Reproduction in Crop Plants

By Deborah Muenchrath, Arden Campbell, Laura Merrick, Thomas Lübberstedt, Shui-Zhang Fei (ISU)

Introduction

Most agronomic and horticultural crop species are **angiosperms**. Angiosperms are vascular plants that produce their seeds enclosed in a matured ovary, a fruit; the fruit arises from a flower. In contrast, some tree crops—such as pine or spruce—are **gymnosperms**, which are vascular plants possessing "naked seeds" that are not enclosed within fruit structures. There are two groups of angiosperms: **monocots** and **dicots**. Although all angiosperms have some reproductive features in common, species vary in their mode of reproduction. A species' reproductive mode is fundamental to the methods applied to develop improved cultivars.

Fig. 0 Pollen grains on a Hippeastrum flower. Photo by Krucku, licensed under CC BY-SA 3.0 via Wikimedia Commons.

Objectives

- Review hereditary mechanisms and flower anatomy.
- Understand the sexual reproduction processes of pollination, fertilization, and seed development.
- Become familiar with asexual reproduction.
- Comprehend the implications of reproductive mode for crop breeding strategies.

Hereditary Mechanisms

Heredity, Genotypes, and Phenotypes

Plant breeders take advantage of the mechanisms of **heredity** to develop and maintain cultivars. The observable characteristics and performance of cultivar (of a plant), its **phenotype**, is the result of the cultivar's **genotype**, as influenced by the environment. In other words, phenotype is a function of both genotype and environment, plus the interaction between genotype and environment.

$$P = G + E + (G \times E)$$

where:

$P =$ Phenotype;

$G =$ Genotype;

$E =$ Environment

Equation 0

Fundamental to effective and efficient plant breeding is an understanding of the hereditary mechanisms that affect genotype:

- Nuclear division and chromosomes
- Modes of reproduction

Deoxyribonucleic Acid (DNA) And Chromosomes

Every cell nucleus contains the genetic material of the cell, **deoxyribonucleic acid (DNA)**, located in **chromosomes**. Each chromosome is a single DNA molecule. Associated with the DNA are special proteins called histones (see the round yellow shapes in Fig. 0 around which the DNA is wound like "beads on a string" along the chromosome) that are related to the organization of the DNA, as well as enzymes involved in replication of the DNA strand. In plant cells, DNA and associated genetic information are mainly located in nuclear chromosomes.

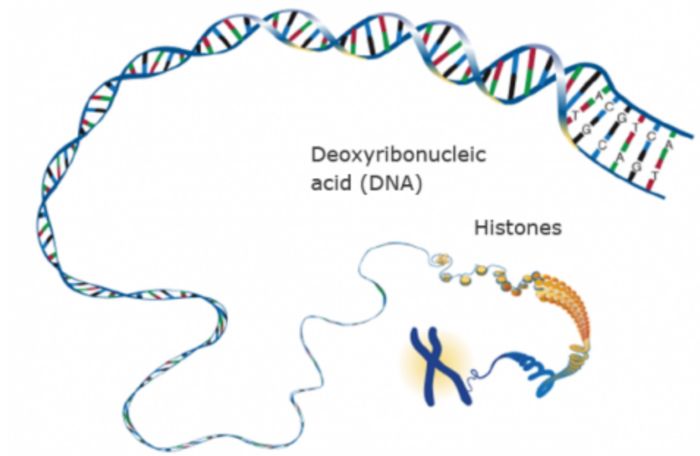


Fig. 0 Nuclear DNA wound around histone proteins that provide structural support to the chromosome. Illustration by NIH-NHGRI.

However, some additional DNA and genetic information is located in **specialized cell structures** that are "extra-nuclear," meaning found outside of the cell nucleus.

Chromosomes And Genomes

A **genome** is the basic set of chromosomes inherited as a unit from one parent. **Somatic cells** (non-germ cells) of **diploid** species contain two sets (2n) of the basic genome (**haploid**) (1n) number of chromosomes. Among species, the number of chromosomes varies. Within a species, the chromosome number (2n in somatic cells and 1n in **germ cells**) is ordinarily constant. However, **crop species** include both diploids and **polyploids**, which are plants with more than two sets of chromosomes in their cells.

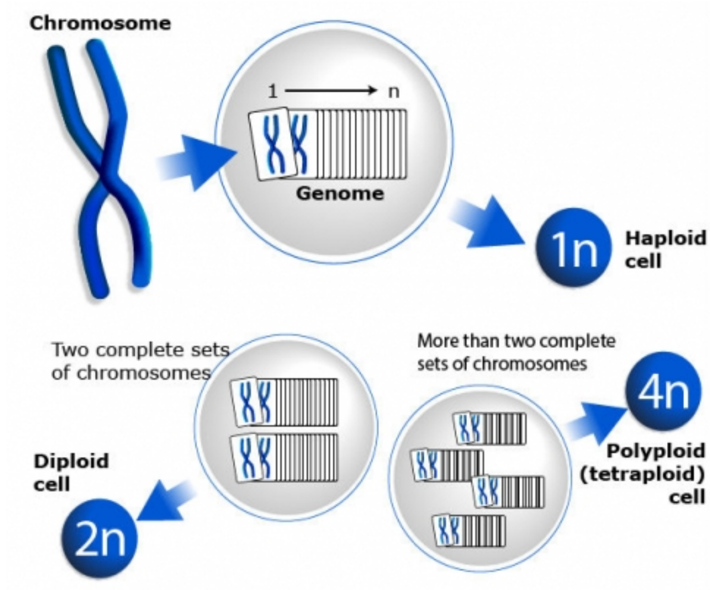


Fig. 0 A complete set of chromosomes forms a genome. Complete genomes are contained in haploid, diploid and polyploid cells.

Crop Chromosome Number

Crop species include a wide range of chromosome numbers. The genomic formula of crop species (with 2n representing the somatic chromosome number, n, the haploid number, and x, the basic chromosome number) can reveal whether or not the crop is a polyploid. For example, vanilla, coconut, pecans, alfalfa, leek, and sour cherry all have the same number of chromosomes, but the first three are diploids (2n=2x=32), and the last three are polyploids (2n=4x=32). Polyploids can be classified as either **autopolyploids** (see crop examples labeled as "auto" in the table where their status is known) or **allopolyploids** ("allo" in the table). Autopolyploids are polyploids with multiple chromosome sets derived from a single species, whereas allopolyploids are polyploids with genomes derived from different species.

Fig. 0 Crops and their genomic formulas. Photos by Rillke and Alex Popovkin, licensed under CC-SA 3.0 via Wikimedia Commons

Click each of the items below to see additional information.

Mitosis and Meiosis

Introduction

Mitosis is one phase of the **cell cycle**. Mitosis is divided into four arbitrary stages. Progress between stages, however, is gradual and continuous.

During cell division, DNA is duplicated and distributed to daughter nuclei. The number of chromosomes in the daughter nuclei depends on the process of nuclear division. There are two nuclear division processes by which new cells are formed.

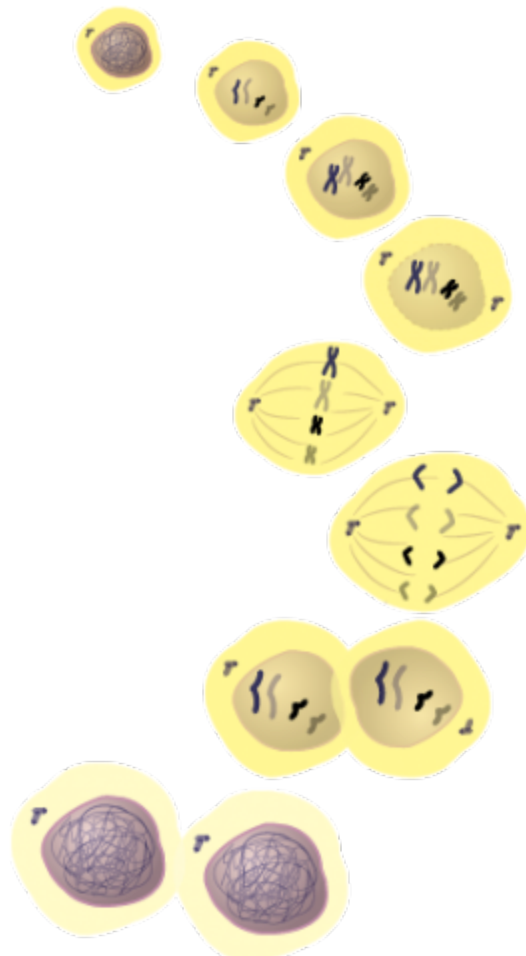


Fig. 0 An encapsulated view of stages in mitosis. Illustration by NIH-NHGRI.

Mitosis

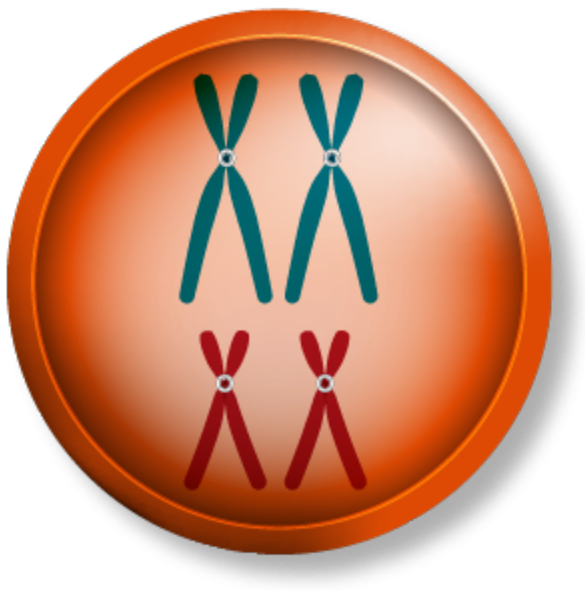


Fig. 0 An illustration of a diploid nucleus with two sets of chromosomes.

Let's follow mitosis, the process by which somatic cells, that is, non-germ cells, are reproduced. We'll begin with interphase of the cell cycle.

This illustration represents a diploid, or 2n, somatic nucleus. It has two sets of chromosomes, shown here as a blue set and a red set.

Each chromosome is duplicated at the end of interphase during the synthesis period of the cell cycle that precedes mitosis.

Mitosis is a process of nuclear division. It has four stages.

- Prophase
- Metaphase
- Anaphase
- Telophase

Let's see what happens during each of these stages.

Meiosis

Overview

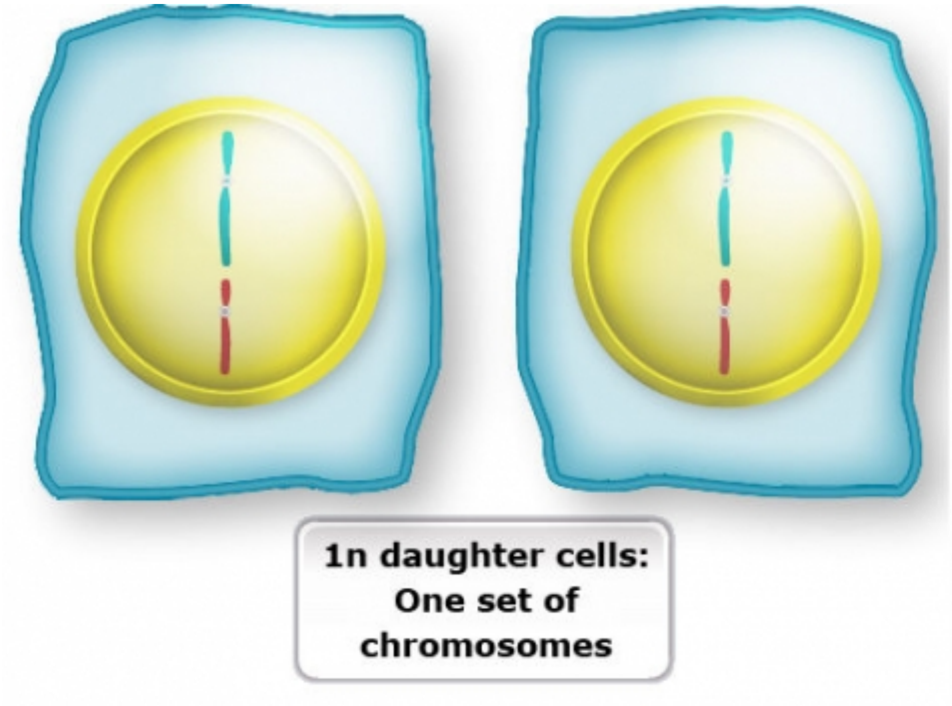


Fig. 0

In contrast to mitosis, meiosis is the process through which germ cells, that is, microspores and megaspores, are derived. Meiosis is similar to mitosis except in two important aspects.

- Meiosis involves two successive divisions.
- Homologous chromosomes replicate only once during the two divisions. Thus, the diploid microspore and mega spore mother cells are meiotically reduced to the haploid, or 1n, chromosome number of the gametes.

In meiosis, there are two successive divisions, called meiosis I and meiosis II. Each of these is divided into four phases analogous to those of mitosis. Like mitosis, these stages progress in a gradual and continuous manner.

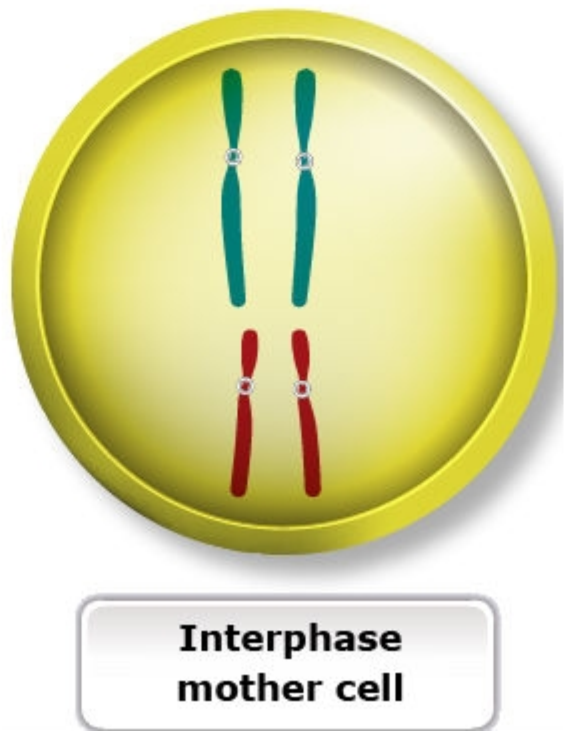


Fig. 0

Similarities to Mitosis

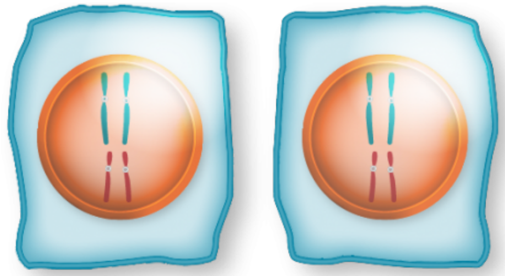
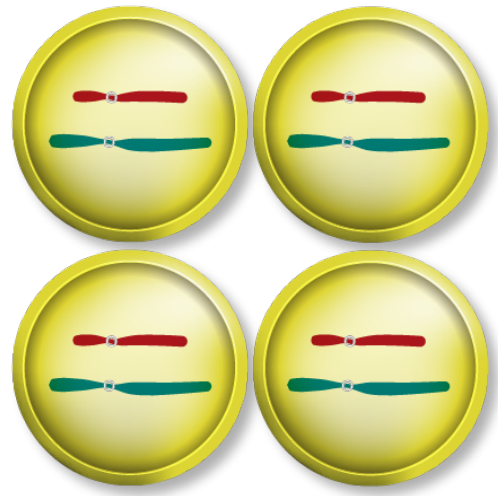
Meiosis I resembles mitosis in that:

- The division results in the production of two daughter cells
- Cells are derived from a microspore or megaspore mother cell

- Replication of homologous chromosomes precedes it

Review

Now review these two processes: mitosis and meiosis. Again, pay attention to commonalities and differences. You should be able to identify key features of each process and stage.

	 **Mitosis**	 **Daughter cells formed by meiosis.** **Meiosis**
Divisions	Equational division	One equational division, one reductional division
Results in	Two 2n daughter cells	Four 1n daughter cells
Stages	Four: • Prophase • Metaphase • Anaphase • Telophase	Eight or nine: • Prophase I • Metaphase I • Anaphase I • Telophase I • Interkinesis (sometimes) • Prophase II • Metaphase II • Anaphase II • Telophase II

Study Question 1

Identify the cell division process that best fits each statement by dragging the label to the box next to it.

Study Question 2

Barley has a diploid chromosome number of 14. Identify the number of chromosomes in various cell or tissue types.

Sexual Reproduction

Sexual Reproduction

Reproduction enables the propagation of new individuals. Reproduction in crop species may occur sexually, asexually, or both.

- **Sexual reproduction**: Requires the fusion of egg and sperm cells (known as **gametes**) to obtain the next generation. The life cycle of a typical angiosperm involves sexual reproduction based on the process of meiosis, in which the chromosome number of cells in the female and male reproductive organs is reduced by half to form female and male gametes. Meiosis is the process responsible for the genetic segregation observed in progeny of **heterozygous** individuals.
- **Asexual reproduction**: Propagation occurs without the fusion of male and female gametes. Asexual reproduction is based on the multiplication of cells by mitosis and results in two new cells that are genetically identical to each other and to the cell from which they originated.

Fig. 0 Reproduction enables new plants to sprout. Photo by Iowa State University.

Synopsis of the Life Cycle of the Angiosperm Plant

In the animal kingdom, the production of gametes follows immediately after the meiotic divisions. Normally, therefore, the **gametes** are the only haploid (1n) representatives of the animal life cycle. In plants, however, almost invariably (and without exception in higher plants) the immediate products of the meiotic divisions are not gametes but **spores**. The higher plants (angiosperms) we recognize, e.g., the oak tree, turfgrass, clover, wheat, are the diploid (2n) or **sporophytic** stage of the plant's life cycle. In these plants the haploid vegetative or **gametophytic** stage is short-lived and quite inconspicuous. The sporophyte produces spores as a result of sporogenesis or meiosis. Spores undergo a few nuclear divisions in a process known as gametogenesis to form mature gametophytes. Gametes develop within the gametophytes.

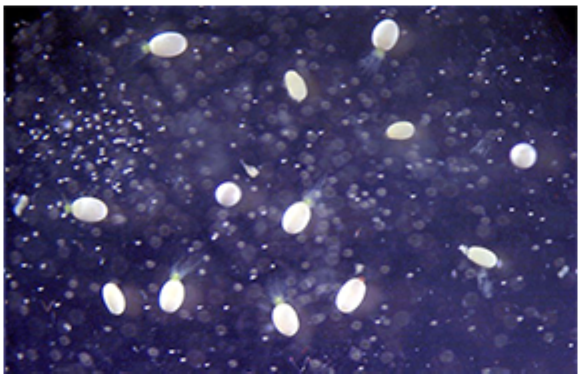


Fig. 0 Microspores and megaspores of Marsilea. Photo by Curtis Clark, licensed under CC-SA 3.0 via Wikimedia Commons.

All higher plants produce two types of spores, **microspores** and **megaspores**. Corresponding to these two types of spores are the two different modes of their development, microgametogenesis and megagametogenesis, which culminate respectively in two dissimilar and relatively simple plants, the mature microgametophytes and megagametophytes.

Male Spore Formation

Microsporogenesis

Each of many 2n microsporocytes (pollen mother cells) within the anther undergoes meiosis with the result that four haploid (1n) microspores are produced within the anther for each original microsporocyte.

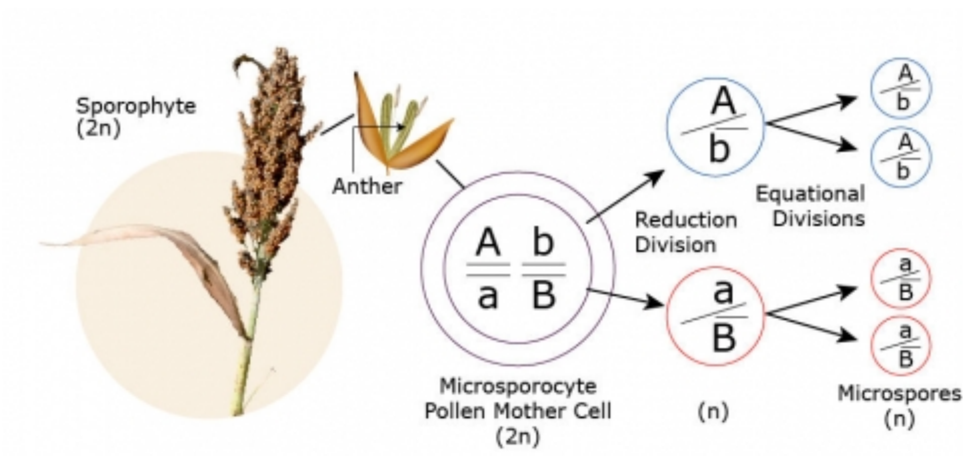


Fig. 0 Microsporogenesis process. Photo by Iowa State University

Microgametogenesis

The single nucleus of each microspore divides once by mitosis and one of the two daughter nuclei draws about itself a mass of deeply staining cytoplasm. This nucleus is known as the generative nucleus while the other is the tube nucleus. The generative nucleus undergoes a single mitotic division to form two male gametes, or sperm cells. (In some plants this division does not occur until pollination has taken place and the generative nucleus is moving through the pollen tube.) This constitutes a pollen grain or a mature microgametophyte.

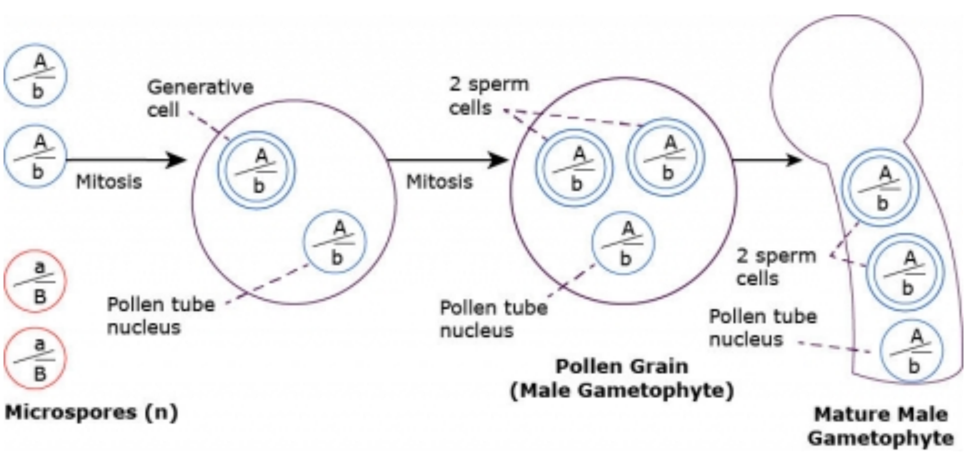


Fig. 0 Microgametogenesis process.

Female Spore and Gamete Formation

Megasporogenesis

A 2n megasporocyte (megaspore mother cell) in each ovule undergoes meiosis. Four megaspores result, each with a haploid chromosome number. Three of these disintegrate; the fourth develops into the mature female gametophyte.

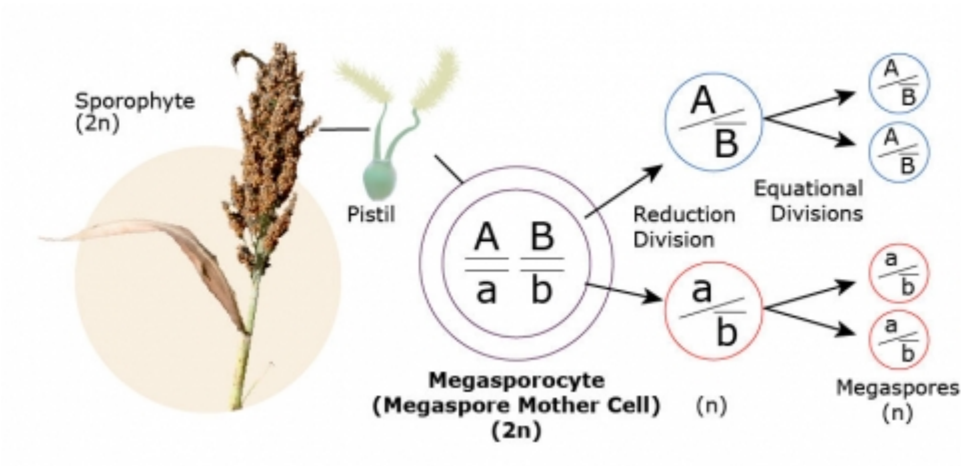


Fig. 0 Megasporogenesis process. Photo by Iowa State University.

Megagametogenesis (development of the female gametophytes and gametes)

The surviving megaspore enlarges greatly to form the embryo sac. Three successive mitotic divisions, starting with the original nucleus of this megaspore, produce eight haploid daughter nuclei within the embryo sac. These orient themselves as follows: the two polar nuclei lie together in the middle of the sac; three nuclei are located at the end of the sac where the sperm will enter, the center one becoming the female gamete or egg, and the two flanking ones the synergids; the remaining three, the antipodal cells, come to lie at the opposite end of the sac. The number of antipodal cells, however varies greatly from zero in Oenothera species to more than 100 in some grass species. The embryo sac with the eight haploid nuclei thus arranged is the mature megagametophyte the female gamete or egg, and the two flanking ones the synergids; the remaining three, the antipodal cells, come to lie at the opposite end of the sac. The number of antipodal cells, however varies greatly from zero in Oenothera species to more than 100 in some grass species. The embryo sac with the eight haploid nuclei thus arranged is the mature megagametophyte.

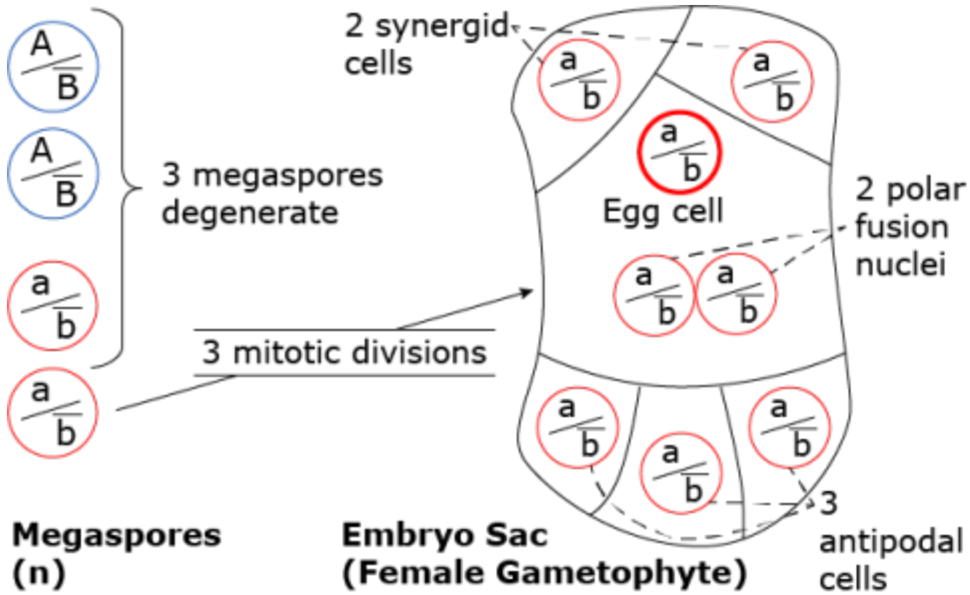


Fig. 0 Megagametogenesis process.

Double Fertilization

Pollen grains are freed by opening of the anther wall and are carried to the stigma of the same or other plants. Each pollen grain soon sends out a small thin pollen tube (generated by the tube nucleus) which penetrates the tissues of the stigma and digests its way through these and the stylar tissues down to one of the ovules. The sperm cells pass down the pollen tube behind the tube nucleus. Once the pollen tube reaches the ovule it penetrates the embryo sac, the tube nucleus disintegrates, and the two sperm cells enter. One of the sperms fuses with the haploid egg to produce the 2n zygote, while the other fuses with the two polar nuclei to give a 3n (triploid) product, the endosperm nucleus.

Further Development

The triploid endosperm tissue grows more rapidly than the embryo at first. Later on, the embryo, which develops from the zygote, grows at the expense of the endosperm. Depending on the species, endosperm tissue may or may not persist at the time the seed has completed growth. With the resumption of growth (seed germination) the embryo continues development until it reaches the mature sporophyte stage, at which time microspores and megaspores are again produced.

Study Question 3

What single factor distinguishes sexual reproduction from asexual types of reproduction?

Enter your answer here.

Show Answer

Reflection

The **Module Reflection** appears as the last "task" in each module. The purpose of the Reflection is to enhance your learning and information retention. The questions are designed to help you reflect on the module and obtain instructor feedback on your learning. Submit your answers to the following questions to your instructor.

1. In your own words, write a short summary (< 150 words) for this module.
2. What is the most valuable concept that you learned from the module? Why is this concept valuable to you?
3. What concepts in the module are still unclear/the least clear to you?

References

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For Your Information

Endomitosis

Interphase occurs between meiosis II and endomitosis. Chromosomes replicate during interphase. Endomitosis is a process of cell division resulting in the production of the pollen grains. Endomitosis is also divided into phases. Figures 23 through 36 show these phases, as well as the gradually increasing accumulation of starch granules in the cell. The starch grains progressively obscure the visibility or resolvability of the cellular structures of the male gametophyte.

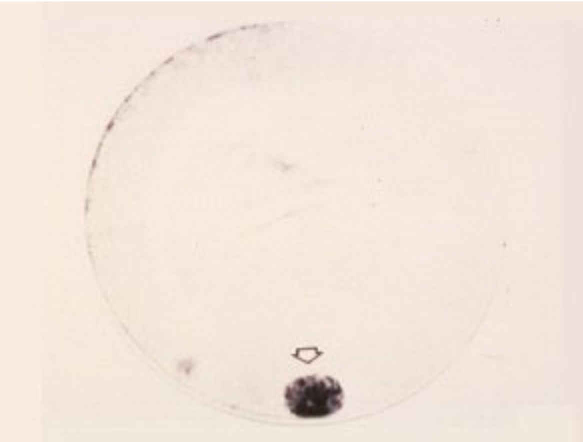


Fig. 0 Interphase. The cell nucleus is round, condensed and nondifferentiated . Chromosomes replicate during this period.

Fig. 0 First Prophase. The chromosomes condense into short thick threads surrounding the nucleolus.

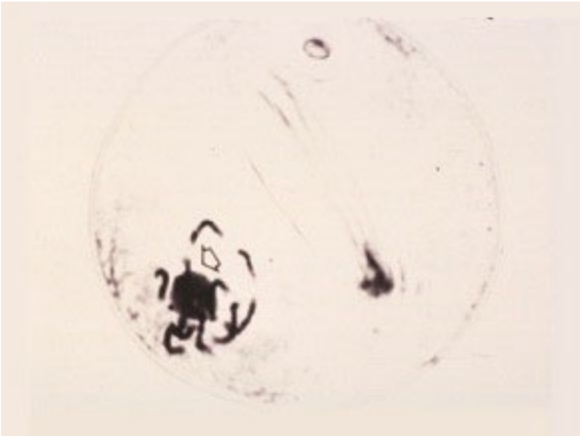


Fig. 0 Middle First Prophase. The chromosomes continue to condense into short thick threads which allow identification of individual chromosomes. The nucleolus and the nucleolus-organizing region of chromosome six are visible.

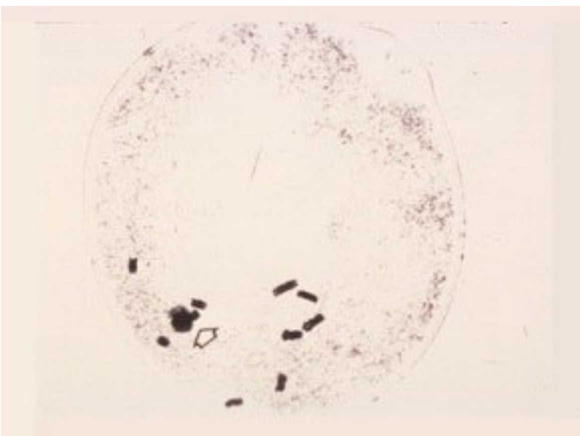


Fig. 0 Late First-Prophase. The chromosomes further condense to become short thick rods. The nucleolus and the nucleolus-organizing regions with chromosome six are clearly seen.

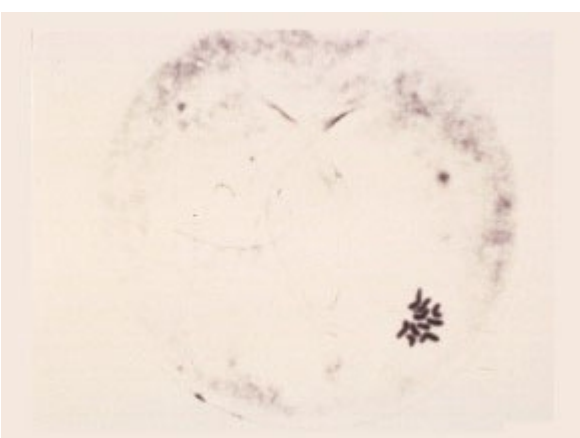


Fig. 0 First Metaphase. The nucleolus disappears and the ten chromosomes are arranged in one plane close to one another.

Fig. 0 First Anaphase. The sister chromatids are now separated and moving towards the opposite poles.

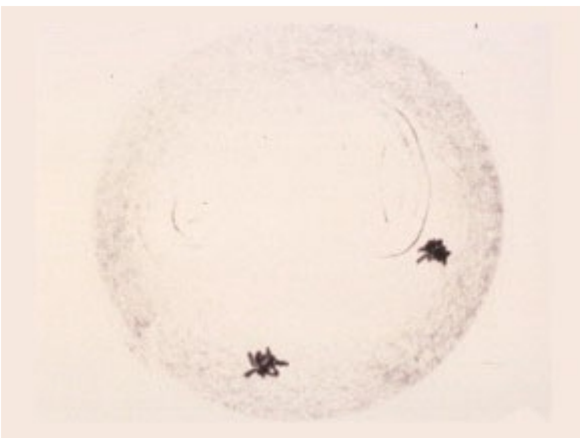


Fig. 0 Late First Anaphase. The separated chromosomes have reached the opposite poles and formed two chromosome clusters.

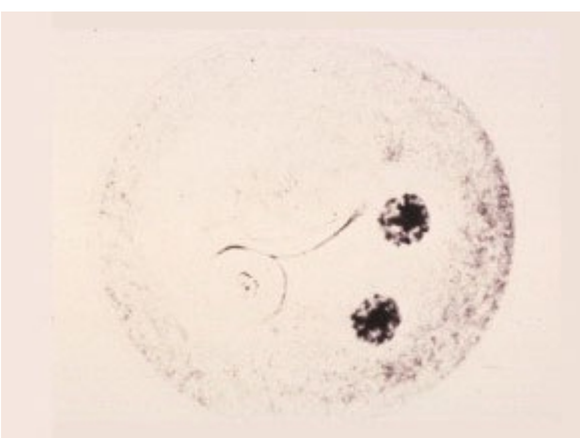


Fig. 0 First Telophase. The chromosomes at each pole are now extended and surround the nucleolus.

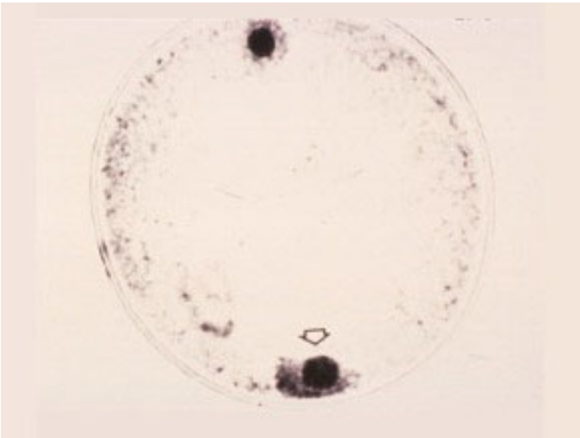


Fig. 0 Binucleate. Two nuclei are formed at the opposite poles. The generative nucleus (bottom) is usually located near the germ pole. It will further divide to form two sperm.

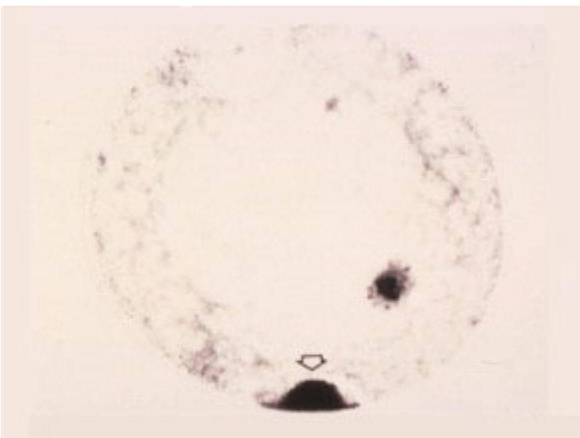


Fig. 0 Second Prophase. The generative nucleus underneath the surface of the intine wall becomes cup-shaped and will proceed to the second nuclear division. The vegetative nucleus is not at resting stage and appears to continue its metabolic activities.

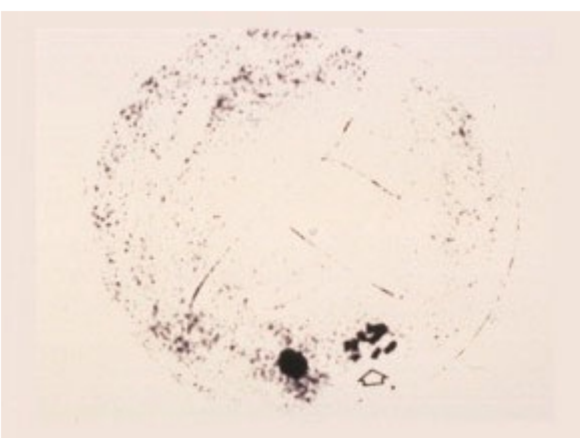


Fig. 0 Second Metaphase. The nucleolus disappears, the ten chromosomes are arranged in one single plane. The vegetative nucleus is dark-stained.

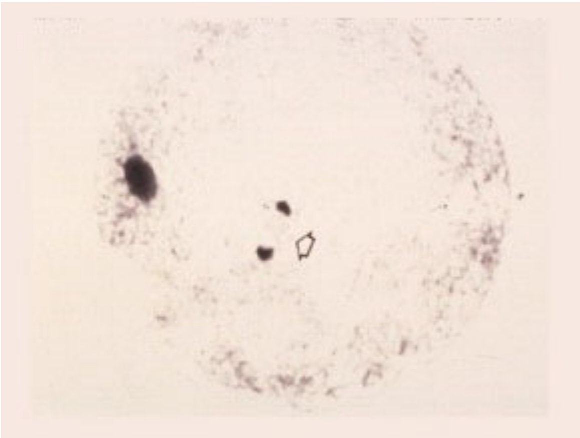


Fig. 0 Second Anaphase. The sister chromatids are now separated and moving towards the opposite poles . The vegetative nucleus remains large and clear.

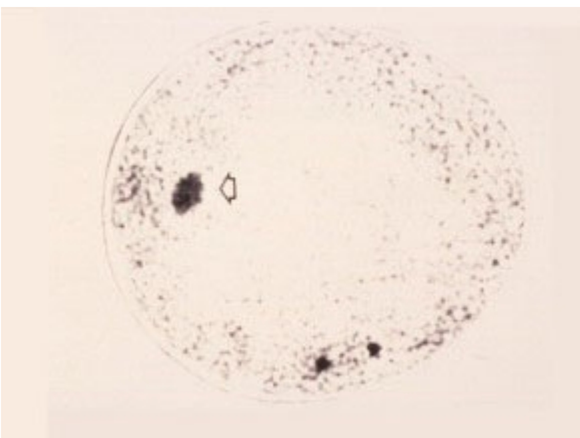


Fig. 0 Second Telophase. The chromosomes at each pole are now extended and surround the nucleolus. The vegetative nucleus remains large and clear.

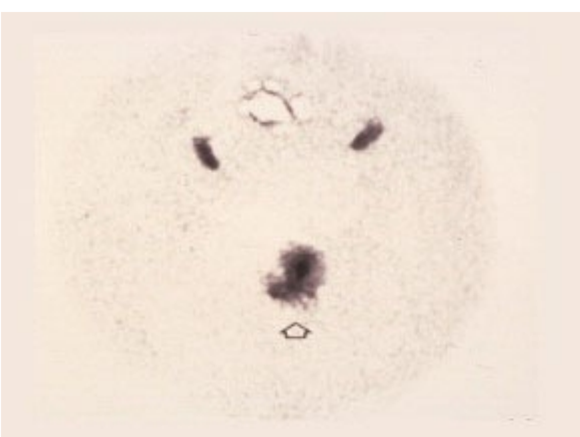


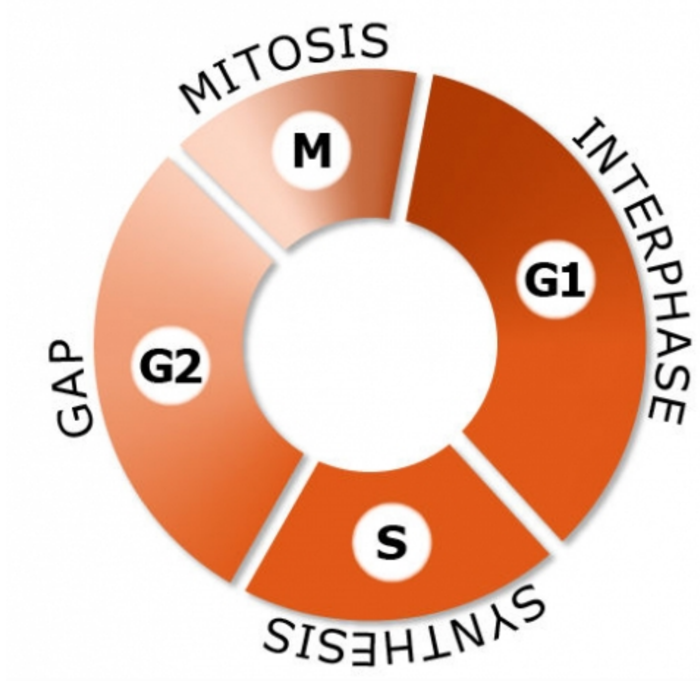
Fig. 0 Mature Pollen. The mature pollen grain now has three nuclei. The top two condensed, crescent-shaped nuclei, surrounding the germ pore are the sperms. The large one at the bottom is the vegetative nucleus.

Nuclear vs. Organellar DNA

Although by far the main portion of DNA and genetic information is located on nuclear chromosomes, additional DNA (and genetic information) is located in two types of organelles in plant cells: plastids and mitochondria. Each plant cell usually contains multiple plastids and mitochondria, which contain multiple copies of circular DNA each. Different from the inheritance of nuclear DNA, organellar DNA is maternally inherited in most plant species and not undergoing meiosis.

Mitochondrial DNA is the small circular chromosome found inside mitochondria, a type of organelle found in cells, and that are the sites of energy production.Illustration by NIH-NHGRI.

Cell Cycle



- **G2-Gap** This period occurs after DNA replication is complete, but before mitosis begins.
- **S-Synthesis** DNA replication occurs. This phase can be identified because it is the only phase during which the cell can incorporate radioactive thymidine into nuclear DNA. (Thymidine is related to one of the purine bases of DNA, thymine.)
- **G1-Interphase** Occurs after the completion of mitosis and precedes DNA replication.
- **M-Mitosis** The nucleus divides, distributing a complete set of chromosomes to each daughter nucleus. The cell subsequently undergoes cytokinesis, cytoplasmic division, completing the formation of the two daughter cells; each repeats a new cell cycle. Of the cell cycle phases, mitosis is the shortest, typically lasting only 1 to 3 hours.

Microsporogenesis

Microsporogenesis is the process by which male gametes (pollen grains) are formed. This process can be divided into three parts: 1. Meiosis I 2. Meiosis II 3. Endomitosis Each of these is subdivided into several stages. The stages of microsporogenesis are transitory. The sequence of stages is shown in the following photos (from Chang and Neuffer, 1989). Each photo represents a momentary expression, which may not be a good representation of the complete event. The event in each photo is indicated by an arrow.

Meiosis I

Meiosis I is a reductional division-the number of chromosomes in the nucleus is reduced to the haploid number. Meiosis I has four phases: prophase I, metaphase I, anaphase I, and telophase I.

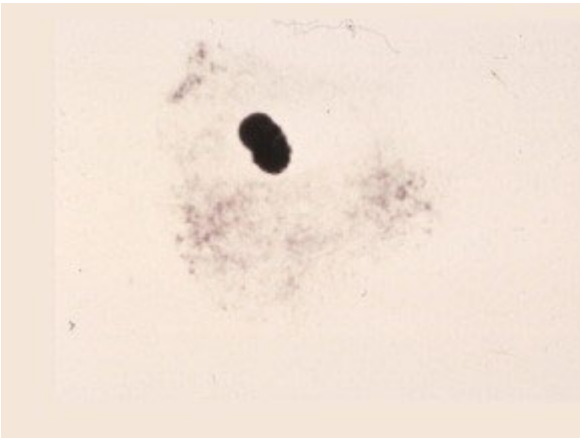


Fig. 0 Premeiotic Interphase. The irregularly shaped pollen mother cell has dense protoplasm, no vacuoles, no clear cell wall structure and an undifferentiated nucleus.

Prophase I

Prophase I is the longest phase of Meiosis I. During Prophase I, the nuclear membrane breaks down, the chromosomes contract, and the spindle forms. Prophase I has several substages: lepotene, zyotene, pachytene, diplotene, and diakinesis.

Fig. 0 Leptotene. Cell becomes round with dense protoplasm. The chromatin threads are greatly extended and coiled around the nucleolus. Synapsis is initiated. Single and double strand configuration is evident. The chromomeres are visible.

Fig. 0 Late Zygotene-Early Pachytene. The pairing of the homologous chromosomes is complete. The condensed chromosomes show details of hetero-chromatin and knobs. The nucleolus and nucleolar-organizing region of chromosome six are visible.

Fig. 0 Pachytene. The paired chromosomes are further condensed to become a very thick thread. Individual chromosomes can be identified by their relative lengths, distinctive chromomere patterns, position of knobs, and other recognizable characteristics. The nucleolar-organizing region of chromosome six is clearly attached to the nucleolus.

Fig. 0 The chromosomes continue to condense into short, thick threads. The paired chromosomes appear to be repulsing

one another, except regions where an actual crossover took place. The chiasmata are frequently seen as X-shaped and looped chromosome configurations.

Fig. 0 Late Diplotene. The chiasmata are terminalized and the very short condensed chromosome pairs are separated from each other. The X-shaped and looped chromosome configurations are still shown. The nucleolar- organizing region of chromosome six is firmly attached to the nucleolus.

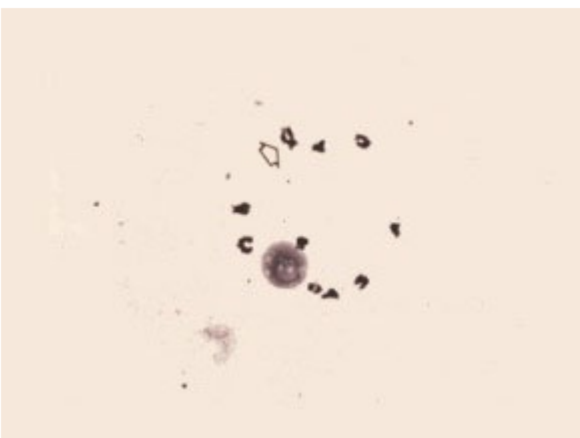


Fig. 0 Diakinesis. The condensed chromosome pairs are separated from each other. The chiasmata , the X-shaped and looped configurations are still seen.

Metaphase I

During metaphase I, chromosomes migrate to the spindle equator.

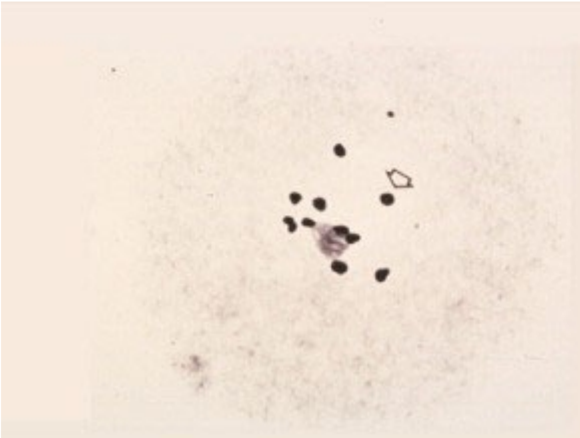


Fig. 0 Late Diakinesis. The chromosome pairs are dark, round bodies and the nucleolus starts to disappear.

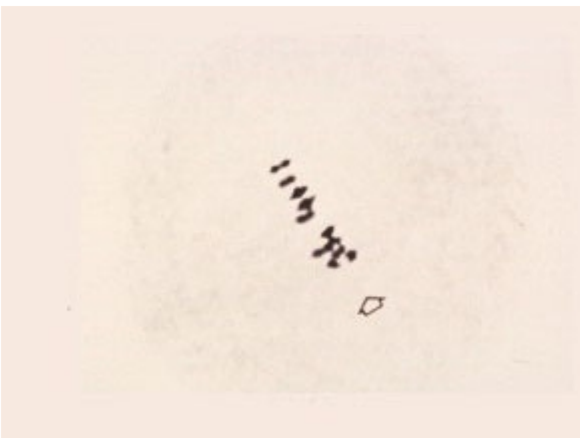


Fig. 0 Metaphase I (side view). The nucleolus has disappeared. The paired chromosomes lie at the equatorial plate of the spindle structure. The chiasmata have moved to the ends of the paired chromosome.

Fig. 0 Metaphase I (polar view). The paired chromosomes appear as dense bodies scattered on a single plane of the protoplast.

Anaphase I

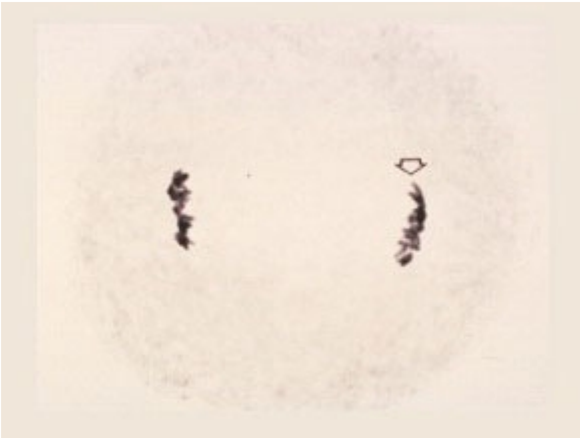


Fig. 0 Anaphase I. The paired chromosomes separate and move toward the opposite poles. The V-shaped configuration of the chromosome is due to movement of the centromere ahead of the arms. The number of chromosomes at each pole is now reduced to half the number possessed by the microspore mother cell.

Telophase I

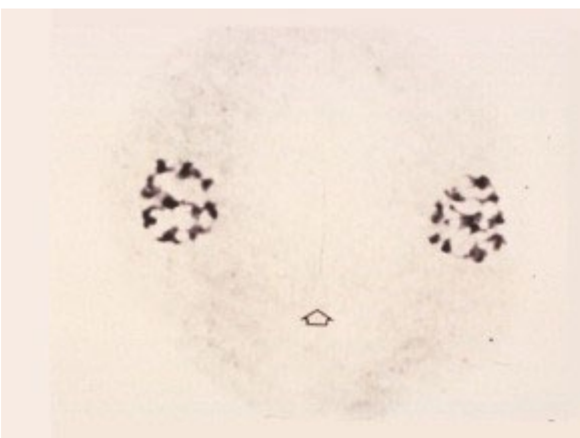


Fig. 0 Telophase I. The chromosomes at each pole are now extended. The nucleolus reappears and the cytoplasm divides (cytokinesis) to form two half-mooned cells.

Meiosis II

Meiosis II is an equational division during which sister chromatids separate and are distributed to daughter nuclei. Thus, each nucleus receives the haploid number of chromosomes. Meiosis II is divided into four phases: prophase II, metaphase II, anaphase II, and telophase II. These phases are analogous to the four phases of Meiosis I.

Prophase II

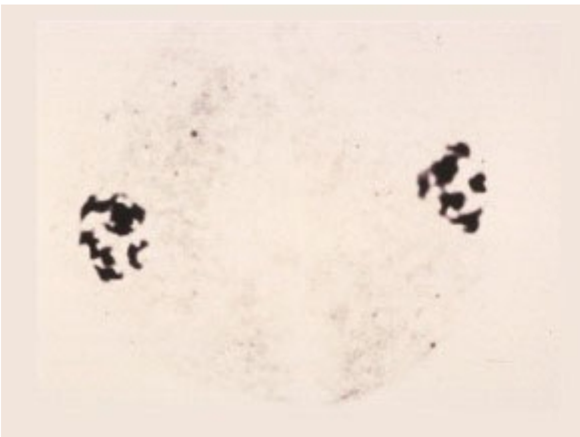


Fig. 0 The chromosomes condense into short thick threads surrounding the small nucleolus.

Metaphase II

Fig. 0 Metaphase II. The chromosomes (each chromosome has two sister chromatids) lie at the equatorial plate of the spindle structure. Nucleoli have again disappeared.

Anaphase II

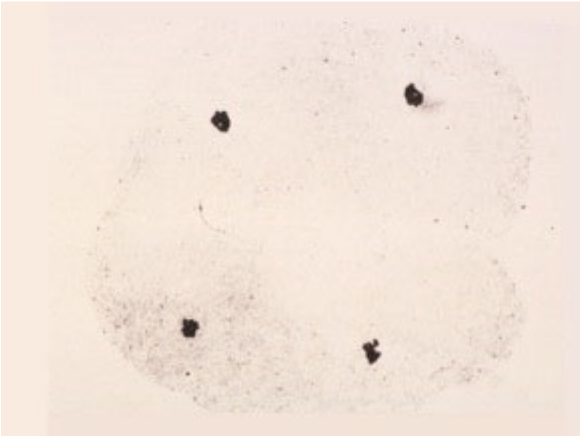


Fig. 0 Anaphase II. The two sister chromatids seen collectively as a dark staining mass, are now separated and have moved towards the opposite poles.

Telophase II

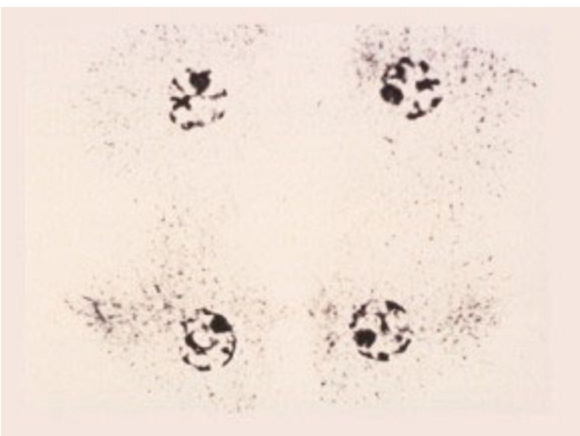


Fig. 0 Telophase II. The chromosomes at each pole are extended, the nucleoli reappear and the cytoplasm divides to form four cone-shaped cells.

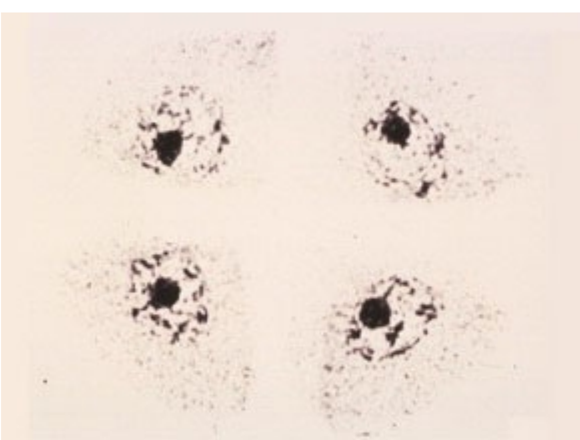


Fig. 0 Four cone-shaped microspores are formed and are enclosed inside the maternal wall, which is being digested and

will thus release the four microspores.

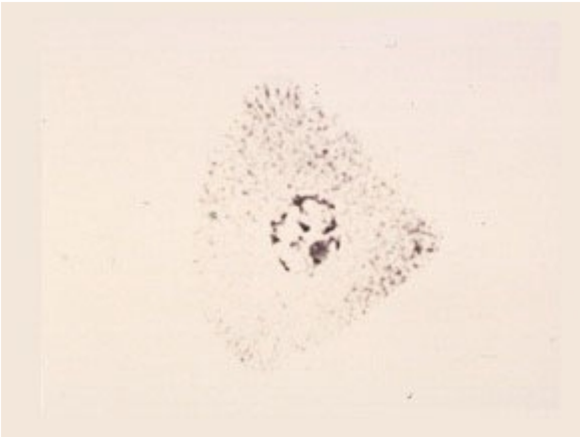


Fig. 0 Free Cell from Quartet. The newly released free microspores are undifferentiated, cone-shaped, and appear to have no distinct cell walls.

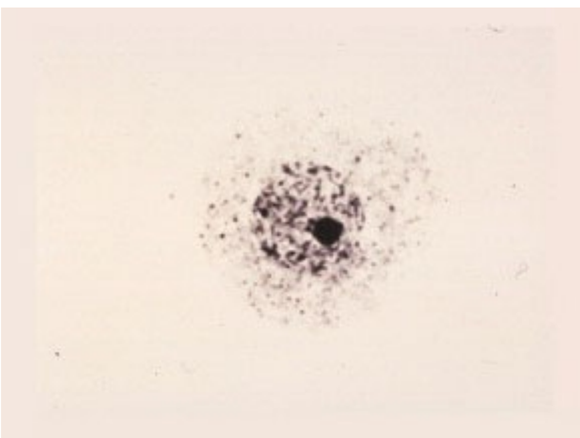


Fig. 0 Early Uninucleate Cell. The shape of the microspores are round with dense cytoplasm. The nucleus is located near the center and the cells are undifferentiated with no vacuoles and no clear wall structure.

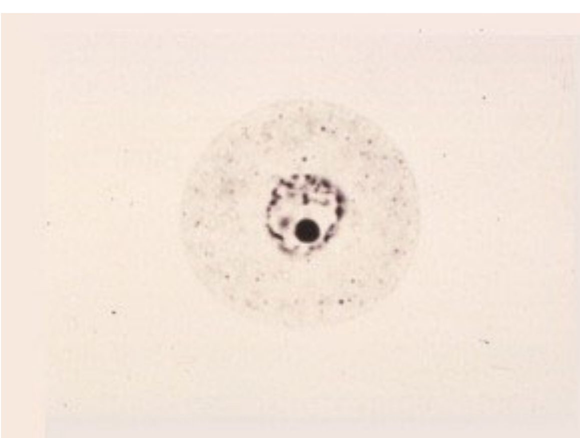


Fig. 0 Late Early-Uninucleate Cell. The microspores start to differentiate. The exine and intine structures are being

formed. The cytoplasm remains dense, but many small vacuoles are being formed. The nucleus is still near the center of the protoplast.

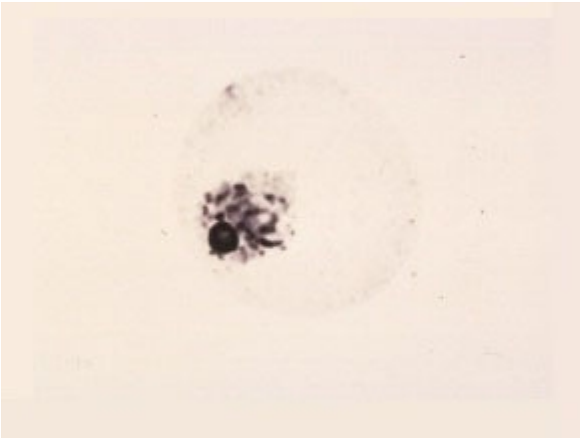


Fig. 0 Middle Uninucleate Cell. A large vacuole is forming in the protoplast, pushing the nucleus to one side.

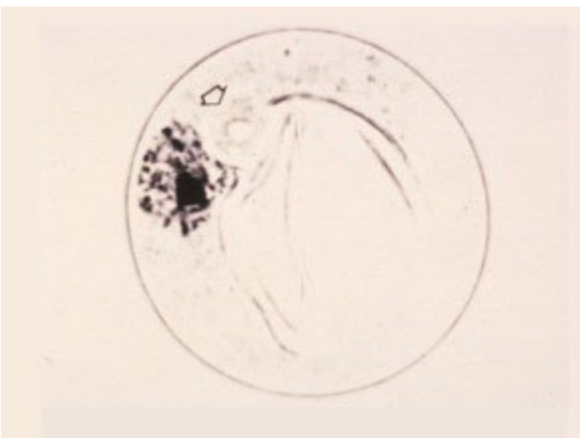


Fig. 0 Late Uninucleate Cell. The differentiation of exine and intine, germ pore and annulus are complete. Creases seen are due to pressure of coverslip on rigid spherical pollen wall. Cell volume increases four to six times.

Acknowledgements

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Crop Genetics Reproduction in Crop Plants Author: Deborah Muenchrath, Arden Campbell, Laura Merrick, Thomas Lübberstedt, and Shui-Zhang Fei (ISU)

Multimedia Developers: Gretchen Anderson, Todd Hartnell, and Andy Rohrback (ISU)

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