromosomes (left) in a cell undergoing nuclear division.

b) Duplicated Chromosomes

- Prior to nuclear division, **DNA replication** (Fig. 1.7a) occurs at the **S phase of Interphase**.

- **DNA replication** is a process that duplicates DNA and lead to the **doubling** of the **mass** of DNA in a cell. *(We will cover the process of DNA Replication later in Topic 05. Genetics & Inheritance (II) - DNA Replication & Gene Expression)*

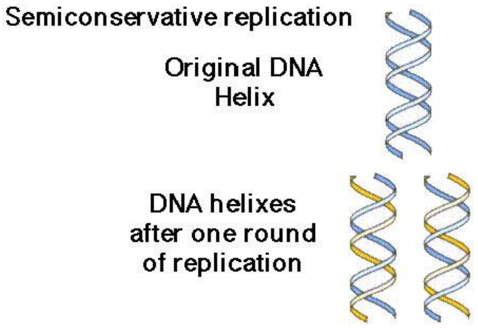
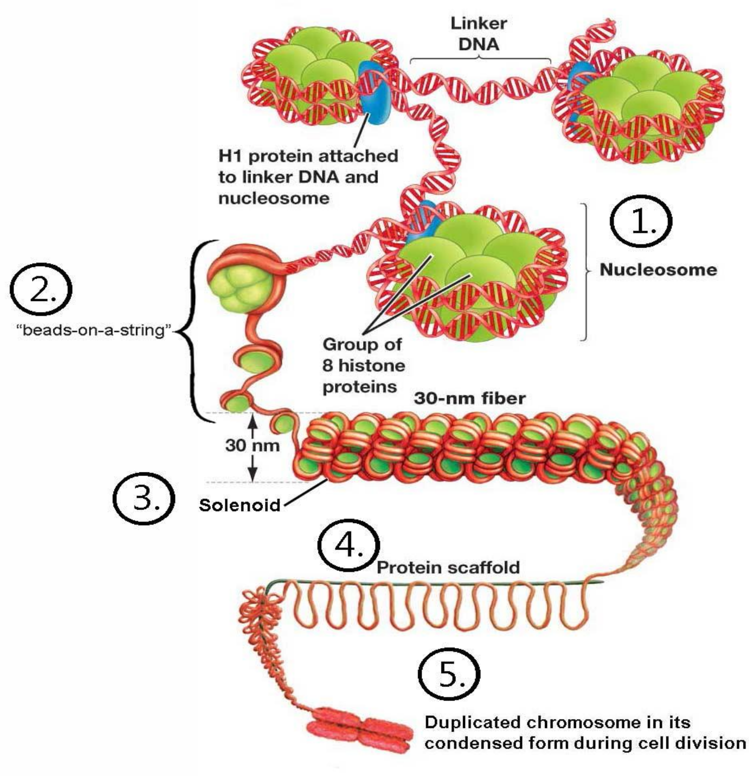


Fig. 1.7a: Replication of one DNA molecule produces two DNA molecules that are genetically identical to each other.

- After each chromosome is **replicated**, there are now **two** genetically identical DNA molecules joined together by a centromere (Fig. 1.7d). This is the **duplicated chromosome** (Fig. 1.7d).



1. The negatively-charged DNA molecule is wrapped around positively-charged proteins called **histones** to give **nucleosomes**. (Each histone is made of 8 protein subunits – a protein **octamer.**)

2. The nucleosomes are joined by **linker DNA** to give the "beads-on-a-string" form of chromatin.

3. This structure is then coiled to form the **30nm solenoid** (about **six** nucleosomes per turn).

4. In preparation for nuclear division, the solenoid is further coiled with the aid of a **protein scaffold**.

5. Further **scaffolding** and **condensation** results in the formation of the **mitotic duplicated chromosome**.

Fig. 1.7b: The structure and organisation of duplicated chromosomes.

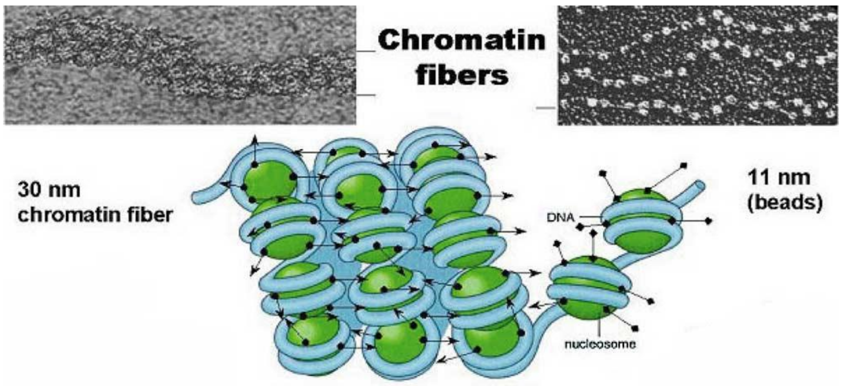


Fig. 1.7c: Electron micrographs and diagrammatic representations of chromatin.

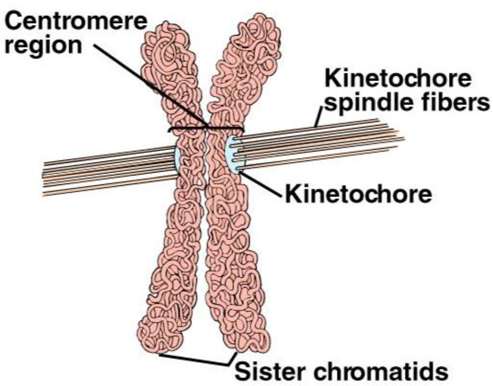


Fig. 1.7d: A duplicated chromosome at metaphase showing the attachment of spindle fibres to the kinetochore protein complex which is attached to the centromere region.

- Two **genetically identical sister chromatids** are held together at the **centromere** (Fig. 1.7d).

- The centromere (~3 million base pairs of DNA) is a region on the DNA molecule, consisting mostly of **repetitive** DNA sequences.

- The **kinetochore** is a **complex of proteins** that binds to the centromere and attaches spindle fibres during **prophase** to help separate the sister chromatids during anaphase.

NOTE:

- **One chromatid of the duplicated chromosome** comprises **one highly coiled and condensed DNA molecule**.

- The **duplicated chromosome** comprises **two highly coiled and condensed DNA molecules.**

- To recap (Fig. 1.7e) :
  1 DNA is a double-stranded molecule.
  2 A negatively charged DNA molecule is wrapped around positively-charged histone octamers to give rise to "beads on a string".
  3 Chromatin in the nucleus of the cell during interphase.
  4 After DNA replication, the two DNA molecules formed are connected at the centromere.
  5 Condensation of these two DNA molecules forms two genetically identical sister chromatids of a duplicated chromosome.

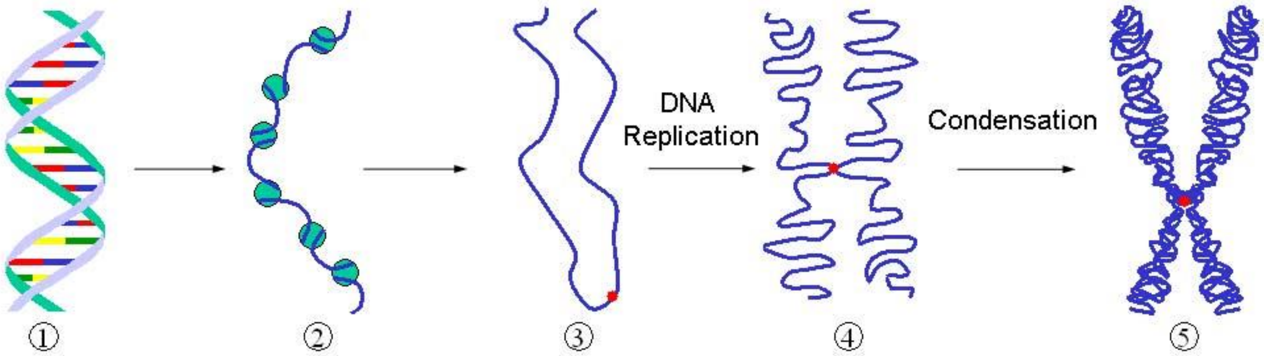


Fig. 1.7e: The relationship between DNA molecules, chromatin and duplicated chromosomes.

c) Genetically Identical Chromosomes (Sister Chromatids)

- **Genetically identical sister chromatids** means that the two chromatids have **exactly the same nucleotide sequences**.

- This means that the sister chromatids have the **same alleles** (Fig. 1.8).

- It is necessary for the sister chromatids to be genetically identical for **nuclear division**.

- During mitosis, the sister chromatids separate to become the chromosomes of two daughter nuclei. This ensures that **daughter nuclei** would be **genetically identical** to each other. This **maintains genetic stability after every mitotic division**.

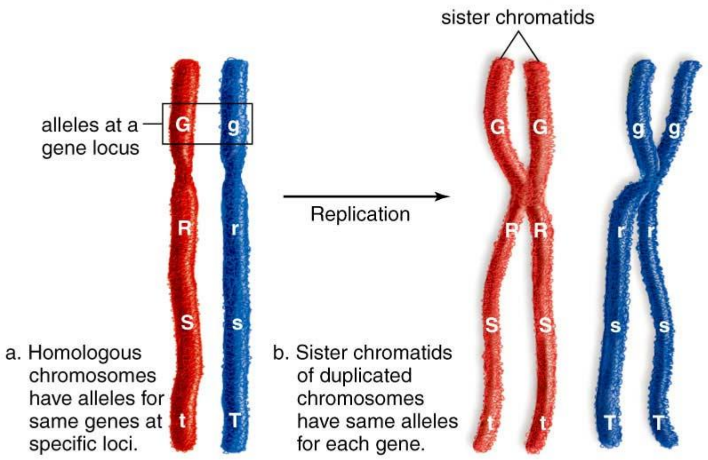


Fig. 1.8: After replication, genetically identical sister chromatids are produced.

1.6 Amount / Mass of DNA

- A method to measure the amount of DNA is by taking the mass of DNA in a cell.
  - The unit for measuring mass of DNA is the **picogram** (pg).
  - 1 picogram = 10^{-12} grams.
  - For example, the amount of DNA in a cell at resting state is **10 picograms**. The amount of DNA in the same cell **after DNA replication** at S phase of Interphase would be **20 picograms**.

1.7 Ploidy: Number of sets of Chromosomes in a cell

- **Ploidy** refers to the **number of sets** of chromosomes in a cell of an organism (Fig. 1.9), **<u>not</u>** the mass of DNA nor the total number of chromosomes.

- Each set contains **n** chromosomes**,** where n is a number **specific to the organism**.

- E.g.
  - Domestic cats have 38 chromosomes per somatic cell; 2n = 38, n = 19. Gametes contain 19 chromosomes each.
  - Chickens have 78 chromosomes per somatic cell; 2n = 78, n = 39. Gametes contain 39 chromosomes each.

- **Haploid:** cells with **one set** of chromosomes **(n)**
  Diploid: cells with **two sets** of chromosomes **(2n)**
  Triploid: cells with **three sets** of chromosomes **(3n)**

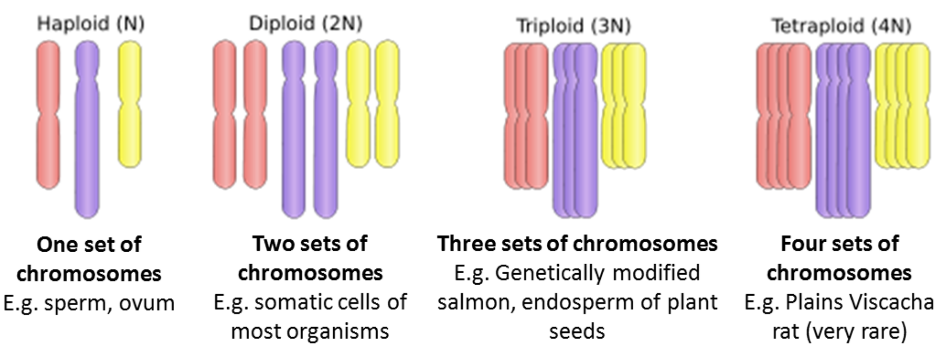


Fig. 1.9: Diagrammatic illustration of ploidy. In this example, one set comprises three different chromosomes.

a) Diploid

- A **diploid** cell or diploid organism has **two sets of chromosomes**. In sexually reproducing organisms, one set is from the **male** parent and the other set is from the **female** parent.

- The diploid condition is designated as **2n**, where *n* denotes number of chromosomes in one set of chromosome.
  - E.g. In fruit-flies, 2n = 8; n = 4
  - A number is given to every different type of chromosomes in a cell of a specific organism (exception is the sex chromosome, either X or Y).
  - In fruit flies, there are 4 different types of chromosomes. The chromosomes are numbered as chromosome 1, chromosome 2, chromosome 3 and chromosome X or Y as in the diagram (Fig. 1.10).
  - Chromosome X and Y are known as **sex chromosomes** in most species. Chromosomes 1, 2 and 3 are known as **autosomes**.
    - **Autosomes** are chromosomes carrying genes that code for phenotypic characteristics **except** sex and sexual characteristics.
    - **Sex chromosomes** carry the genes that determine the sex of the organism.

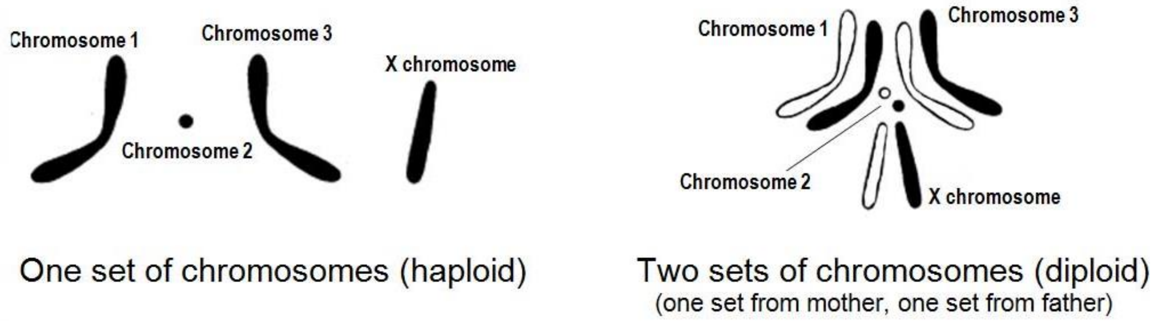


Fig. 1.10: (Left) A gamete would contain one set of chromosomes, namely Chromosomes 1, 2, 3 and the X chromosome from one parent. (Right): A cell from a diploid female fly contains two sets of chromosomes.

- Advantages of possessing two sets of chromosomes or being diploid:
  - **Greater genetic variation** as each individual will have a mixture of characteristics from **both** parents.
  - If a gene on one chromosome of a pair is faulty, the second chromosome may provide a **normal back up copy** (with the exception of the sex-determining chromosome in males).

b) Haploid

- A cell or an organism is haploid if it contains **<u>half the diploid number</u> (n) of chromosomes**.
- The haploid condition is usually found in the **gametes** (sperm or ovum). Haploid organisms like male worker bees exist.
- A haploid cell or organism has only **one set of chromosomes** (half the diploid number of chromosomes). E.g. a somatic human skin cell has 46 chromosomes (2n) while a haploid human egg cell has 23 chromosomes (n).

c) Polyploidy

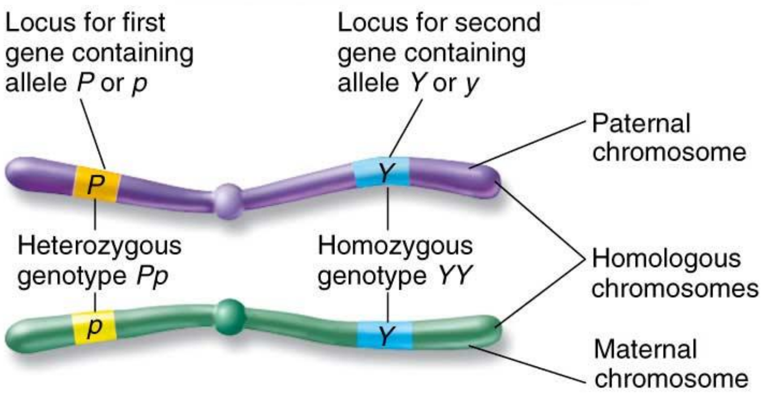
- A cell or an organism is **polyploid** if it contains more than 2 sets of chromosomes.
- **Polyploidy** occurs very rarely in animals. E.g. the Plains Viscacha Rat is tetraploid (4n). Polyploidy can be induced artificially; e.g. genetically modified salmon are triploid (3n).
- Polyploidy is more common in plants. E.g. Domestic oat (6n), peanut (4n) and sugar cane (8n).

1.8 Homologous Chromosomes

- Homologous chromosomes are **pairs** of chromosomes of the **same length**, **same centromere position** and possesses **genes for the same characteristics** at the **same loci** (Fig. 1.11a).

- One chromosome is **inherited** from the **mother** (the maternal chromosome) and the other is **inherited** from the **father** (the paternal chromosome). Some pictures (Fig. 1.11a) illustrate pairs of homologous chromosomes with different colours to signify the paternal and maternal chromosomes.

- A pair of homologous chromosomes is also known as a bivalent when they are paired up together during prophase I of meiosis.



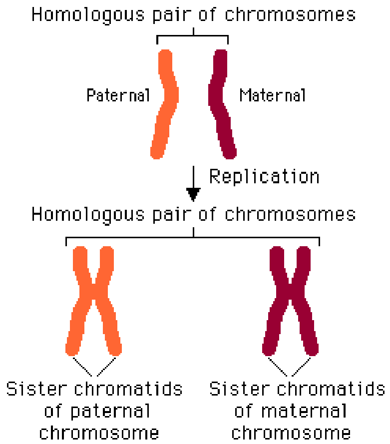


Fig. 1.11a: A homologous pair of chromosomes. Note that they are of the same length, have the same centromere position and the same gene loci. The chromosomes are genetically non-identical.

- In a **female** human somatic cell, there are 23 pairs of homologous chromosomes: 22 pairs are **autosomes** and 1 pair is the **sex chromosomes, XX** (Fig. 1.11b).

- In a male human somatic cell, there are 22 pairs of homologous chromosomes: The last pair, which are the sex chromosomes (**XY**), is not a homologous pair (Fig. 1.11b and 1.11c) as the X and Y chromosomes have different gene loci and are of different lengths.

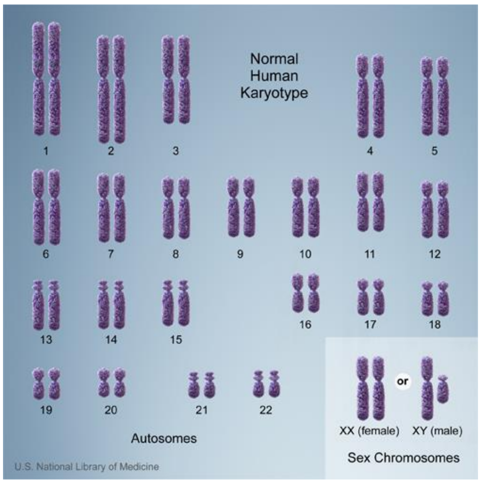
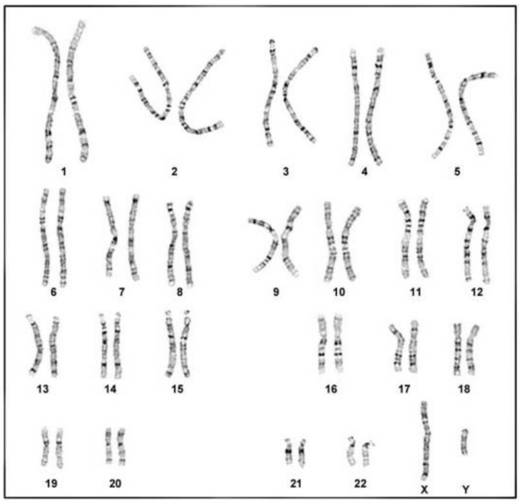


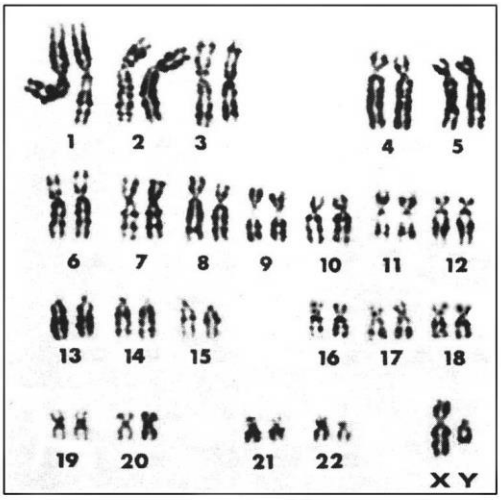
Fig. 1.11b: A schematic diagram of a karyotype showing the 46 chromosomes in the human genome. There are 23 pairs of homologous chromosomes in females and 22 pairs of homologous chromosomes in males (as the X and Y chromosomes are not homologous). In this diagram, the maternal and paternal chromosomes are not coloured differently, but it is obvious that Y chromosome can only come from father.

- Comparison between chromosomes in a homologous pair:

Similarities	• **Same length**.
	• **Same centromere position**.
	• Carry the **same gene at the same locus**.
	• **Same staining pattern**.
	• **Same corresponding loci** for genes encoding the same characteristic (except for sex chromosomes).
Differences	➢ **Not genetically identical** because of differences in **DNA nucleotide sequences**.
	➢ **Each chromosome** in a homologous pair **comes from different parent (one paternal and one maternal)**.
	➢ **Different alleles** of the **same gene locus** on a pair of homologous chromosomes **may code for different phenotypes** (e.g. At the gene locus for eye colour, the chromosome may carry an allele that code for blue eye while the other homologous chromosome may carry a different allele that code for brown eye).

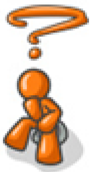


(i) Karyotype of chromosomes



(ii) Karyotype of duplicated chromosomes

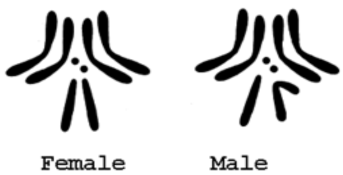
Fig. 1.11c: The 46 chromosomes in a somatic human cell (male). Image (ii) shows chromosomes before DNA replication or after nuclear division has taken place. Image (iii) shows duplicated chromosomes during nuclear division.



How many chromosomes are found in a <u>diploid</u> cell from a fruit fly?

How many set(s) of chromosomes are there in each diploid cell?

What are the chromosomes present in each set?



a) Non-Sister Chromatids

- This refers to **chromatids of a pair of homologous chromosomes** (Fig. 1.12). They are **not genetically identical as they come from different sources (two parents)**.

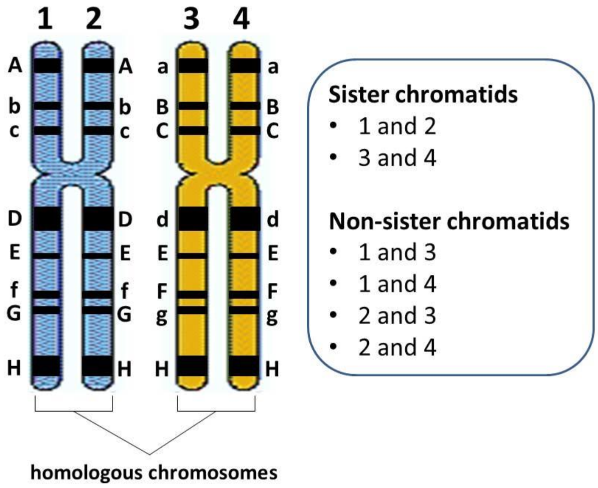


Fig. 1.12: A pair of homologous chromosomes, sister chromatids and non-sister chromatids.

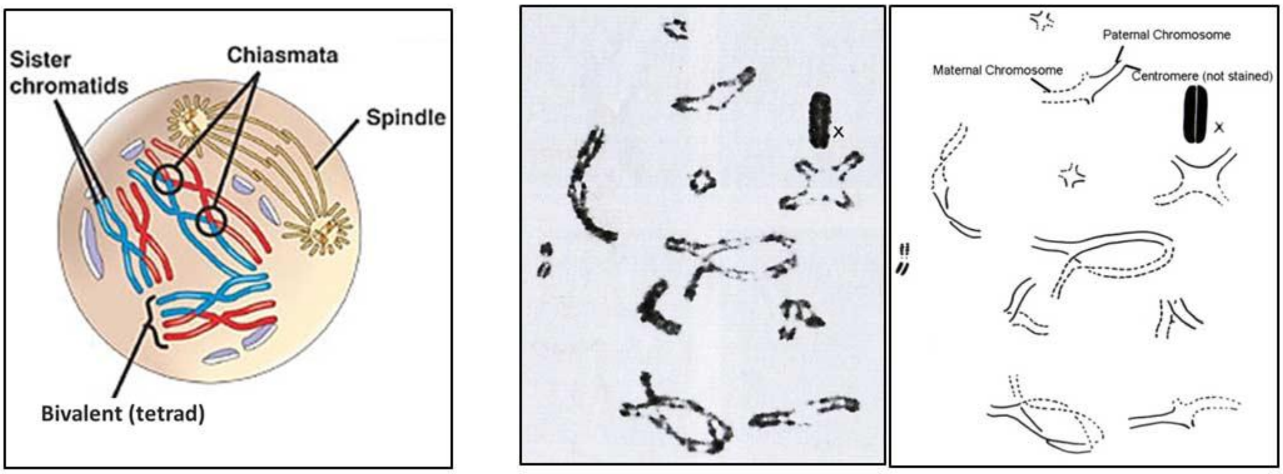


Fig. 1.13: (Left) A typical schematic representation of bivalents at prophase I of meiosis. **(Right)** Electron micrograph of a chromosome spread taken at from a cell at prophase I with its corresponding pictorial representation. Note the various shapes that a bivalent can assume.

b) Synapsis

- It is the **<u>process of pairing up</u>** of homologous chromosome to form bivalents (Fig. 1.13).
- This process happens in **prophase I** of **meiosis**.

c) Crossing-Over

- The **process** of the **exchange of corresponding sections of genetic material** between **non-sister chromatids of homologous chromosomes during prophase I of meiosis** is known as **crossing-over** (Fig. 1.13 and 1.14).

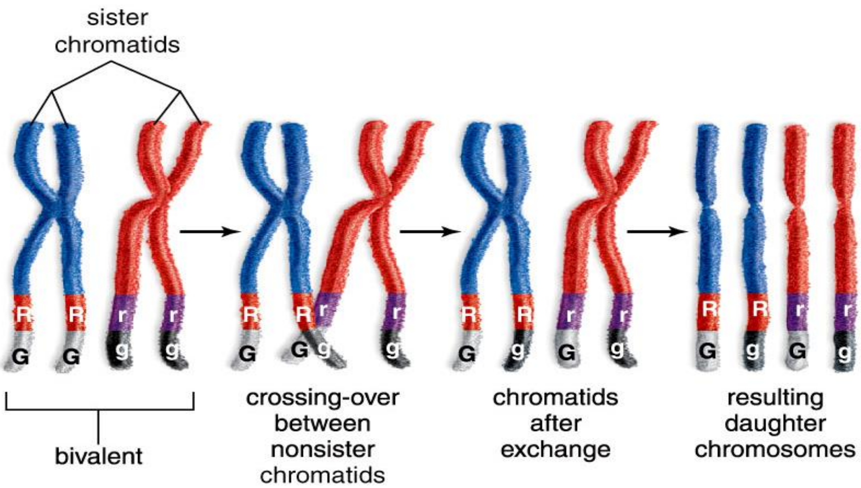


Fig. 1.14 Crossing-over between non-sister chromatids of homologous chromosomes results in non-identical sister chromatids.

d) Chiasma (*pl*: Chiasmata)

- The X-shaped **structure** formed between **non-sister chromatids of homologous chromosomes** during crossing over (Fig. 1.14 and 1.15).

- The <u>**site**</u> where **corresponding sections** of **non-sister chromatids** of **homologous chromosomes** may <u>**break**</u> **and** <u>**exchange**</u> **places with an** <u>**equivalent**</u> **portion of another chromatid**.

- This happens in **prophase I** of **meiosis I** after bivalents are formed.

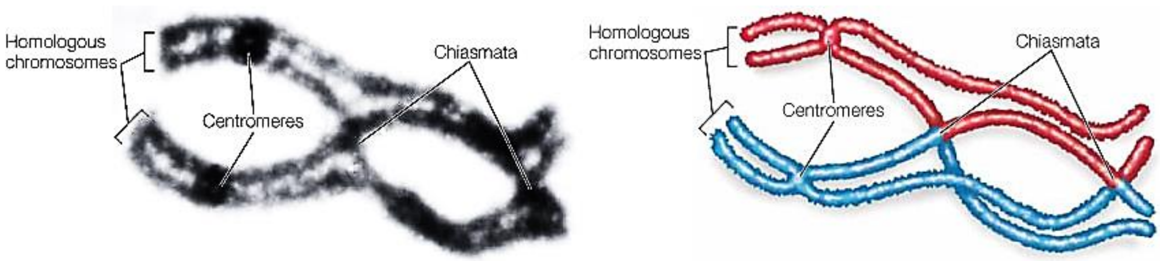


Fig. 1.15: An electron micrograph of a crossing-over event at prophase I of meiosis, with a pictorial representation of the micrograph.

e) Non-identical Sister Chromatids

- After crossing over, one member of the sister chromatids is no longer genetically identical to the other sister chromatid (Fig. 1.16). They are known as **non-identical sister chromatids**.

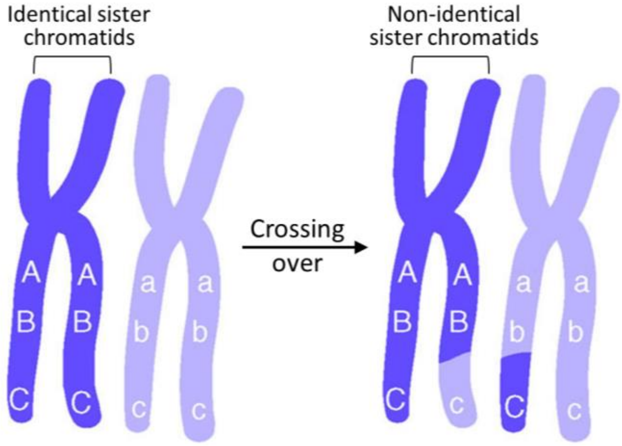


Fig. 1.16: Exchanging of corresponding segments of non-sister chromatids of homologous chromosomes results in sister chromatids that are no longer identical.

1.9 Mendel's Laws of Independent Assortment and Segregation

a) Independent Assortment of Homologous Chromosomes

- This occurs during **metaphase I of meiosis**.
- "Assortment" simply means "arrangement" or "orientation".
- The **orientation** of the bivalents at the metaphase plate is **random**.
- The arrangement or **orientation of one bivalent** is **completely independent of the other bivalent** along the metaphase plate (Fig. 1.17).
- As this arrangement is random, Possibility 1 and Possibility 2 (Fig. 1.17) are equally possible. There is a 50% chance of either occurring).
- Hence, there would be approximately equal amounts (25%) of each kind of gamete (*BS*, *Bs*, *Sb*, or *sb*) after gamete formation.

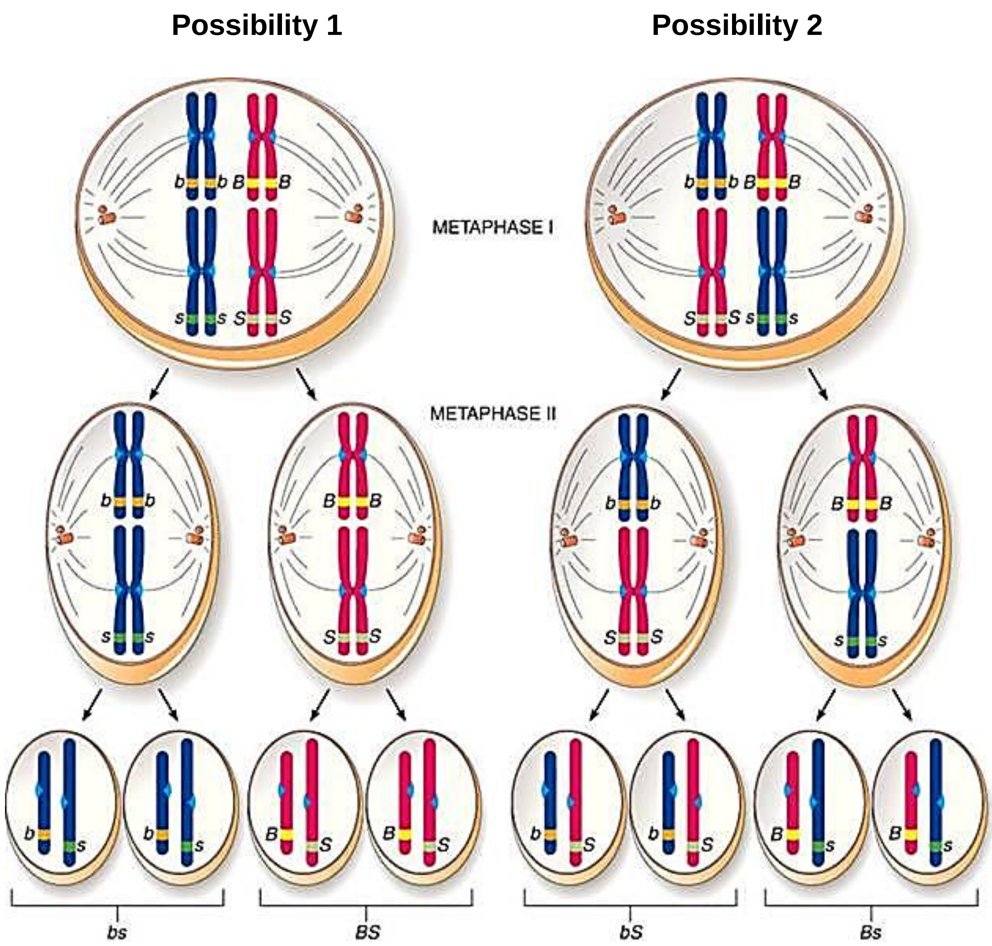


Fig. 1.17: Independent assortment of homologous chromosomes

b) Independent Assortment of non-identical sister chromatids

- This occurs during **metaphase II of meiosis**.
- The **orientation** of the chromosomes at the metaphase plate is **random**.
- The **arrangement or orientation of one chromosome** is **completely independent** of **the other chromosome** along the metaphase plate
- For example, there are two possible arrangements of the duplicated chromosome with gene locus H (Fig. 1.18) and both are equally likely.
- Different combinations of chromatids will result if non-identical sister chromatids are present due to crossing over during prophase I.

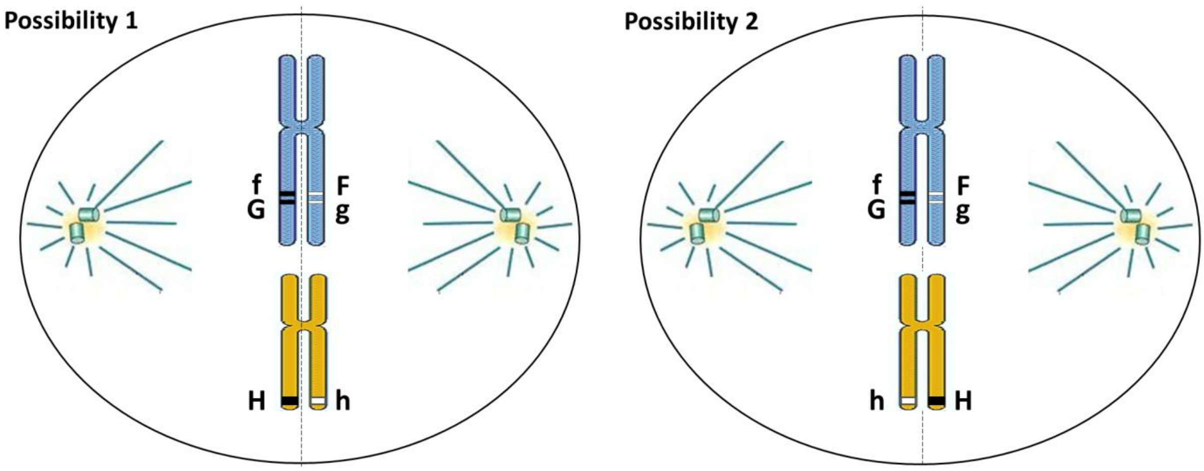


Fig. 1.18: Independent assortment of non-identical sister chromatids during metaphase II. Note how the chromosome below can easily flip laterally to allow the H allele to end up on the right side of the cell.

2. Cell Theory and the Cell Cycle

- The Cell Theory - **All cells arise from pre-existing cells by cell division**. The ability of organisms to reproduce is the one characteristic that best distinguishes living things from non-living matter.

- The continuity of life is based on the reproduction of cells, or **cell division**.

- The cell division process is an integral part of the **cell cycle**, which can be defined as the time period from the **formation of a cell** from a dividing parent cell until the point when the **cell itself divides again**.

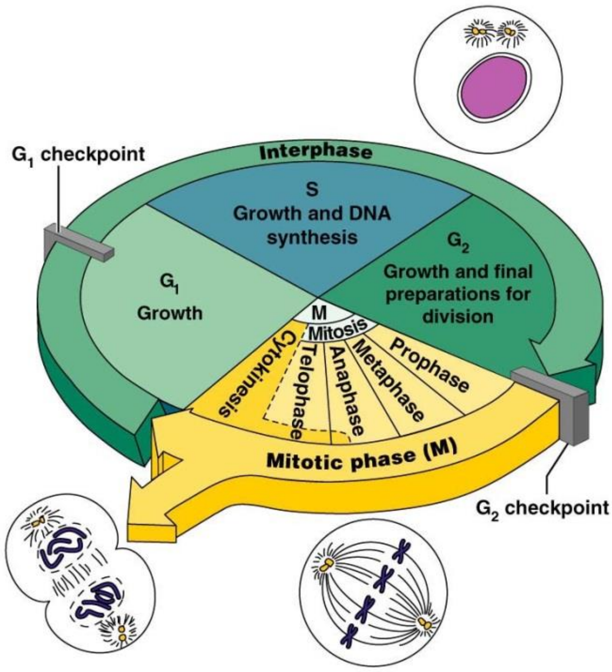
- **Mitosis** is an integral part of the **cell cycle**, which is the life of a cell from its origin in the division of a parent cell until its own division into two daughter cells. At the end of each cell cycle, **genetically identical daughter cells** are produced.

- **Meiosis** is a specialised type of nuclear division that occurs in all **sexually reproducing** eukaryotes.

- The **division of the nucleus**, either by mitosis or meiosis, is usually followed by the division of the cytoplasm, called **cytokinesis**.

- **Nuclear division** (mitosis or meiosis) is just one small part of the eukaryotic cell cycle. (Fig.2.1)

- After learning about nuclear division, you will learn about the molecular control system that regulates the cell cycle and what happens when the control system malfunctions.



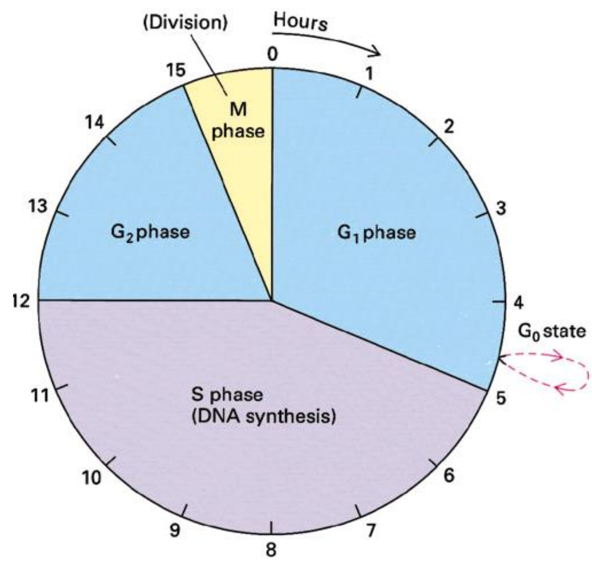


Fig. 2.1: (Left) Diagrammatic representation of the cell cycle.
(Right) Approximate time frame of each phase in a 16-hour cell cycle.

- The **length of a cell cycle** varies from cell to cell, and also **depends** on **nutrient availability**, **oxygen supply** and **temperature**. Actively dividing cells usually undergo a regular cycle lasting 15 to 20 hours.

- The eukaryotic **cell cycle** can be divided into three parts:

    1. **Interphase:** which consists of three subphases, G_1, S and G_2, during which the cell produces many materials required for its own growth and for carrying out its functions. DNA replication occurs in S phase of interphase before mitosis or meiosis can occur.

    2. **Mitosis/meiosis: nuclear division** including the division of genetic material.

    3. **Cytokinesis:** division of the cytoplasm.

- The **stem cells** of an organism (Fig. 2.2) are usually capable of continuous renewal (i.e. cell division).

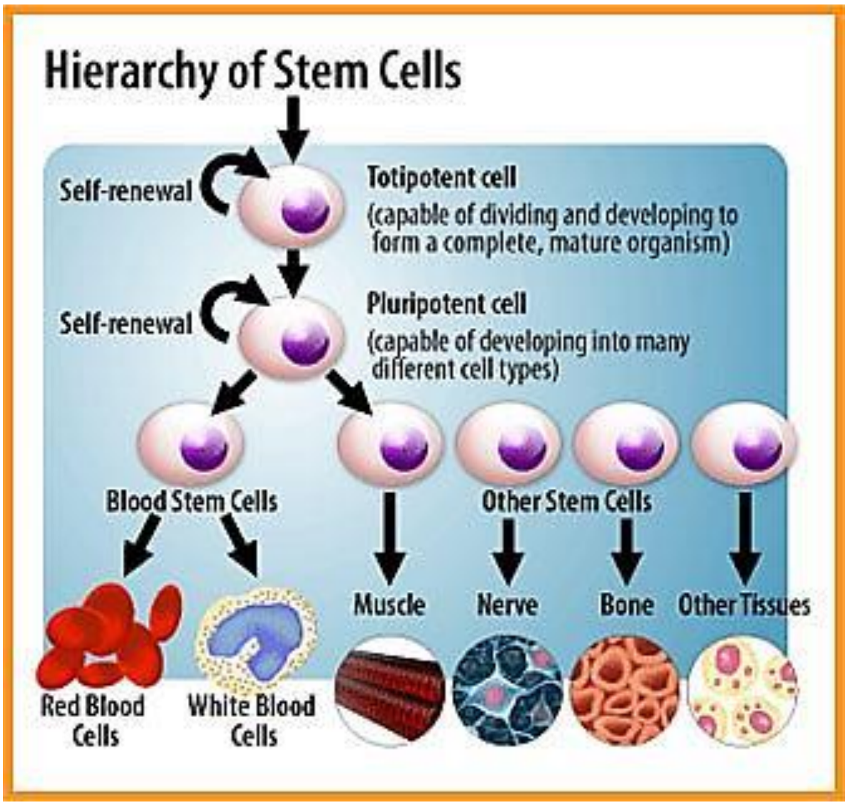


Fig. 2.2: Stem cells and the specialised cells they can differentiate into.

- Most cell types **never divide again** after they have grown and **become specialized** e.g. guard cells in plants and most cells in the nervous system (e.g. neurons or nerve cells, Fig 2.2).

- **DNA**, the genetic material in the nucleus, is the source of information responsible for the development and growth of the cell, as well as the whole organism.

- Hence the DNA of the parental cells **needs to be passed to the daughter cells** when cell and nuclear division occurs.

- **Nuclear division** is the process which the nucleus of the cell divides. There are two types of nuclear division:

    1. **Mitosis** – A process by which a **nucleus** divides **<u>once</u>** to produce **two daughter nuclei**, each **genetically identical** to the original/parental nucleus (Fig. 2.3).

    2. **Meiosis –** A process by which a **nucleus** divides **<u>twice</u>** to produce **four daughter nuclei**, each containing **half the number of chromosomes** of the original/parental nucleus. It is also known as **reduction division** since the process halves the number of chromosomes in the parental nucleus.

- **Cytokinesis** or **cytoplasmic division** is the process by which the rest of the cell (other than the nucleus) divides to give two daughter cells. Cellular organelles are also redistributed in the process.

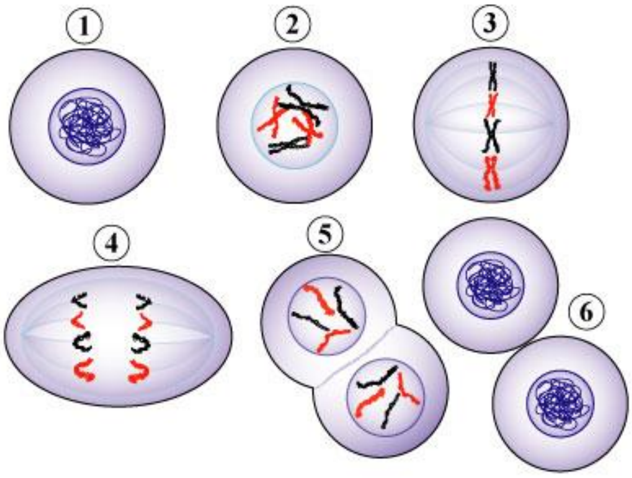


Fig. 2.3: Mitosis. From stages **1** – **5**, the cell undergoes nuclear division. Note that two nuclei are formed during stage **5**. From stages **5** – **6**, the cell undergoes cytoplasmic division, which eventually gives rise to two cells by stage **6**.

- **Organisation of DNA, the genetic material in the cell**

    - All the **DNA** found in a cell of a particular organism is called its **genome**.

    - While the genome of a **prokaryotic** cell is often a **single** DNA molecule (a single circular chromosome), the **eukaryotic** genome consists of a **number** of DNA molecules (a number of linear chromosomes). The overall length of eukaryotic DNA is many times that of prokaryotic DNA. For example, a typical human cell has about 2 metres of DNA, which is 250,000 times longer than the diameter of the nucleus.

    - For this enormous length of DNA to be packed into the nucleus, be replicated and then distributed equally between the two daughter cells, the **DNA molecules are packaged into chromatin** *(Part 1 of Cell and Nuclear Division, page 6*).

3. Interphase

3.1 Features of the Interphase

- During interphase, the genetic material within the nucleus is in the uncondensed thread-like structure which cannot be seen clearly, called **chromatin.**
- This phase lasts for at least **90%** of the cell cycle and is usually the **longest** phase.
- Interphase can be sub-divided into three phases (Fig. 3.1): **G_1 (Gap 1) phase, S (Synthesis) phase and G_2 (Gap 2) phase**.

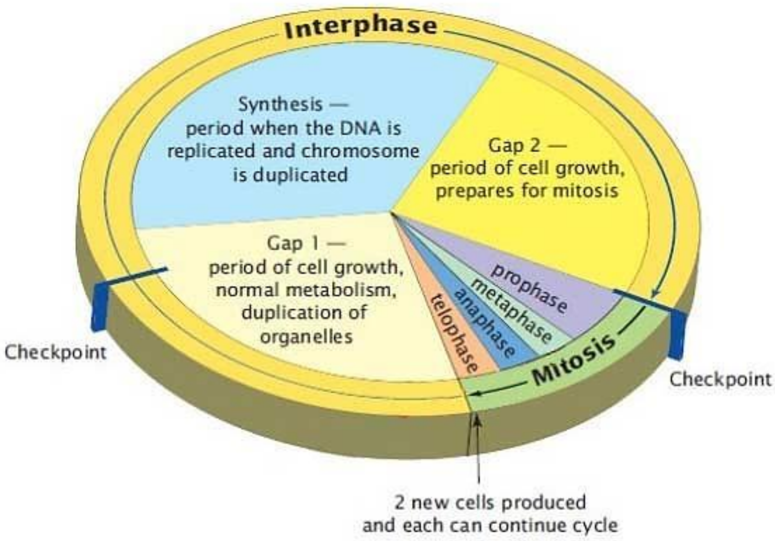


Fig. 3.1: The Cell Cycle and the three stages of Interphase.

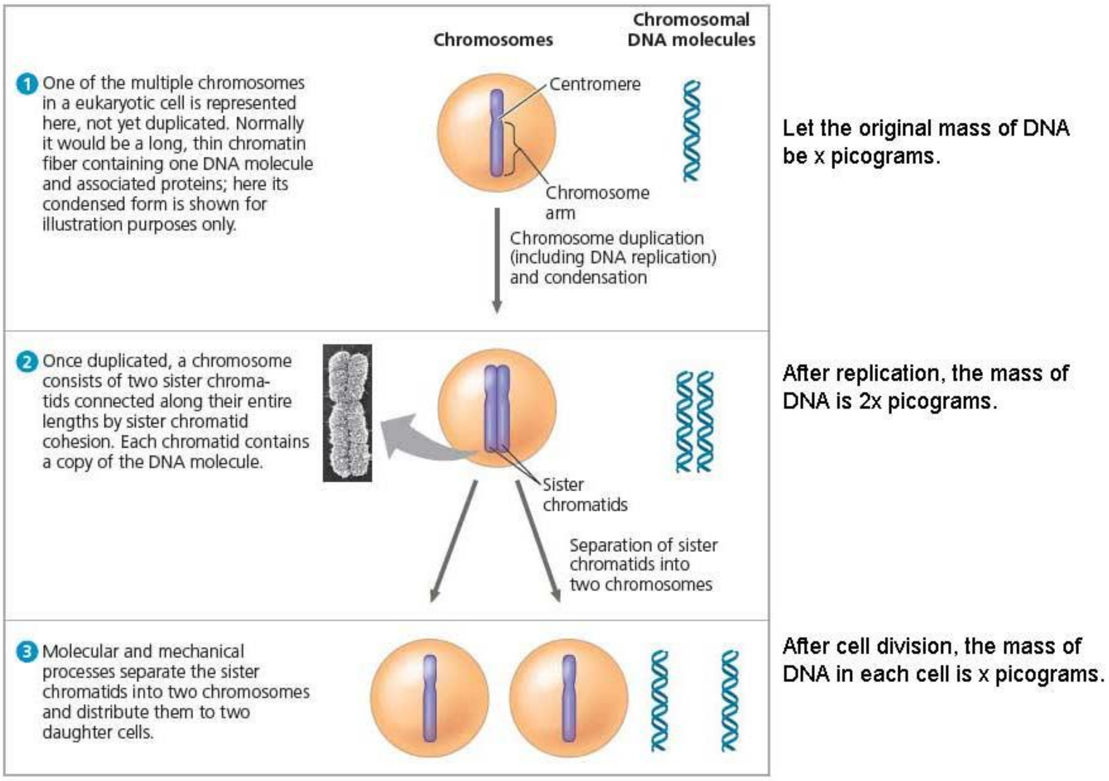
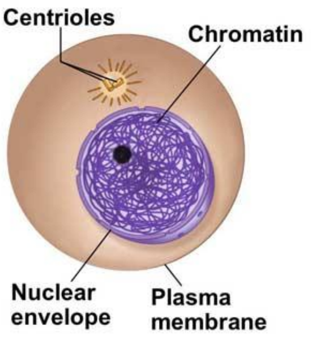
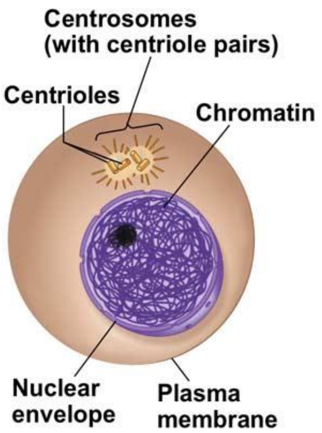


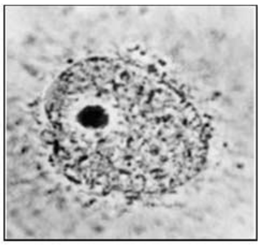
Fig. 3.2: The replication of DNA before mitosis allows for two daughter cells with the same amount of DNA in each cell to be formed by nuclear division.

INTERPHASE



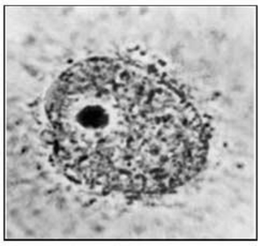


At the G_1 phase:



DNA replication occurs at the S phase

After the G_2 phase



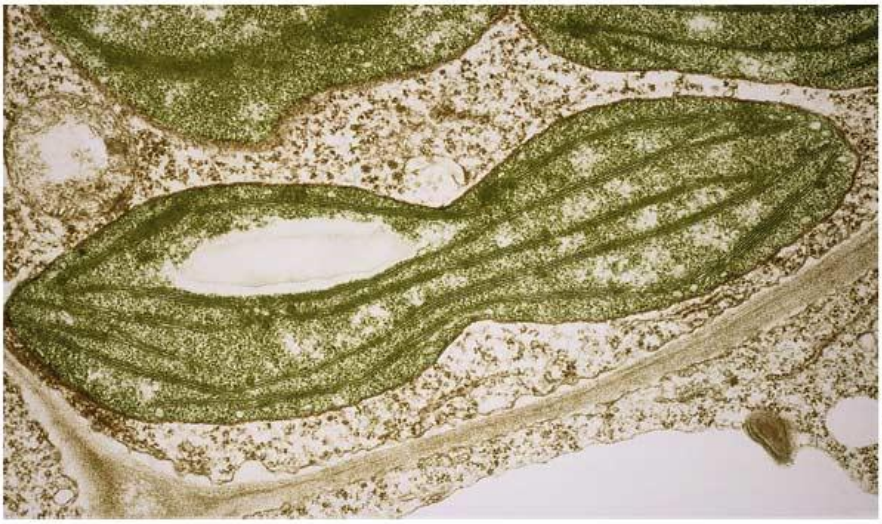
Mass of DNA:
Let the original mass of DNA in the cell be x pictograms.

The cell now has 2x picograms of DNA as compared to x picograms in the G_1 phase.

Ploidy:
The ploidy of the eukaryotic cell in the diagram is diploid (2n).

- If you could condense the DNA in the cell at the G_1 phase and the DNA at the G_2 phase, what structures would be formed? Draw them out.

Description	Rationale
G_1 phase	
• **Cell growth** occurs and the cell **builds up a large store of materials** like **ATP** and:	• Sufficient **energy** and **nutrients** are necessary for mitosis to take place.
○ Synthesis of various **enzymes** required in the S phase, especially those involved in **DNA replication**.	• DNA replication requires **enzymes** *(We will cover this in DNA and Genomics.)*
○ **Synthesis of cytoplasmic organelles** such as ribosomes, chloroplasts (in photosynthetic cells) and mitochondria. Note: Mitochondria and chloroplasts replicate by binary fission.	• The new cells require organelles for survival. *(These organelles will not be shown in the following diagrams but bear in mind that they are there.)*
• The **G_1 checkpoint** checks that the cell has enough nutrients to proceed.	• The cell cannot proceed with cell division if it does not have enough energy and materials.
S phase	
• **DNA replication** occurs and the cell now **has two identical copies of its genome**.	• In order to divide the parent cell's DNA **equally** between two daughter cells, **two genetically identical copies** (nucleotide sequences remain identical) of the genome are required.
• **The mass of DNA doubles** (Fig. 2.2).	
• The **ploidy** of the cell remains **unchanged**.	• The **ploidy** of the cell remains unchanged as there is **no new genetic information** being added or taken away.

I N T E R P H A S E	
  Chloroplast and mitochondrion dividing.	
G_2 phase • The cell continues to build up **a store of energy** and synthesizes more **cytoplasmic organelles** such as **mitochondria, chloroplasts,** and **ribosomes**.	• Provides a safety gap to ensure that DNA replication has been completed before entering mitosis or meiosis.
• The cell manufactures more **proteins** such as **histones**, **ribosomal proteins** and **tubulin**.	• **Tubulin** is the protein that forms the **spindle fibres**, which will be instrumental in the next phase**.** • Recall what are **histones** and **ribosomes** are for: o **Histones** are involved in forming **chromatin** and organising DNA. After S phase and DNA replication, the cell has more DNA and requires more histones to organise genetic material for mitosis. o **Ribosomes** synthesis proteins like tubulin, a component of spindle fibres involved in mitosis. o **Ribosomes** are also required for protein synthesis in the new daughter cells after cytokinesis takes place.
• The **G_2 checkpoint checks for DNA damage** after DNA replication.	• This **prevents DNA mutations** from being passed on to the daughter cells.

3.2 Organisation of the Eukaryotic Chromosome

- After each DNA molecule **replicates** in the S phase (Fig. 3.2), there will be **two identical DNA** molecules joined together by a **centromere**.

- As the cell **enters mitosis** (i.e. the dividing cell), the duplicated chromatin **condenses** to become a **duplicated chromosome** (Fig. 3.3). Each duplicated chromosome consists of two **genetically identical sister chromatids** held together at the **centromere**.

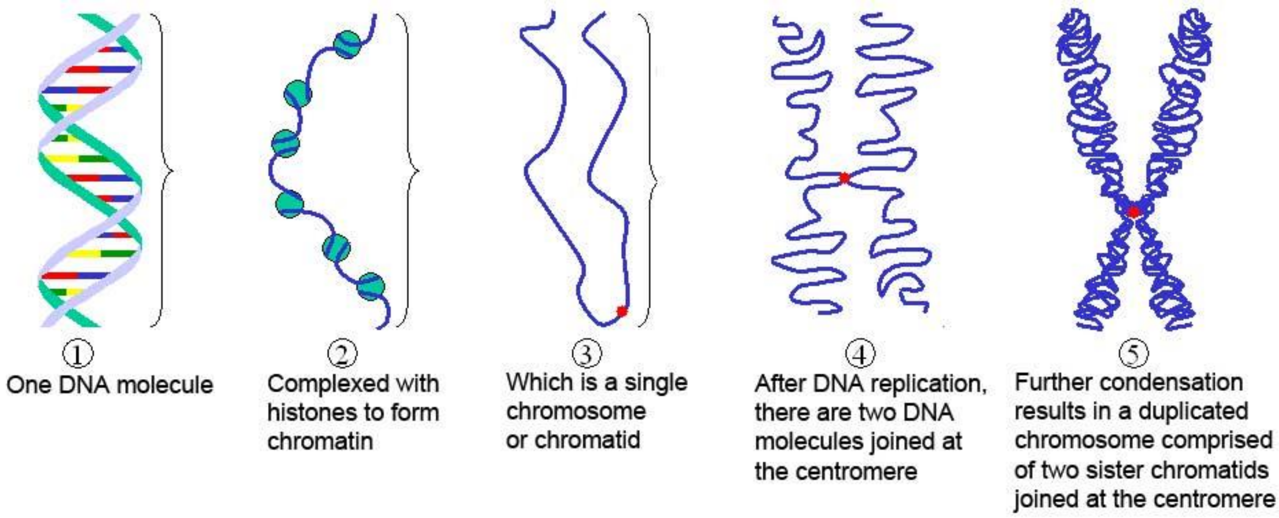


Fig. 3.3: The relationship between DNA molecules, chromatin and duplicated chromosomes

An animation on how the eukaryotic chromosome condenses to form the structures seen during nuclear division: https://dnalc.cshl.edu/resources/3d/07-how-dna-is-packaged-basic.html

- Each **chromatid** carries several hundred to a few thousand **genes**, the units that specify the organism's characteristics or traits.

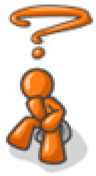
- Later in the mitotic process, the two sister chromatids of each duplicated chromosome separate and end up in each of the two nuclei. Thus, the resulting nuclei / cells are **genetically identical**.

4. Mitosis

- Mitosis is the process by which a **nucleus divides <u>once</u>** (Fig. 4.1) to produce **two genetically identical daughter nuclei**, each containing the **same number of chromosomes** and the **same nucleotide sequences** (i.e. same alleles) as the original nucleus.

- The **rate** of mitosis can **vary widely**. For example, every 8 to 10 hours in epithelial cells of intestine and no division at all for nerve and red blood cells.

- Hence the length of the cell cycle depends on the **type of cell** and **external factors** e.g. food, temperature and oxygen supply.



Can bacteria undergo cell division?

Can bacteria undergo mitosis and meiosis?

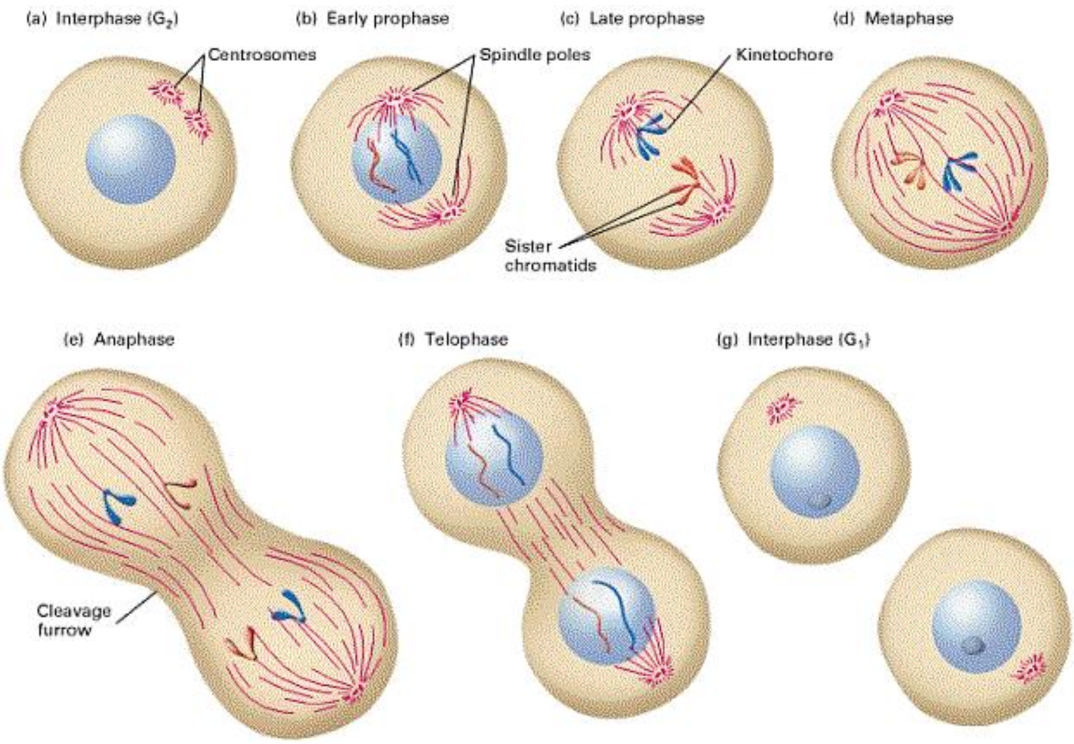


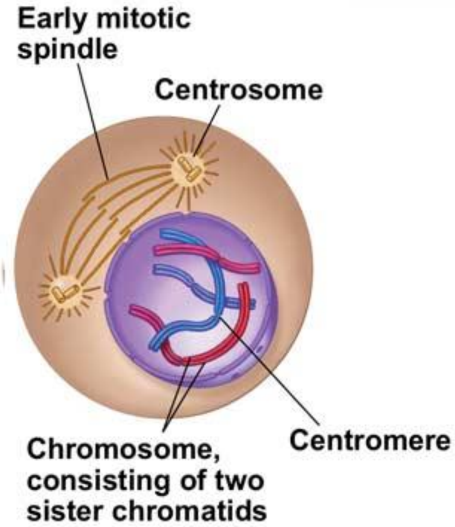
Fig. 4.1: Interphase followed by mitosis and cytokinesis of a diploid cell.

4.1 Stages of Mitosis

- Note that interphase is **not** part of mitosis, but it has to happen prior to mitosis.

- Mitosis is divided into four phases: **prophase, metaphase, anaphase** and **telophase**.

PROPHASE



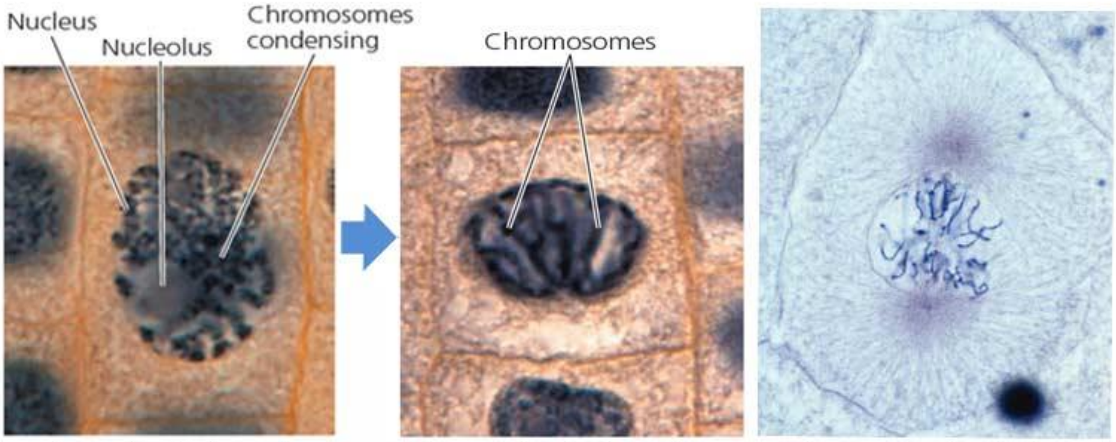
Mass of DNA:
Let the original mass of DNA in the cell be x picograms.

The cell now has 2x picograms of DNA as compared to x picograms at the G_1 *phase.*

Ploidy:
The ploidy of the eukaryotic cell in the diagram is diploid (2n).

If the cell has a total of
2n = 4 chromosomes

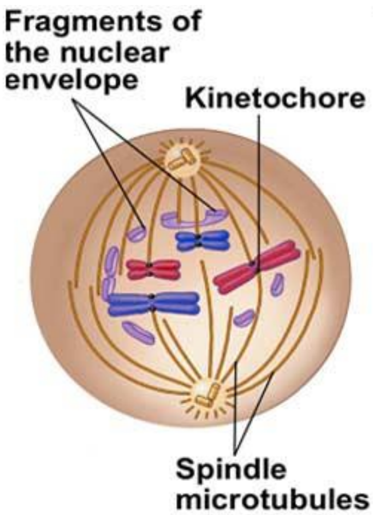
The cell now has
2n = 4 ***duplicated*** *chromosomes.*

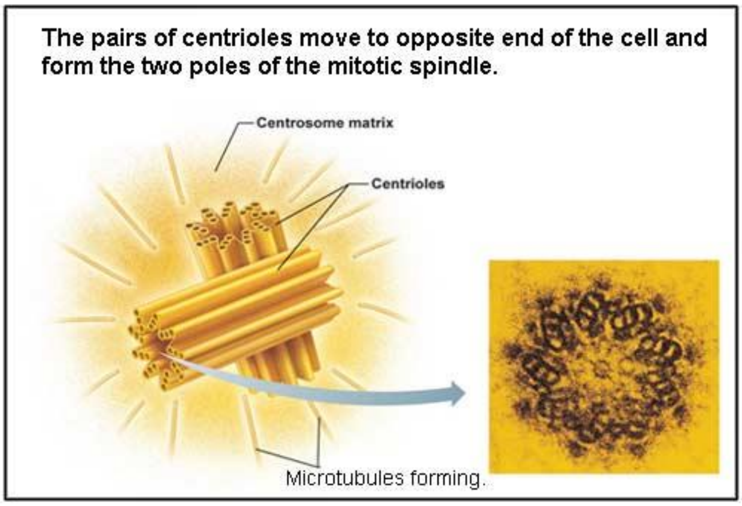


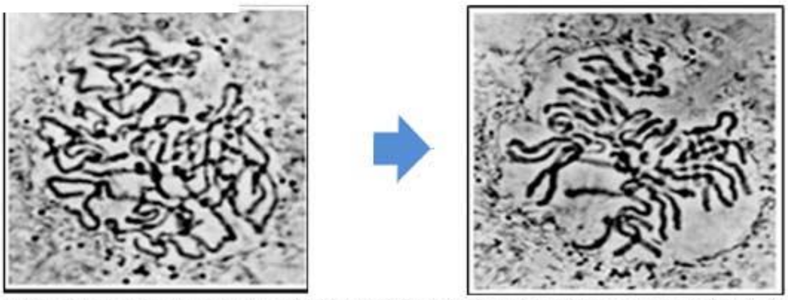
Early prophase in plant cell. Late prophase in plant cell. Late prophase in animal cell.

Description	Rationale
• **Chromosomes** become **visible** due to **condensation / packing of chromatin**. • Each chromosome is seen to consist of **two sister chromatids joined at the centromere**.	• Replicated DNA needs to be organised into condensed duplicated chromosomes *(Part 1 of Cell and Nuclear Division, page 6)* in order to be divided equally.
• In animal cells, two pairs of **centrioles** (or two centrosomes) move to **opposite ends of the cell** for **formation of spindle fibres across the two poles.**	• The function of centrioles is to form the **mitotic spindle**, a framework of tubulin fibres responsible for the division of genetic material.
• The **nucleolus** is no longer visible.	• The functions of the nucleolus have **ceased** for cell division to take place.

PROPHASE







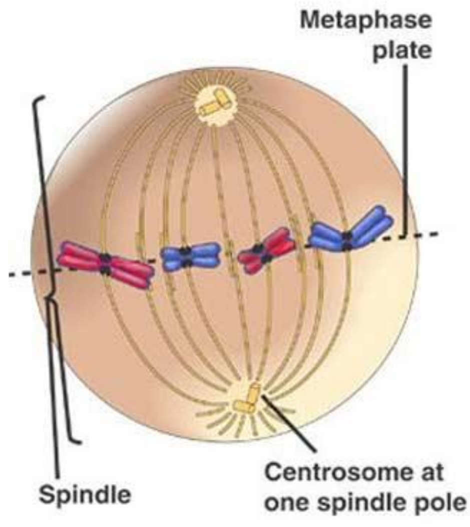
The nuclear membrane disintegrates and the chromosomes become more distinct.

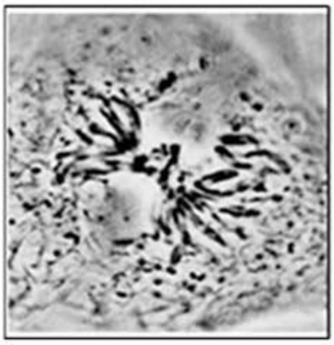
Description	Rationale

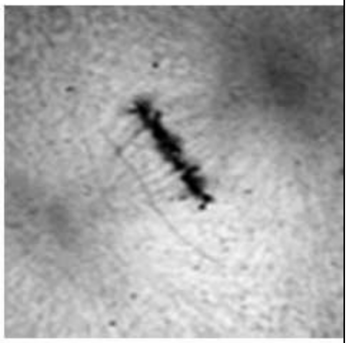
• **Longest stage** in mitosis.
• Formation of the **mitotic spindle** takes place:
  ○ From each centrosome, short **microtubules** develop and form a **star-shaped structure** called an **aster**.
  ○ **Microtubules** arise from the **centrosome** (a pair of centrioles) and form **spindle fibres**.
	• Many of the key events of mitosis depend on spindle fibres of the mitotic spindle.

• **Nuclear envelope disintegrates.** The nuclear membrane dissociates into small vesicles and the nuclear pore complexes also dissociate.	• Spindle fibres will need to attach to the kinetochores bound to the centromeres of the chromosomes
• The spindle fibres are **attached to the kinetochores bound to the centromeres of each chromosome** in late prophase.	• The spindle fibres will **move the chromosomes towards the centre of the cell** in the next phase.

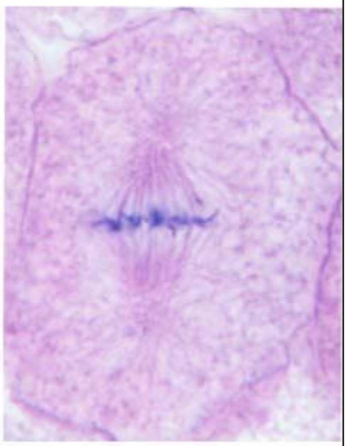
M E T A P H A S E

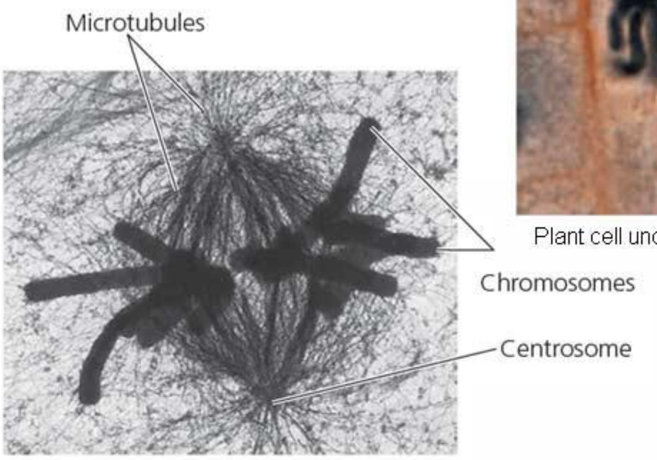







Plant cell undergoing metaphase.

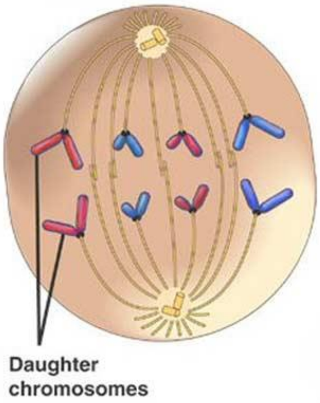

Animal cell undergoing metaphase

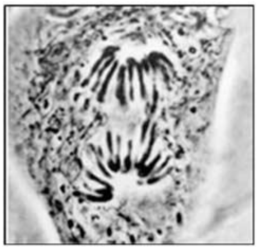


Mass of DNA in cell: *2x picograms of DNA*
Ploidy of cell: diploid
Number of chromosomes**:** *2n = 4 duplicated chromosomes*

Description	Rationale
• The **mitotic spindle** is now fully formed and spindle fibres are attached to the kinetochore on centromere of each duplicated chromosomes.	
• **The chromosomes** are **aligned at the equator of the cell** (i.e. the **metaphase plate**), **equidistant** from the two poles of the mitotic spindle.	• This facilitates the **equal division of chromosomes** in the next phase and the production of **genetically identical daughter cells.**

ANAPHASE

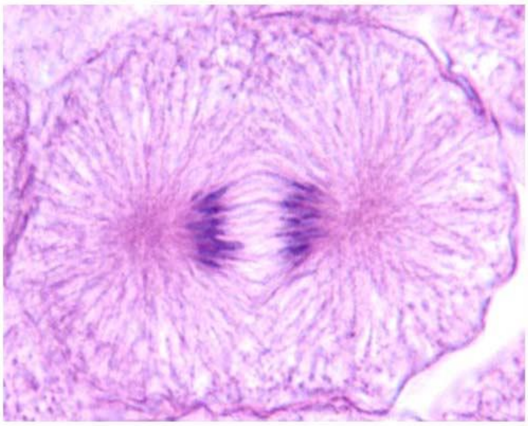


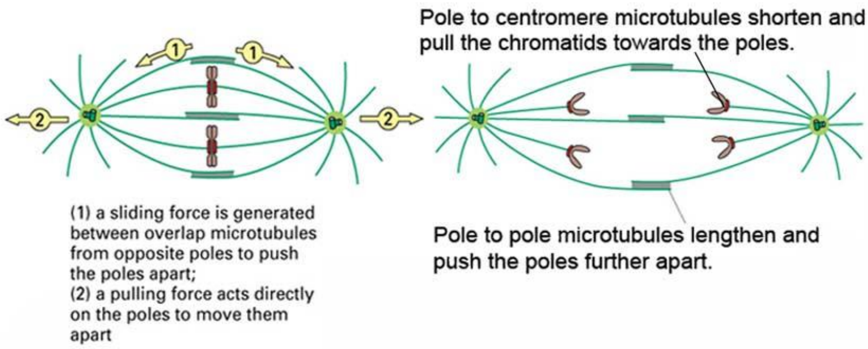


Mass of DNA in cell: *2x picograms of DNA*
Number of chromosomes: 8

A plant cell undergoing anaphase.

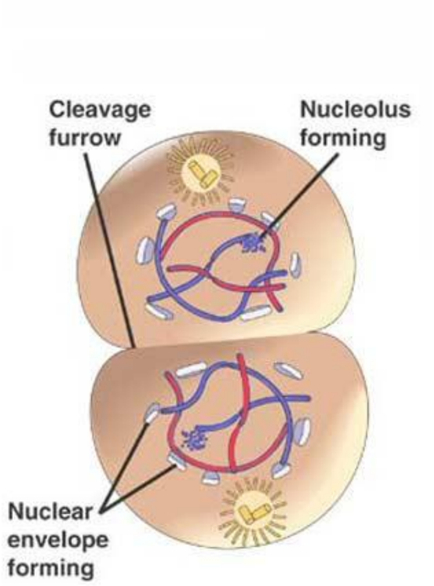
An animal cell undergoing anaphase.

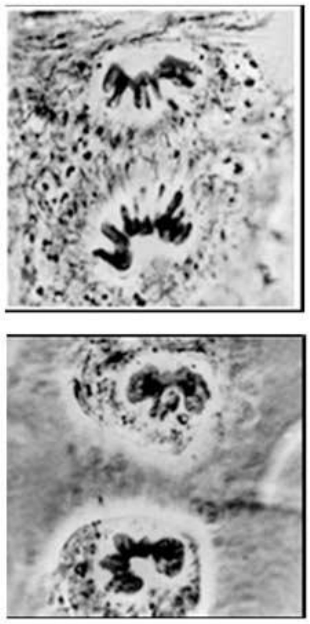




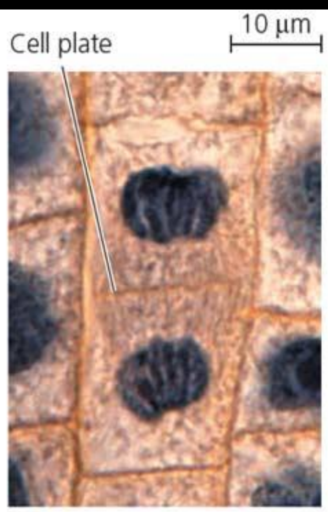
Description	Rationale
• Anaphase is usually the **shortest phase** of mitosis.	• The events of anaphase occur very quickly relative to the other phases**.**
• The **shortening of the centromere-to-pole spindle fibres** occurs.	• This creates tension and enough force to **divide the centromere of each chromosome.**
• At the same time, the **pole-to-pole microtubules lengthen**, pushing the poles apart.	• This causes the poles to move further apart in readiness for cytokinesis.
• The **sister chromatids** from each duplicated chromosome **separate and move**, **centromeres first**, to the two **opposite poles** of the spindle.	• This ensures that the **daughter nuclei** produced are **genetically identical** as the **sister chromatids** are **divided equally** between the two daughter cells.

TELOPHASE

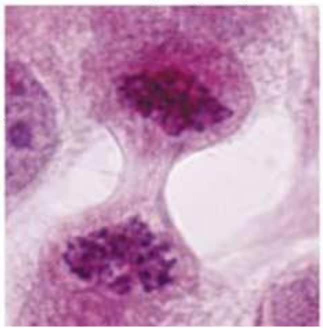




Animal cell undergoing telophase.



Plant cell undergoing telophase.



Mass of DNA in each cell after cytokinesis: *x picograms*
Ploidy of cell: ***diploid***
Number of chromosomes per cell after cytokinesis: 2n=4 chromosomes

Description	Rationale
• The **chromatids** reach their respective **poles** and become the **chromosomes** of the **daughter cells.**	
• **Chromosomes uncoil** and return to their original thread-like form (chromatin).	• The chromatids need to **uncondense** before cellular processes can take place.
• **Spindle fibres disintegrate**	• Spindle fibres are no longer required.
• **Nuclear envelope reforms around the chromosomes** at each pole.	• Resumption of normal function of the nuclear membrane. Recall the function of the nuclear envelope *(Cell Structure).*
• **Nucleoli reappear.**	• Resumption of normal function of the nucleolus. Recall the function of the nucleolus *(Cell Structure).*

View the following animations to reinforce your learning about Mitosis:

1. https://www.youtube.com/watch?v=28OrSBF8EE0
2. *http://www.sumanasinc.com/webcontent/animations/content/mitosis.html*

Summary of Mitosis

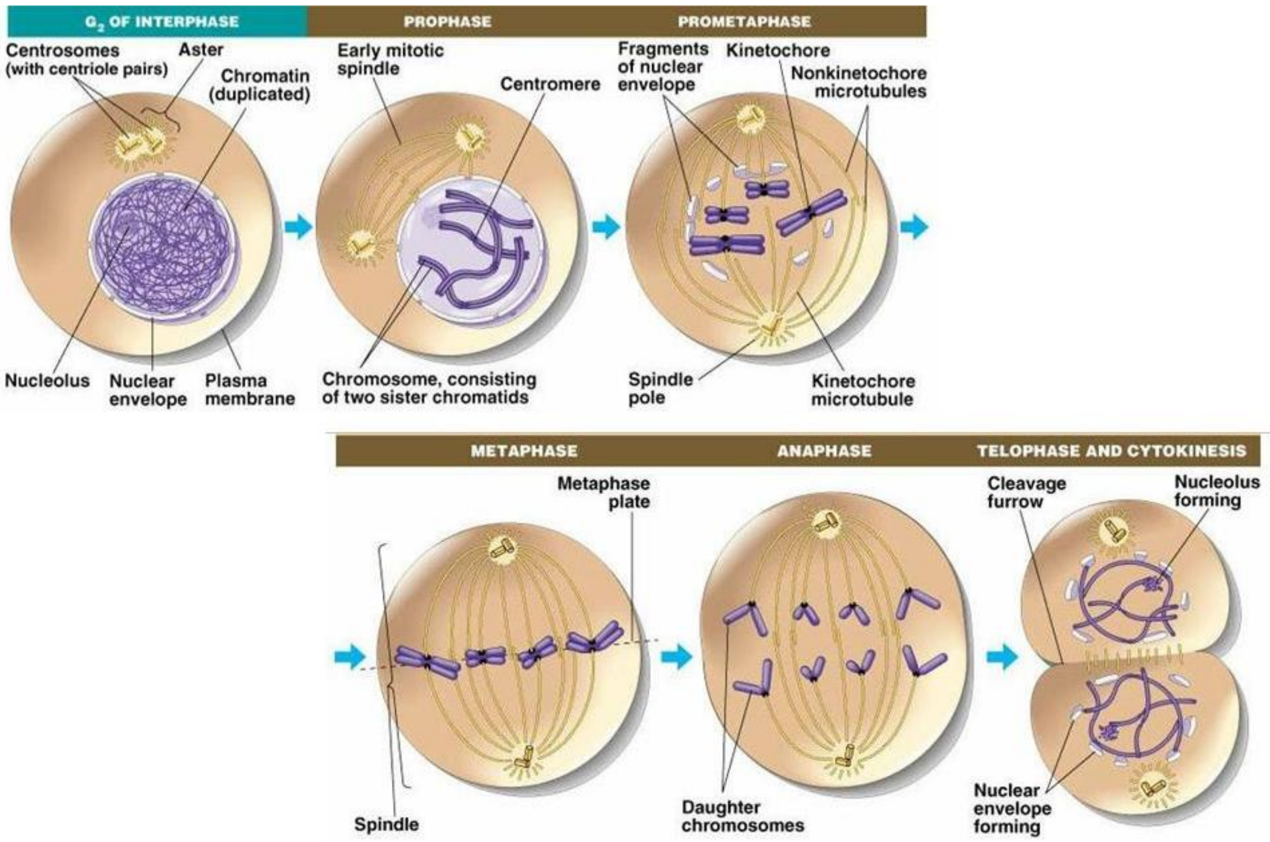


Fig. 4.2: Summary of mitosis.

4.2 Significance of Mitosis

- To **maintain the genetic stability** of the organism.
  - The two daughter cells produced from mitosis contain chromosomes that are **genetically identical** to the parent cell's chromosomes.
  - This is due to:
    - the **separation of sister chromatids** during **anaphase** of mitosis.
    - **no chiasma** formed and **no crossing over** occur during mitosis, maintaining genetic fidelity (i.e. same alleles and the **same nucleotide sequence** on each chromosome).

- To **maintain the diploid state** of the next generation of cells. This is possible due to:
  - **Replication of the parental DNA** during **interphase** before mitosis begins.
    - The amount of DNA is **doubled** during **interphase**,
    - so that DNA **returns to the original amount** after **separation of sister chromatids** at **anaphase** (Fig. 4.2).
  - The **arrangement of the chromosomes at the equator** during **metaphase**.
    - This ensures that the **sister chromatids are divided equally** between the two daughter nuclei during anaphase.

4.3 Functions of Mitosis

Mitotic cell division has several important functions in the life of an eukaryotic organism:

a) The growth of a multicellular organism

- Mitosis enables a multicellular organism to develop from a single fertilized egg cell (called the zygote) after fertilisation. Mitosis increases the number of cells, hence the size/mass of the organism.

- Examples: The growth of a seedling into an adult plant. Growth from a single-cell zygote to adult human.

b) Cell replacement and Tissue repair

- In a multicellular organism, cells are constantly dying from wear and tear or accidents. **Replacement of cells** involves mitosis. E.g. Repair of wounds, dividing cells in the bone marrow continuously make new red blood cells as RBCs have a life span of approximately three months.

c) Regeneration of body parts

- Some organisms are able to regenerate body parts. E.g. starfish replaces their arms via mitosis.

d) Asexual Reproduction

- Producing genetically identical offspring from parents is the key to successful colonisation of a new habitat by a species.

- Asexual reproduction enables the rapid spread of adaptable individuals in a particular type of environment.

- Many organisms like onion and ginger are propagated in this manner.

5. Cytokinesis

- **Cytokinesis** is a process whereby the **cytoplasm of the cell divides** to give two daughter cells with the **same organelles as the parent cell**, each containing one of the newly formed nuclei.

Name the organelles that will be redistributed when the cell undergoes cytokinesis:

- Note that **cytokinesis** and **mitosis** are **separate processes** which depend on different molecular machinery.

- In many cells, telophase and cytokinesis occur **concurrently**. The speed at which each process occurs varies between cells.

- In animal cells, a **cleavage furrow** (Fig. 5.1) appears in the cell membrane as a result of a ring of microfilaments forming midway between the poles of the cell. The cleavage furrow deepens until the cell is pinched into two, producing two completely separated cells.

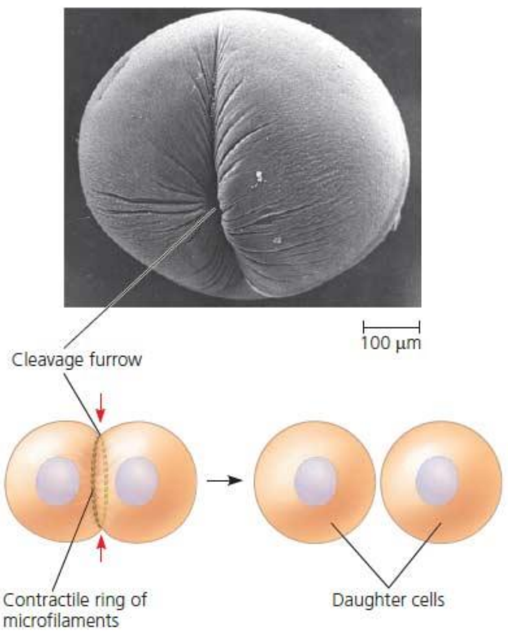


Fig. 5.1: Cytokinesis in an animal cell showing the formation of a cleavage furrow that divides the cell into two daughter cells.

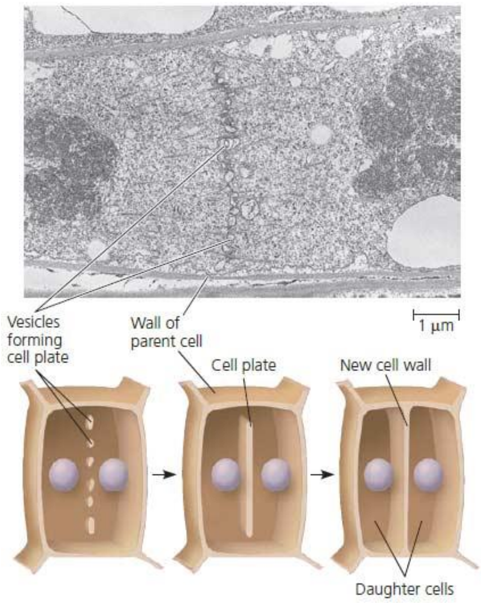


Fig. 5.2: Cytokinesis in a plant cell showing the Golgi vesicles (containing cell wall material) at the middle of the cell.

- In plant cells, a series of **Golgi vesicles line up** in the **middle** of the **parent cell** (Fig. 5.2). The Golgi vesicles **fuse to form the cell plate**, which extends outwards across the equator of the parent cell. The contents of the Golgi vesicles **form the cell wall** of the daughter cells while their membranes contribute to the cell surface membranes of the daughter cells.

The **contents** of the Golgi vesicles involved in plate formation include:

6. Control of Cell Cycle

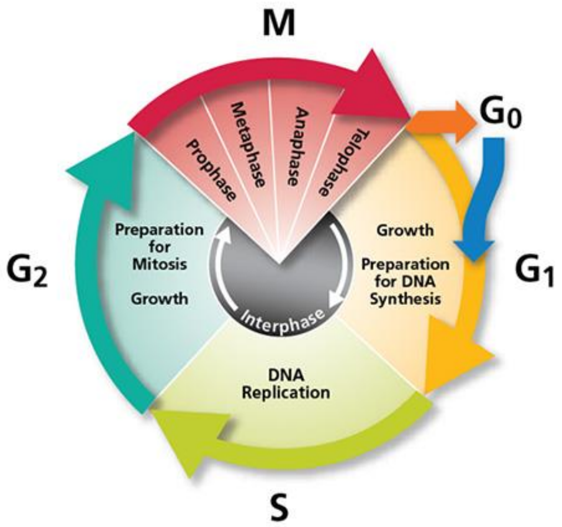
- The cell cycle (Fig. 6.1) is regulated by a distinct **control system**.

- This control system comprises of **checkpoints** (Fig. 6.1) which are **control points** where **stop and go-ahead signals** can regulate the cycle.

- Without fine control of mitosis and the cell cycle, **uncontrolled cell division** occurs, resulting in the risk of developing **cancer**.

6.1 The Three Main Checkpoints of the Cell Cycle

- The three major checkpoints of the cell cycle are:
  - **G_1 checkpoint**
  - **G_2 checkpoint**
  - **M phase checkpoint**



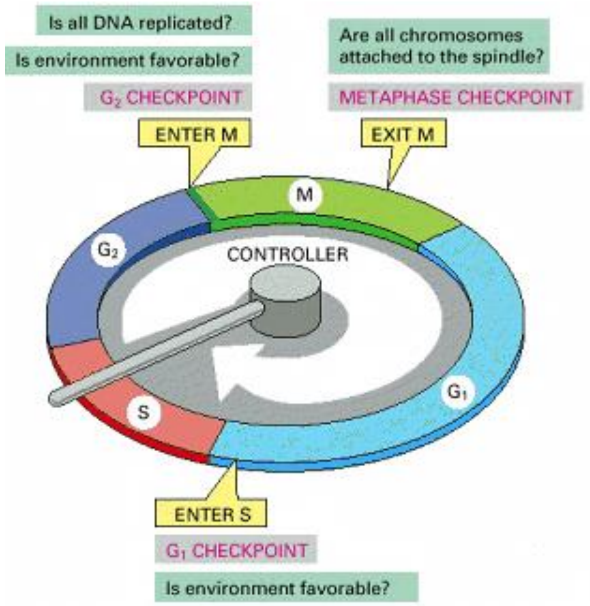


Fig. 6.1: Events of the Cell Cycle and its checkpoints.

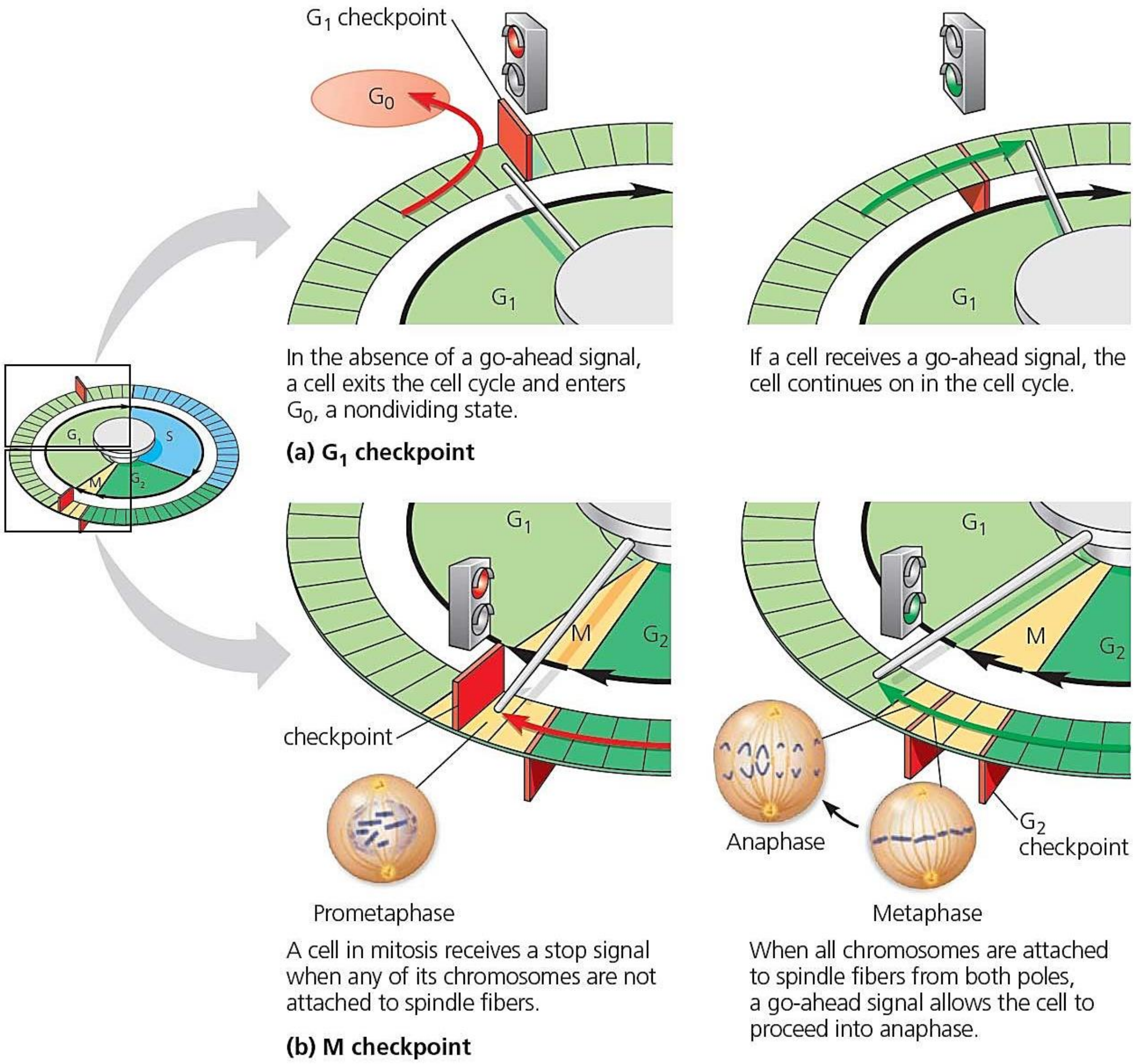
a) G_1 checkpoint

- Seems to be the **most important** checkpoint for most cells.

- Cells check for **sufficient nutrients** (e.g. ATP, proteins and enzymes) present and sufficient growth of the cell for DNA replication and cell division to take place.

- If **go-ahead signal is received,** the cell will **usually complete the G_1, S, G_2 and M phases**, and **divide**.

- If **go-ahead signal is NOT received**, the cell will **exit cell cycle** and switch into **G_0 phase** (Fig. 6.2a), a phase where the cell no longer go through the cell cycle and does not divide.



. **Fig. 6.2:** How the checkpoints function to regulate the cell cycle.

b) G_2 checkpoint

- The cell checks for **DNA damage / mutation** after DNA replication.
- Cell continues on to mitosis or meiosis only if there is no DNA mutation or the DNA damage is repaired.
- This prevents **mutations** from being passed onto the daughter cells.

c) Metaphase checkpoint (Fig. 6.2b)

- The cell checks for the **attachment of spindle fibres to the centromeres of the chromosomes** before **anaphase** is allowed to take place.
- This is also known as the **spindle assembly checkpoint**.
- Cell division will be arrested and switched to the G_0 phase if spindle fibres are not properly attached to the **kinetochores** at the centromeres.
- This prevents mistakes from occurring during cell division. (E.g. nondisjunction.)

6.2 Loss of Cell Cycle Control in Cancer Cells

- **Cancer cells** do not heed the normal signals that regulate the cell cycle. Cancer cells will keep dividing regardless of nutrient availability.
- Another reason for the development of cancerous cells could be **faulty cell cycle control**.
- The cell cycle checkpoints may not function properly as a result of mutations caused by other factors (ionising radiation, carcinogens, etc).
- The mutations may occur in **genes** that code for **proteins** that control the cell cycle. *(You will learn examples of this in the topic of DNA mutations and Consequences.)*
- Cell cycle dysregulation is a characteristic of **tumour cells**.
- In cells where the checkpoints are functional, potentially cancer-causing mutations in DNA are not passed onto daughter cells as the cell enters G_0 before it can undergo cell division (Fig. 6.3).
- In cells where dysregulation of the checkpoints occurs, the mutations are passed onto the daughter cells after cell division (Fig. 6.3).
- This can lead to **accumulation of mutations** that may cause cancer in the future.

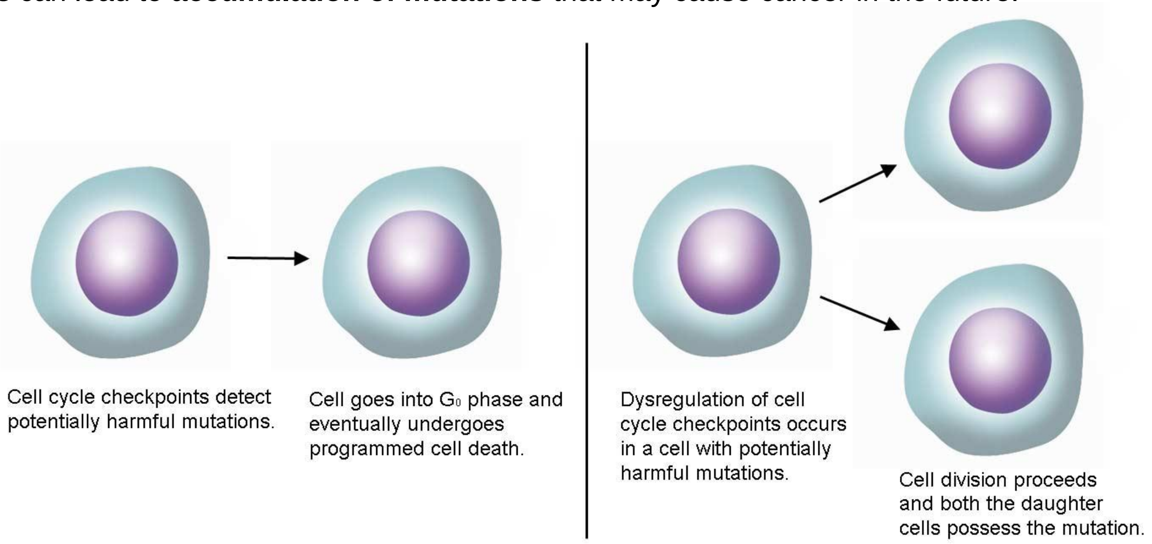


Fig. 6.3: (Left) Checkpoints function to stop cell division when mutations are detected.
(Right) Dysregulation of cell cycle checkpoints leads to cell not heeding normal signals that regulate the cell cycle.

7. Meiosis

- Meiosis is the process by which a **nucleus divides twice** to produce **four daughter nuclei**, each containing **half the number of chromosomes of the original nucleus**.

- Meiosis is known also as **reduction division** since it **halves the number of chromosomes** in the parental nucleus of a diploid organism.

- In the life of a sexually reproducing organism, meiosis occurs during the **formation of gametes** (ovum and sperm) from the germ cells, producing **haploid nuclei** in the gametes. The ovum and sperm fuse together during fertilisation to **restore the diploid condition** in the zygote (Fig. 7.1).

- Offspring inherit genes by **inheriting chromosomes from both parents**.

- In the life cycle of sexually reproducing organisms, fertilisation (fusion of male and female gametes) and meiosis (production of gametes) occurs.

- Meiosis reduces the **number of chromosome sets from diploid to haploid** so that upon fertilisation of gametes, the diploid condition is restored in the offspring (Fig. 7.1).

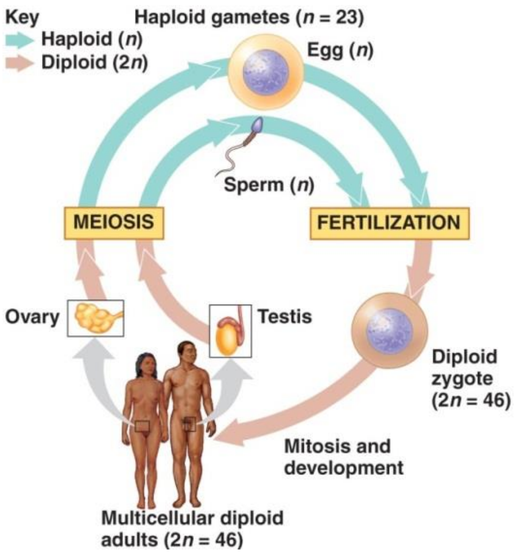


Fig. 7.1: Meiosis in sexually reproducing organisms produced haploid gametes and fusion of gametes restores the diploid condition

- Meiosis produces **genetic variation** that contributes to evolution.

- Similar to mitosis, **interphase** occurs **before meiosis**.

- There are two consecutive nuclear divisions (Fig. 7.2) in meiosis
  - **Meiosis I** (1st meiotic division) – separation of homologous chromosomes
  - **Meiosis II** (2nd meiotic division) – separation of sister chromatids

- After meiosis,
  - The number of chromosomes is **halved** (Fig. 7.2)
  - The ploidy of the cell is reduced. E.g. from **diploid (2n) to haploid (n)**.

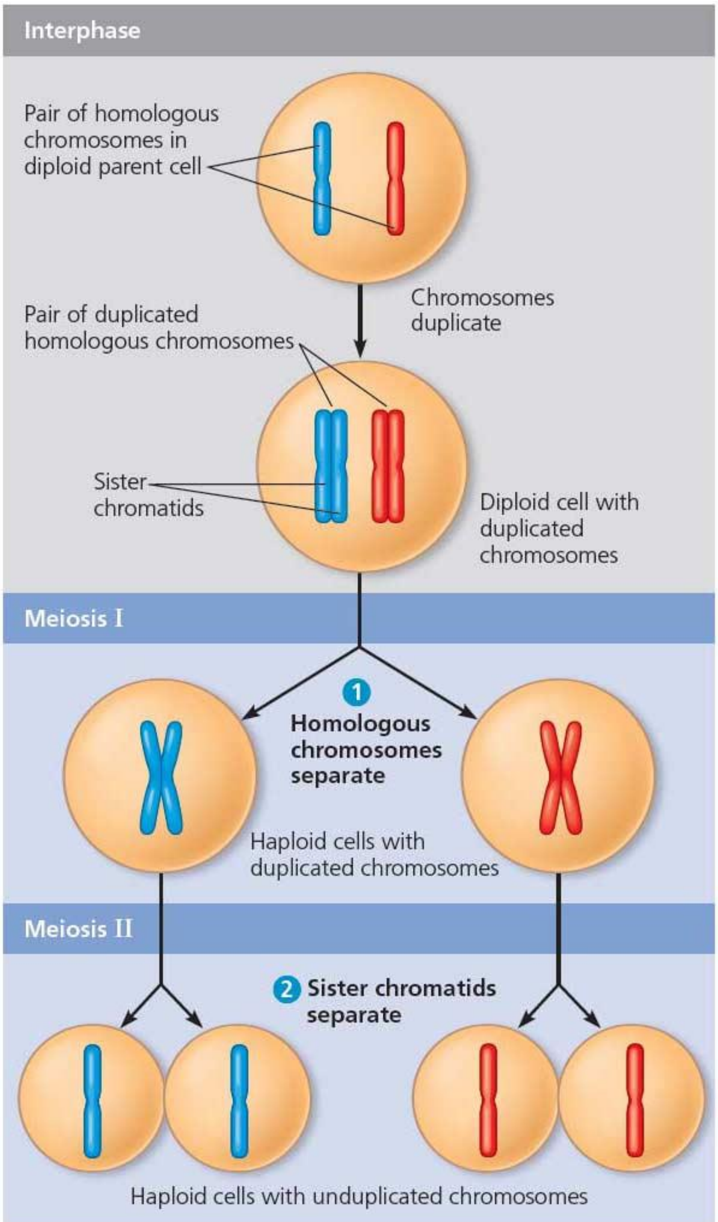
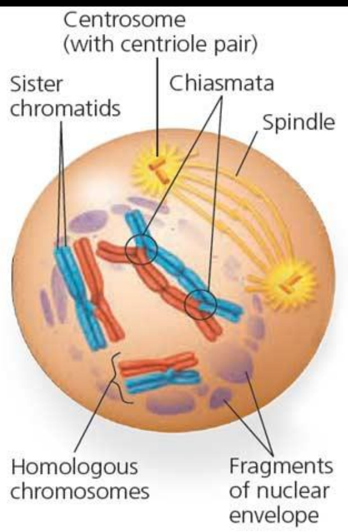
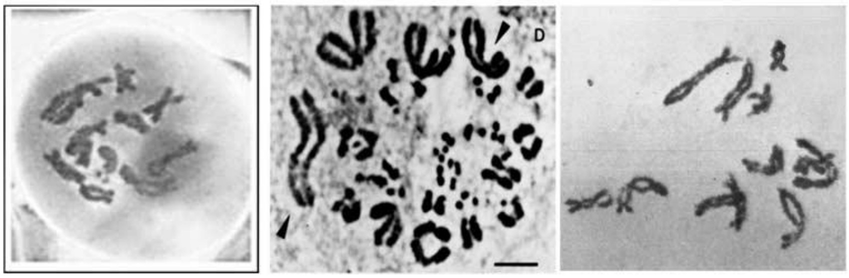


Fig. 7.2: An overview of meiosis, also known as reduction division as the number of chromosomes is halved after two consecutive nuclear divisions—i.e. a diploid cell becomes haploid after meiosis and cell division.

7.1 Stages of Meiosis

MEIOSIS I — **PROPHASE I**

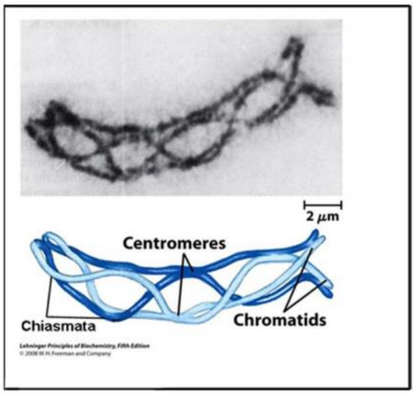


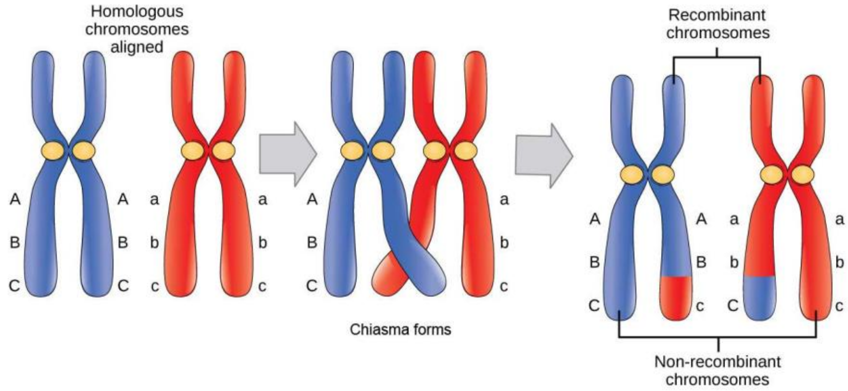


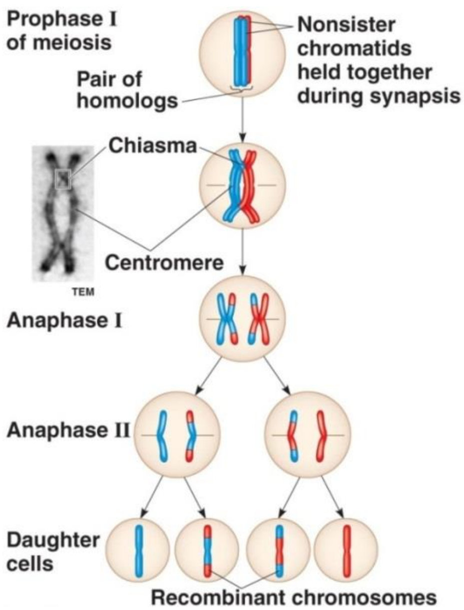
Mass of DNA in cell: *2x picograms of DNA*
Ploidy of cell: Diploid
Number of chromosomes: *2n = 6 duplicated chromosomes*

Description	Rationale
• Chromatin **condenses** to form **visible chromosomes**.	• Replicated DNA needs to be organised into condensed duplicated chromosomes in order to divide intact.
• **Homologous chromosomes** pair up by a process called **synapsis**. Each pair of homologous chromosomes constitutes a **bivalent** (also known as a **tetrad**).	• This prepares the pairs of chromosomes for the process of crossing over.
• Each chromosome continues to shorten and thicken and is seen to consist of **two sister chromatids** joined at the **centromere**.	
• **Centrioles migrate to opposite ends** of the cell to stretch spindle fibres across the two poles.	• The function of centrioles is to form the **meiotic spindle**, a framework of fibres responsible for the division of genetic material.
• The **nucleolus** disappears, RNA transcription no longer occurs and ribosome assembly is halted.	• The functions of the nucleolus have ceased for cell division to take place.
• The **nuclear envelope** begins to **disintegrate**.	• This allows the formation of the **pole-to-centromere and pole-to-pole spindle fibres**. • Many of the key events of **meiosis** depend on spindle fibres of the **meiotic** spindle.

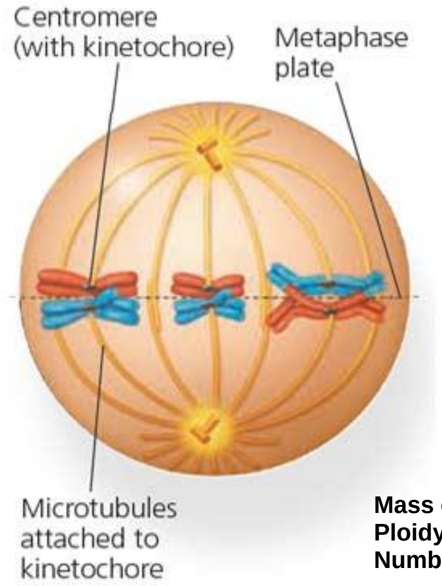
MEIOSIS I — PROPHASE I

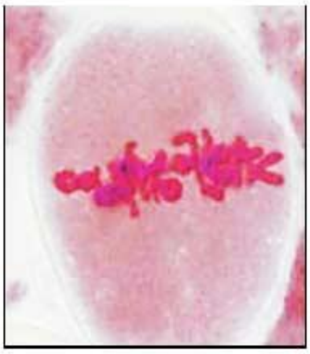




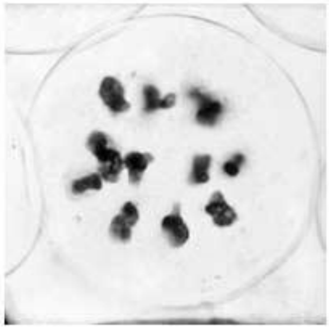
Description	Rationale
• **Chiasmata** (singular: chiasma) may form **between non-sister chromatids of homologous chromosomes**, resulting in **crossing over**. • **Crossing over** occurs, the process in which **corresponding sections** of the chromatids are exchanged. • **After crossing over**, the sister chromatids of a duplicated chromosome are **no longer genetically identical**.	• The chiasmata are the points at which the chromosomes break and re-join. • Formation of chiasmata is needed for crossing over to take place. • Crossing over results in the formation of **new combinations of alleles on chromosomes of gametes** (Fig. 6.1). Hence the gametes will contain **recombinant chromosomes**. • This results in **genetic variation** (in future offspring).  **Fig. 6.1:** Crossing over during prophase I of meiosis results in recombinant chromosomes in daughter cells.
• The **chromatids** are now at their **shortest and thickest**. At this stage, there is still attachment between the sister chromatids throughout their full length.	

METAPHASE I



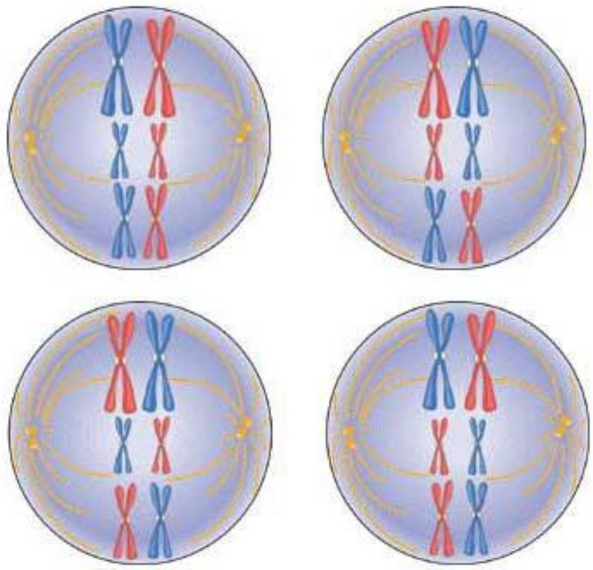


Side view of Metaphase I along the equatorial plane.

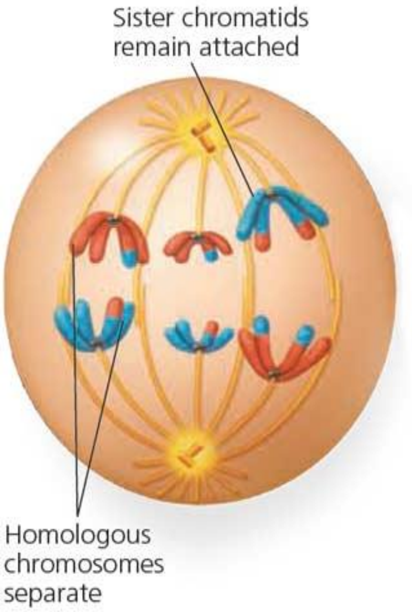


Polar view of Metaphase I.

Mass of DNA in cell: *2x picogram of DNA*
Ploidy of cell: Diploid
Number of chromosomes*:* *2n = 6 duplicated chromosomes*

Description	Rationale
• **Spindle fibres** are **attached** to **kinetochores** at the **centromere** of each duplicated chromosome.	• This is necessary to move the pairs of chromosomes into position.
• The **bivalents** or pairs of homologous chromosomes move to **align** at the **equator** of the **spindle** in **two rows.**	• This arrangement ensures that the homologous chromosomes separate after anaphase I into different daughter cells.
• The **arrangement of the chromosomes of each bivalent** is **independent of the orientation of the other bivalents.** • This is known as **independent assortment** of **homologous chromosomes** (Mendel's Law of Independent Assortment of homologous chromosomes).	• This leads to the **random arrangement** of bivalents that will increase **genetic variation** in the gametes.  Some potential combinations as a result of independent assortment

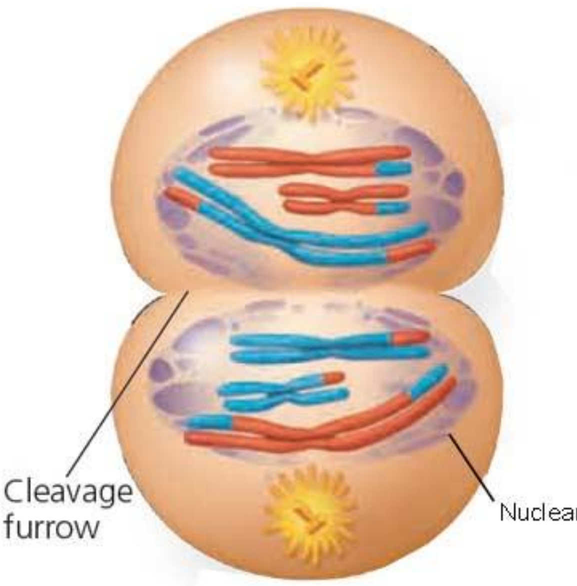
A N A P H A S E I

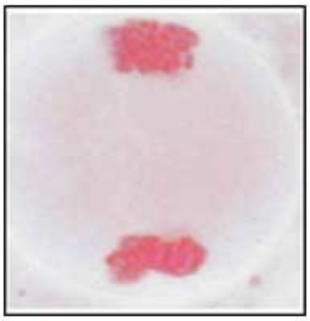


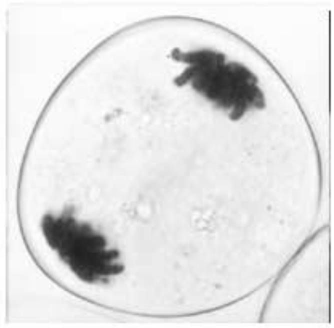
Mass of DNA in cell: *2x picograms of DNA*
Ploidy of cell: Diploid
Number of chromosomes: *2n = 6 duplicated chromosomes*

Description	Rationale
• The **centromere-to-pole spindle fibres shorten**.	• This causes the chromosomes of the homologous pairs to separate from each other.
• At the same time, the **pole-to-pole spindle** fibres **lengthen**.	• This causes the poles of the spindle to move further apart, lengthening the cell.
• **Homologous chromosomes separate** and move to different poles.	• This ensures that the **ploidy** of the resulting daughter cells is **halved**.
• **One duplicated chromosome of each homologous pair** is pulled to one pole and the other chromosome is pulled to the opposite pole.	• The **maternal and paternal chromosomes of each homologous pair** will no longer be in the same cell after cytokinesis.

T E L O P H A S E I



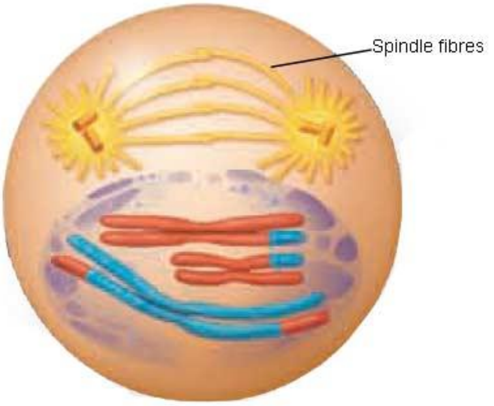


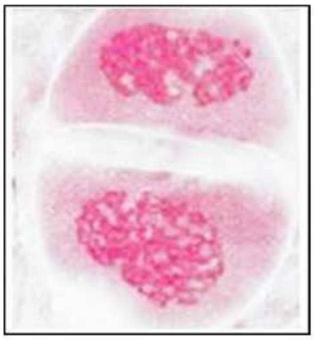


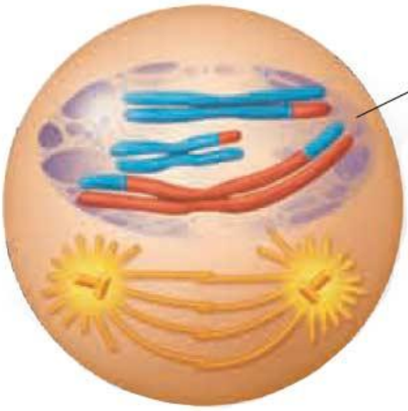
Mass of DNA per nucleus: *x picograms of DNA*
Ploidy of each nucleus: haploid
Number of chromosomes: *n = 3 duplicated chromosomes*

Description	Rationale
• The **chromatids** reach their respective **poles** and become the **chromosomes** of the **daughter cells.** • **Chromosomes uncoil** and return to their original thread-like form.	• The chromatids need to **uncoil** before cellular processes can take place.
• **Spindle fibres disintegrate**.	• Spindle fibres are no longer required.
• **Nuclear envelope reforms around the chromosomes** at each pole	• Recall the function of the nuclear envelope.
• **Nucleoli reappear**.	• Recall the function of the nucleolus.

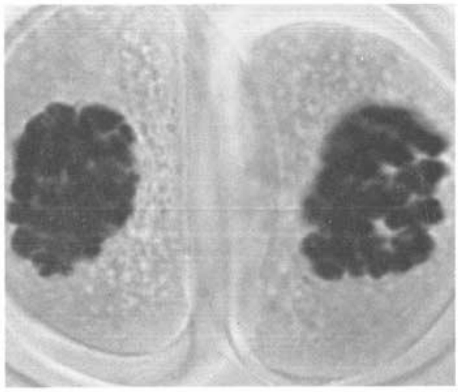
MEIOSIS II — PROPHASE II





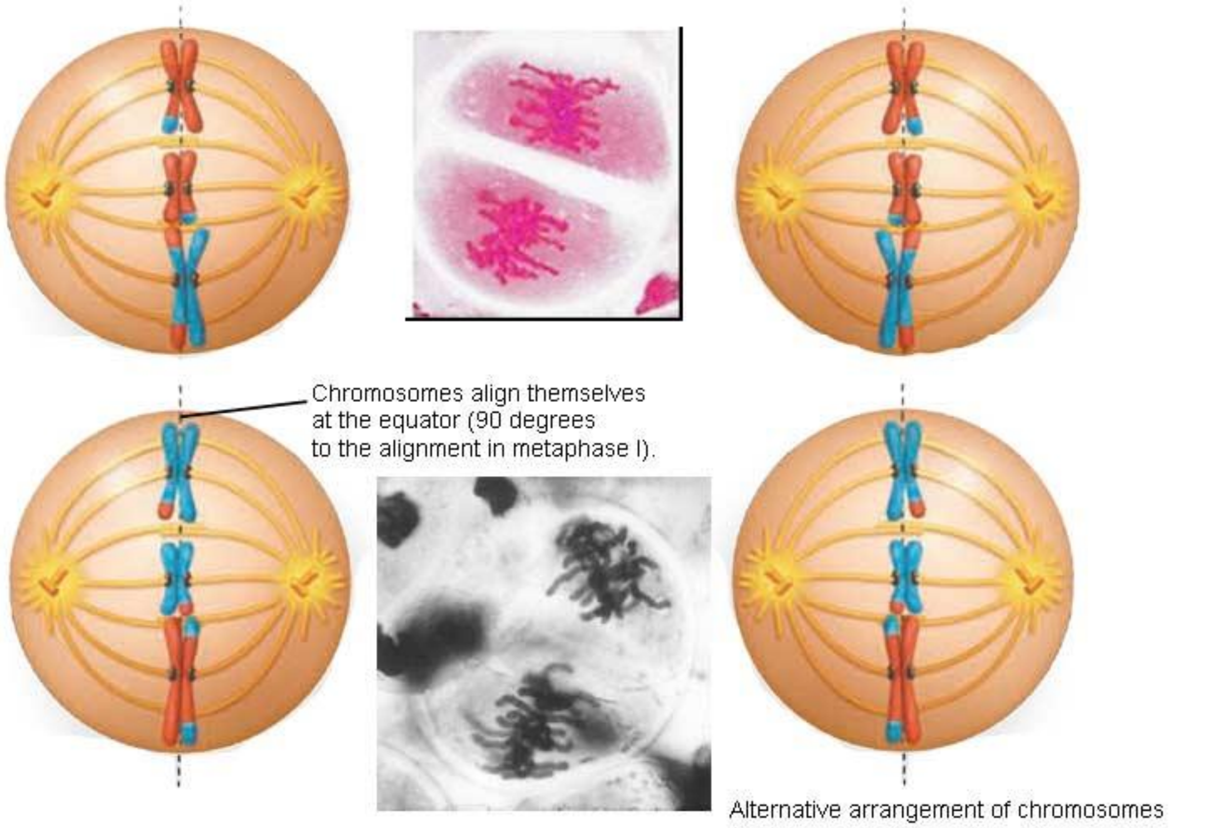


Mass of DNA per cell: *x picograms of DNA*
Ploidy of each cell: haploid
Number of chromosomes: *n = 3 duplicated chrosomes*



Description	Rationale
• In cells where telophase I and interphase (without DNA replication) have occurred, the **nucleoli** are no longer visible and **nuclear envelopes of each cell disintegrate**. This facilitates the formation of the **meiotic spindle**.	• This allows for the formation of spindle fibres **between-poles** and **pole-to-centromere** spindle formation. • **NOTE:** DNA replication does not occur as this would lead to polyploidy after fertilisation.
• If **centrioles** are present, they **move to opposite poles**.	• The function of centrioles is to form the **meiotic spindle**, a framework of **microtubules** spanning the cell that is responsible for the division of genetic material.
• **Spindle fibres develop** but the direction of the axis is **at right angles to the spindle axis of meiosis I**.	• Many of the key events of meiosis depend on spindle fibres of the **meiotic** spindle.

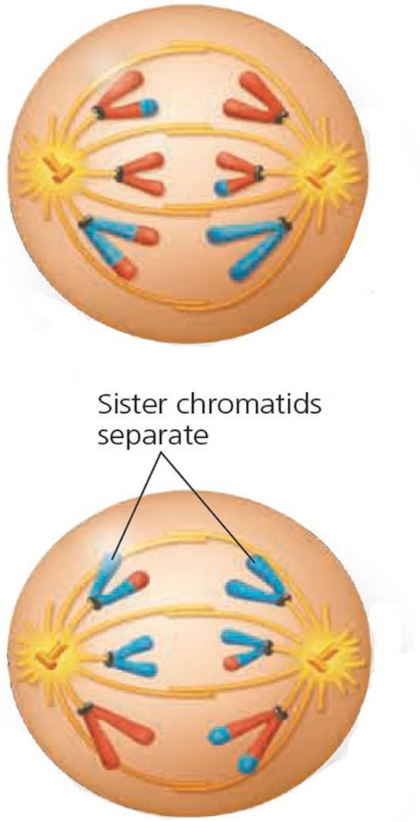
METAPHASE II

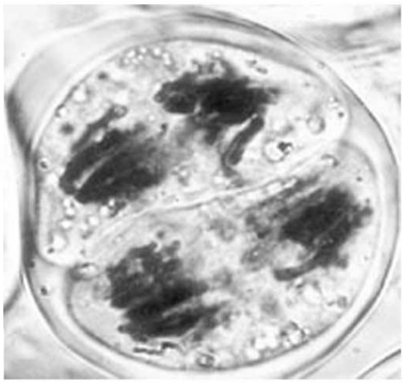


Mass of DNA per cell: *x picograms of DNA*
Ploidy of each cell: haploid
Number of chromosomes: *n = 3 duplicated chromosomes*

Description	Rationale
• The **meiotic spindle** is now fully formed and spindle fibres are attached to the kinetochores on centromeres of the duplicated chromosomes.	
• **The** duplicated **chromosomes** are **aligned at the equator of the cell in one row** (i.e. the **metaphase plate**), **equidistant** from the two spindle poles.	• This facilitates the **equal division of the chromosomes.**
• The arrangement of duplicated chromosomes at the equator is **random and independent (Mendel's Law of Independent Assortment of non-identical sister chromatids).**	• This means that the arrangement of each chromosome is not dependent on the arrangement of other chromosomes. • This results in **genetic variation in the** daughter cells formed.

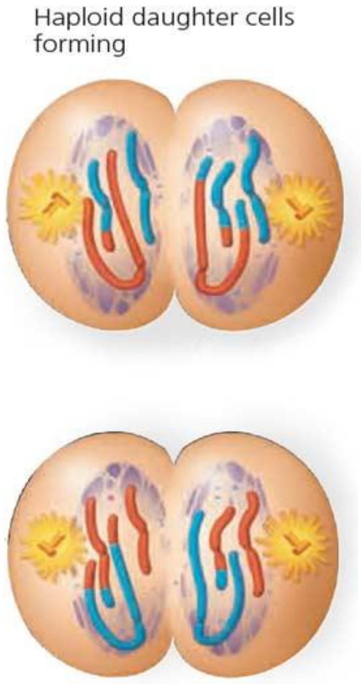
ANAPHASE II

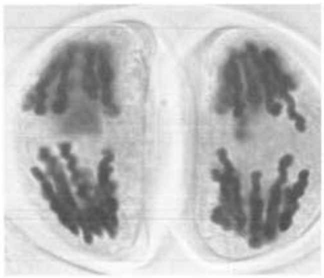


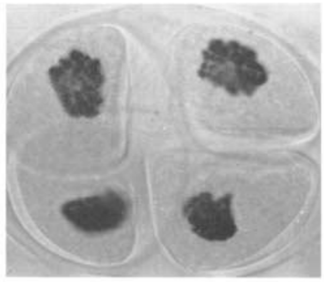


Description	Rationale
• The **centromere-to-pole spindle fibres shorten**.	• Tension is created in the spindle fibres and enough force is produced to **divide the centromeres** of the duplicated chromosomes.
• At the same time, the **pole-to-pole microtubules lengthen**, pushing the poles apart.	• This causes the poles of the meiotic spindle to move further apart.
• **Centromeres** of each duplicated chromosome **divide**.	• This ensures that the chromatids are divided **equally** between two daughter cells.
• The genetically different **non-identical sister chromatids separate** and are **pulled by the spindle fibres to opposite poles**, at the centromeres.	• The daughter nuclei produced after this nuclear division are **genetically different** as the **non-identical sister chromatids** are divided equally between the potential daughter cells. • If crossing over occurs at prophase I, the duplicated chromosomes separate and **non-identical sister chromatids** are **pulled to the opposite poles** at anaphase II

TELOPHASE II







Mass of DNA per nucleus: *x/2 picograms of DNA*
Ploidy of each nucleus: haploid
Number of chromosomes: *n = 3 chromosomes*

Description	Rationale
• The **chromatids reach the respective poles** and become the **chromosomes** of daughter cells. • Upon **reaching the opposite poles of the spindle**, the **chromatids uncoil** and return to their original thread-like form (chromatin).	• The chromatids need to **uncoil** before cellular processes can take place.
• The **spindle fibres disintegrate**.	• Spindle fibres are no longer required.
• Both the **nuclear envelope** and the **nucleoli reform**.	• Recall the function of the nuclear envelope. • Recall the function of the nucleolus.
• At the end of meiosis II, the parental nucleus has divided to give rise to **four genetically different daughter nuclei**. Each daughter nucleus has a **haploid** number of chromosomes.	• Meiosis results in **genetic variation** in sexually reproducing organisms as the gametes contain combinations of alleles different from that in the parental cells. • Meiosis reduces the ploidy so that the **diploid condition will be restored after fertilisation**. • Meiosis II halves the original mass of DNA of the parental cell so that the mass of DNA will be restored after fertilisation.

SUMMARY OF MEIOSIS

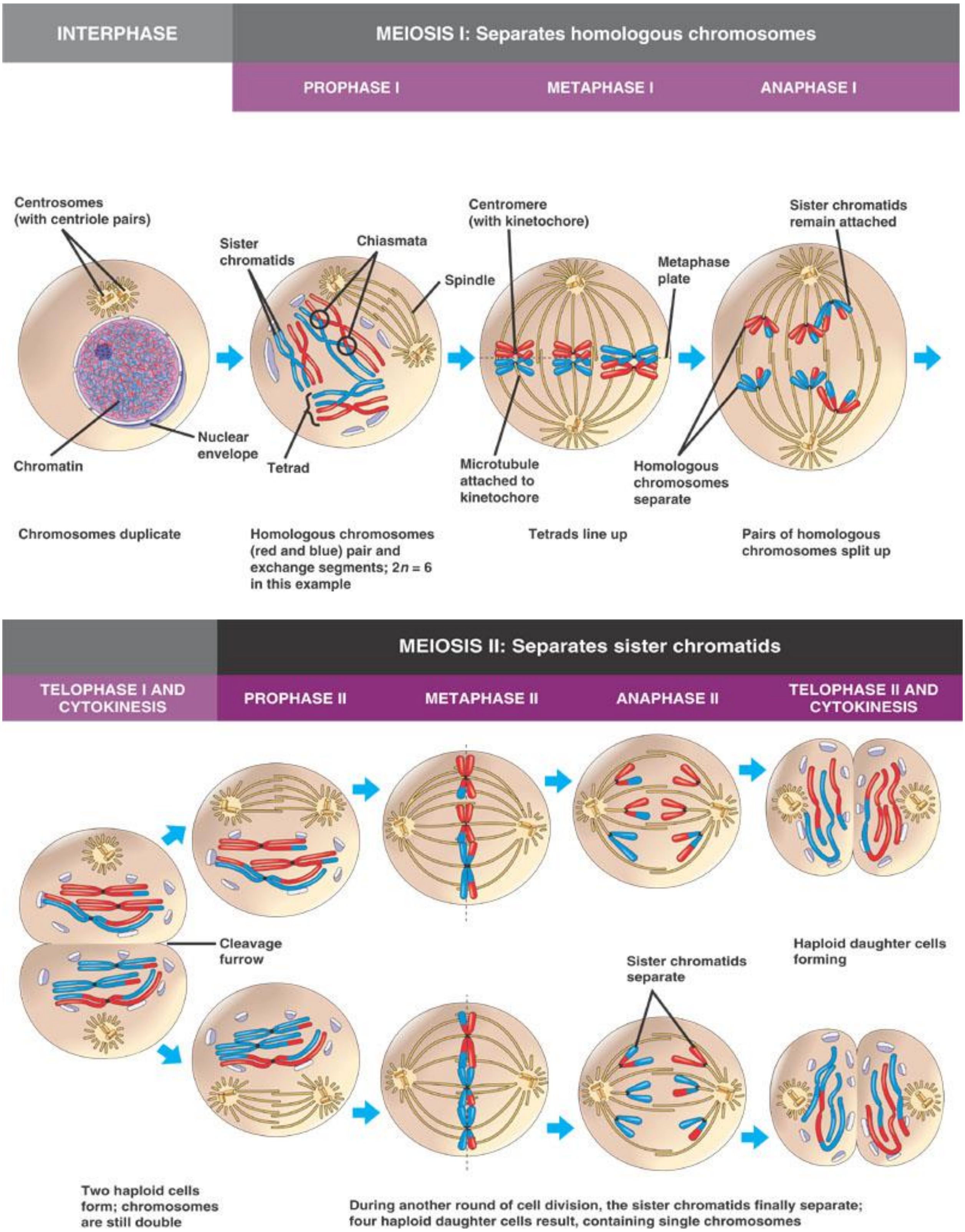


Fig. 7.3: Summary of meiosis

View the following animations to reinforce your learning on MEIOSIS:

1. https://www.youtube.com/watch?v=uck1etJgh34	2. http://www.sumanasinc.com/webcontent/animations/content/meiosis.html

7.2 Significance of Meiosis

- Meiosis results in the production of **haploid gametes** (sperm and ovum) as a result of the **separation of homologous chromosomes during anaphase I**.
    - During **fertilisation**, the **fusion** of male and female nuclei, causes the cell / zygote to **return to its diploid state** (Fig. 7.1 and 7.4).
    - If meiosis did not occur, there would be a doubling in the number of sets of chromosomes in each successive generation (a condition known as **polyploidy**).
- Meiosis results in **genetic variation** which is essential for **natural selection** and **evolution.**
    - Genetic variation produces **variation in the expressed traits** (phenotype) to ensure that the **species as a whole can constantly adapt when environmental conditions change**.
    - Genetic variation allows **natural selection** to operate, where only **individuals best suited to the existing environmental conditions survive** to reproductive age and produce offspring.

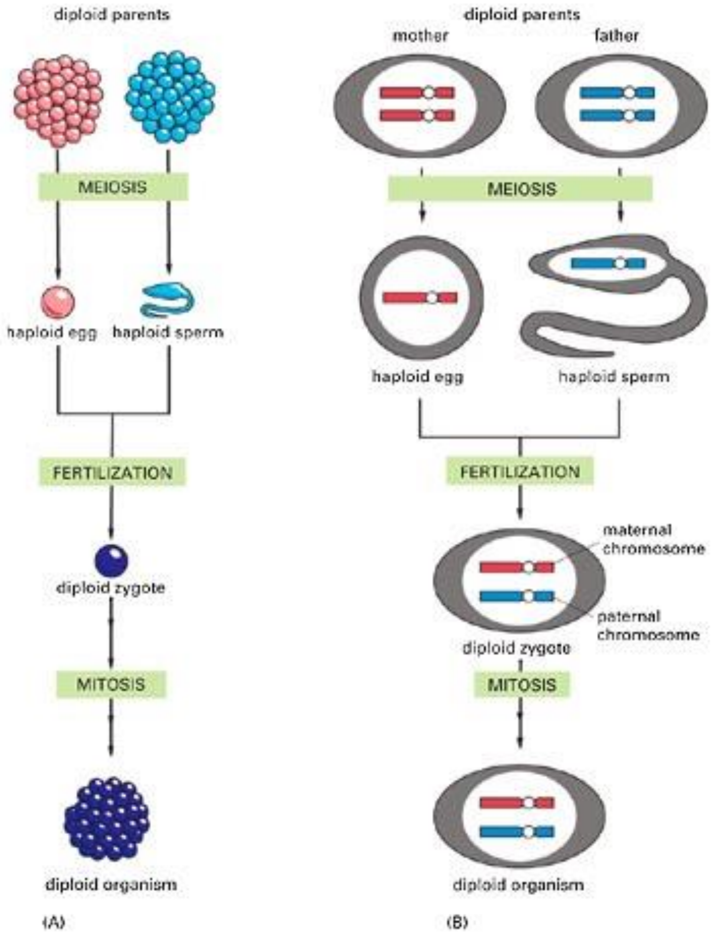


Fig. 7.4: Fusion of two haploid gametes restores the diploid state of the organism

- Refer to lecture notes on "Biological Evolution" in JC2 for detailed explanation on genetic variation and natural selection.

7.3 How Meiosis gives rise to Genetic Variation

a) Crossing over in Prophase I (during Meiosis)

- In prophase I, **non-sister chromatids of homologous chromosomes** align themselves alongside one another, and form chiasma.

- During **crossing over**, **new combinations of alleles** on the chromosomes of the gametes are formed (Fig. 7.5).

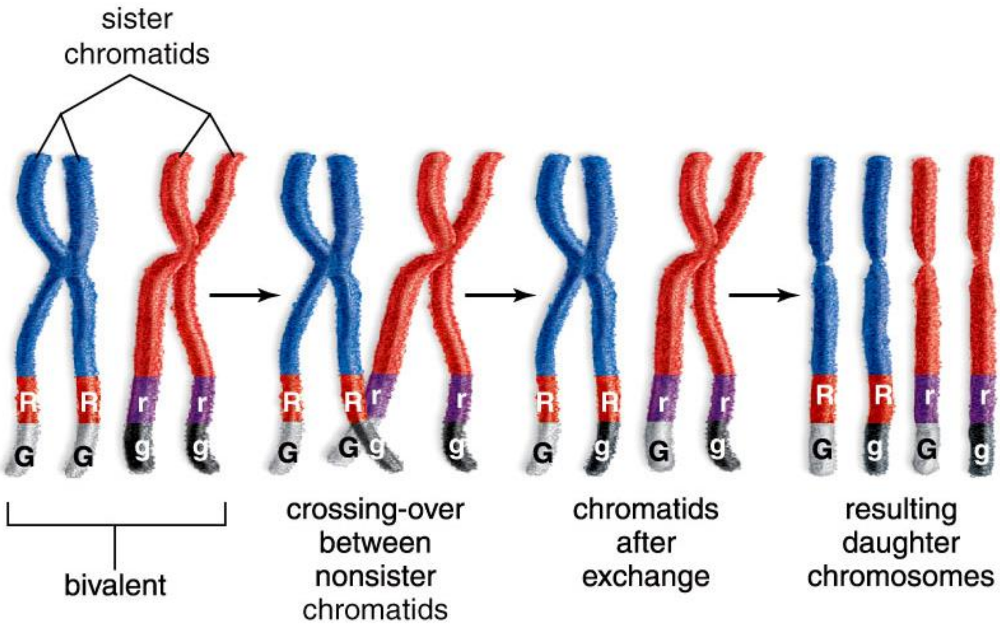


Fig. 7.5: Crossing over between non-sister chromatids of homologous chromosomes results in non-identical sister chromatids with new combinations of alleles.

b) (Mendel's Law of) **Independent Assortment and Segregation** (during Meiosis)

- During **metaphase I** and **anaphase I** respectively, the **arrangement** and subsequent **separation** of the **homologous chromosomes** of each bivalent is **independent** of the orientation of the other bivalents (Fig. 7.6).

- During metaphase II and **anaphase II** respectively, the **arrangement** and subsequent **separation** of the **non-identical sister chromatids** of each chromosome is **independent** of the orientation of the other chromosomes (Fig. 7.7).

- Independent assortment and segregation produces **new combinations** of **chromosomes** in **gametes**.

c) Random fusion of gametes (during Fertilization)

- This source of variation is **not directly caused** by the process of meiosis.

- The **random fusion** of **gametes** produced by meiosis results in even more possible **combinations** of chromosomes formed in zygotes after fertilisation.

- A human with 23 homologous pairs can potentially produce of 2^{23} = 8,388,608 combinations of chromosomes (Formula = 2^n) in their gametes, where *n* represents the number of chromosomes in one haploid set (i.e. one human egg cell contains 23 chromosomes).

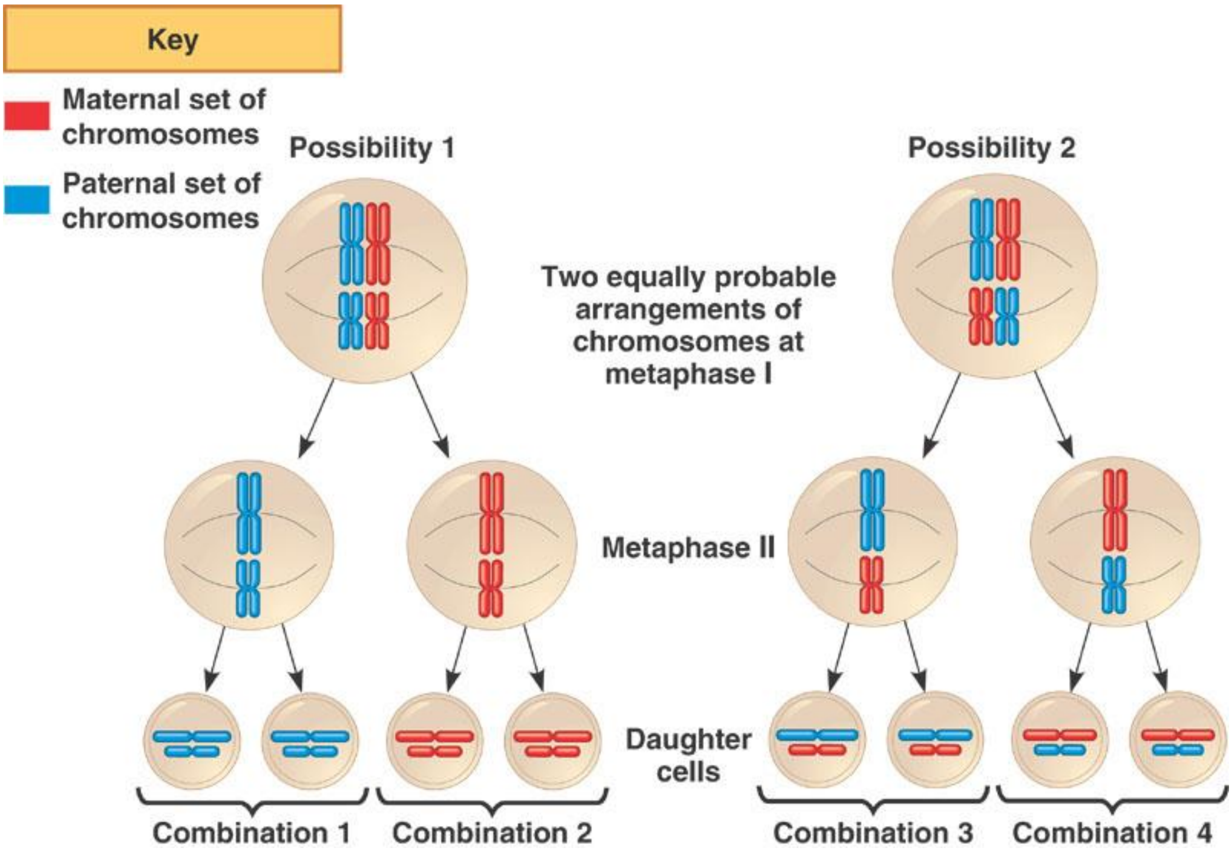


Fig. 7.6: Independent assortment of homologous chromosomes during metaphase I.

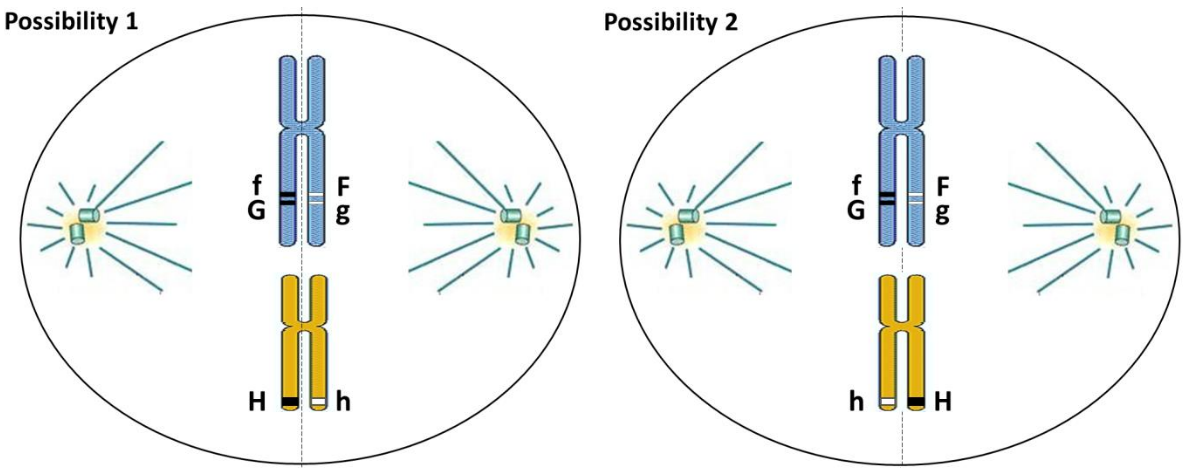


Fig. 7.7: Independent assortment of non-identical sister chromatids during metaphase II. Note how the chromosome below can easily flip laterally to allow the H allele to end up on the right side of the cell instead.

8. Comparisons

8.1 Differences between Cell Division in Animal and Plant cells

Animal Cell	Plant Cell
Centrioles are involved in the formation of spindle fibres.	Centrioles are not involved in nuclear division in **higher plants**.
Cytoplasmic division involves furrowing of plasma membrane and cleavage of cytoplasm.	Cytoplasmic division involves the formation of a **cell plate** derived from Golgi vesicles.
Occurs in tissues throughout the body.	Occurs mainly in the **meristems** (regions where active cell division occurs).

8.2 Differences between Mitosis and Meiosis

Feature	Mitosis	Meiosis
In what kind of cells does it occur?	Occurs in ________________ in all parts of the body.	Occurs in only ___________________ present in the **gonads**.
How many nuclear divisions are there? When do they occur?	**DNA replicates** _________ during the ______ of Interphase and **nucleus divides** _______.	**DNA replicates** ______ during ____________ _______________ but there are ___________ **successive nuclear divisions**.
How do the homologous chromosomes behave during prophase?	Pairs of homologous chromosomes _____________ ____________ during prophase.	Pairs of homologous chromosomes associate to form _____________ during ____________ via **synapsis**.
Are chiasmata formed? Elaborate	**Chiasmata** are **never formed**.	**Chiasmata** between ___________________ may form during ___________________.
Does crossing over occur? Always occur?	**Crossing over NEVER occurs**.	**Crossing over** may occur during _______________________.
How do the homologous chromosomes behave during metaphase?	**Pairs of homologous chromosomes** form a **single row** at the equator of the spindle during ________________.	**Pairs of homologous chromosomes** form _________________ at the equator of the spindle during ___________________.
What are being separated during anaphase?	_________________________ move to opposite poles of the spindle during **anaphase**	________________________________ move to opposite poles of the spindle during **anaphase I**. __________________________ _______________________ move to opposite poles of the spindle during **anaphase II**.
What is the number of chromosome of the daughter cells?	Daughter cells have the **same number of chromosomes** as the parent cell.	Daughter cells have only ________ **the number of chromosomes** found in the parent cell.
Are the daughter cells genetically identical to the parent cell? Explain.	In the absence of mutation, daughter cells are **genetically** _________________ to the parent cell.	Daughter cells are **genetically** ____________ from parental cells due to independent assortment of _________________ _____________ during metaphase I and independent assortment of ______________ ___________________ during metaphase II.
How many daughter cells are formed? What are they known as? What is their ploidy?	__________________ **daughter cells** are formed.	__________________________ **daughter cells** are formed. E.g. In male humans - four sperm cells are formed. In female humans - one ovum and three polar bodies are formed.
What is its role in the organism's body?	Enables **multicellular** adult organism to arise from the _______________	Produces _____________________. Reduces number of chromosome by half so that after _________________, **diploid state** can be **restored**.
	Produces cells for **growth**, **repair** and in some species, **asexual reproduction**.	Introduces ____________________________ in the gametes formed.

Checklist for Cell Cycle:

Are you able to confidently answer all?

1. List the phases of the cell cycle and describe the sequence of events that occurs during each phase.

2. Describe the major events of cell division that enable the genome of one cell to be passed on to two daughter cells.

3. Compare cytokinesis in animals and in plants.

4. Describe the behaviour of centrioles and spindle fibres (microtubules) during each phase of mitosis.

5. Describe the roles of checkpoints in the cell cycle control system.

6. Explain how haploid and diploid cells differ from each other. State which cells in the human body are diploid and which are haploid.