CELL AND ORGANISMAL REPRODUCTION

ASSUMED KNOWLEDGE

Before commencing this section, make sure that you understand:

- The distinction between prokaryote and eukaryote organisms
- The terms gene, chromosome, locus, allele

Most of you will have come across these in BIOL 110. They are also defined in the glossary at the back of your textbook.

LECTURE 1: THE CELL CYCLE AND MITOSIS

LECTURE SYNOPSIS

- Life arises only from life.
- Dividing cells pass through a regular sequence of five major phases: G_1, S, G_2, mitosis and cytokinesis.
- Cell division functions in reproduction, growth, and repair.
- The eukaryotic genome is organised into chromosomes in each cell.
- Mitosis, or nuclear division, in eukaryotic cells ensures that each new cell receives a full set of chromosomes identical to that in the parent cell.
- Mitosis alternates with interphase (G_1, S and G_2) in the cell cycle.
- Mitotic spindle distributes chromosomes to daughter cells. For each chromosome two chromatids form and separate.
- Cytokinesis divides the cytoplasm. The mechanism and/or timing of cytokinesis differ among animals, fungi, plants and protists.

LEARNING OBJECTIVES

By the end of this lecture you should be able to:

- Discuss why cell division occurs
- Outline the main stages of the cell cycle
- Explain how chromosomes are sorted and moved during mitosis

REQUIRED READING

Chapter 7, pages 158-166

KEY TERMS

Interphase	Prophase
Mitosis	Metaphase
Mitotic spindle	Anaphase
Cytokinesis	Telophase

LECTURE NOTES

Why do cells divide?

There are three common circumstances in which new cells genetically identical to the parent cell are required. These are:

- Reproduction of unicellular organisms. Each new cell is a new organism.
- Growth of multicellular organisms, all of which originate from a single cell.
- Renewal and repair of tissues, such as replacement of blood cells.

The new cells are formed by division of one cell into two daughter cells. This also requires duplication of the chromosomes, and their separation into two identical sets by the process of mitosis.

A different kind of cell division is needed in sexual reproduction, to halve the number of chromosomes in each cell. This involves the process of meiosis, and will be examined later in this section.

Cell division in prokaryotes and eukaryotes

Prokaryotes such as bacteria have a relatively simple cell structure, with a single circular DNA molecule. Prior to cell division this molecule is replicated, so that a copy can go to each daughter cell. The duplicate DNA molecules attach to the plasma membrane, and are pulled apart as the cell grows. The cell then divides into two, with one DNA molecule in each half. This process is called binary fission, and is illustrated on Knox page 158.

Eukaryotes, including animals, plants, fungi and protists are more complex organisms, with much bigger genomes. The amount of genetic information is too great to carry on one DNA molecule, so it is packaged in several pieces called **chromosomes**. Each chromosome consists of a single very long DNA molecule, in a complex with many proteins. A eukaryote cell will only function properly if it contains exactly the right number and type of chromosomes. Most of the processes that can be seen in cell division in eukaryotes are concerned with ensuring that the daughter cells receive the correct chromosomes.

All of the material presented below relates to cell division and reproduction in eukaryotes.

The cell cycle

In order to divide a cell must

- Grow to produce more cytoplasm and organelles
- Duplicate its chromosomes
- Arrange the chromosomes into two identical sets (mitosis)
- Form a new cell around each set of chromosomes (cytokinesis).

Together these processes make up the cell cycle. As you will have gathered from the reading, the most time-consuming part is growth and DNA replication, which take up about 90% of the duration of the cell cycle. Mitosis and cytokinesis are relatively rapid, typically taking an hour or two in actively dividing cells.

Interphase and DNA replication

Interphase (inter = between) is often thought of as a period of rest before and after the spectacular activity of mitosis and cytokinesis. However, at a biochemical level this is the period in which most of the work of cell division is done. The cell must more or less double in size during interphase. It must also replicate its genetic material so that a complete set can go to each daughter cell. You considered DNA replication in BIOL 110 - have a look at Knox p210 to refresh your memory.

DNA replication during the S phase of interphase results in the cell containing two identical copies of every chromosome. The two duplicate copies of each chromosome remain attached to each other, and are known as sister **chromatids**. This attachment is important because it makes the job of sorting the chromosomes during mitosis much simpler.

It is not possible to see the chromosomes with a light microscope during interphase. The reason for this has to do with the function of chromosomes - carrying the genetic information for the synthesis of proteins and RNA molecules. This information can only be read if the DNA molecule making up the chromosome is in its extended form, in which it is too fine to be resolved in the light microscope.

Mitosis - getting ready

Mitosis can be thought of as a process for sorting out the replicated DNA molecules (chromosomes) into two identical, complete sets, to ensure that each daughter cell receives a full set of genes. It is conceivable that this could be done while the DNA molecules are in their extended, working, form, but it would be a bit like trying to sort out a bowl of spaghetti with each strand hundreds of metres long. It is much easier to do if the chromosomes are packed into a more compact form. This happens in the first part of mitosis, known as **prophase**. Coiling and folding of the chromosomes makes them much shorter, but also much thicker, so that they become visible. This is the first sign that mitosis is commencing.

The other important process that happens during prophase is the formation of the **mitotic spindle**. The chromosomes cannot move by themselves, but are pulled through the cell by this spindle, consisting of fibres of special proteins. (The microtubules from which the spindle is made are also the basic structural units of the flagella of protists and sperm cells).

Separating the chromosomes

Events during mitosis are really a continuous process. As you study this section, try to concentrate on what is happening to the chromosomes, rather than beginning with the names of the phases.

Once the chromosomes have condensed, they must attach to the spindle fibres. In particular, each chromatid in a pair of sister chromatids must attach to a fibre coming from opposite poles of the spindle. This attachment of chromosomes to spindle fibres occurs during the stage known as **prometaphase**.

The separation of sister chromatids and movement to opposite poles of the spindle now occurs synchronously, so that all of the chromatids arrive at their destination together and none get 'left behind' when the cell actually divides. First the chromosomes are lined up along a starting line across the middle of the cell. This very distinctive arrangement of the chromosomes is called **metaphase**. When the chromosomes are ready, lined up with each sister chromatid attached to a spindle fibre from opposite poles of the spindle, the chromatids are quickly drawn apart. The two sets of chromatids moving to the spindle poles with their arms trailing behind them form another distinctive arrangement known as **anaphase**.

Splitting the cell

By the end of anaphase, the work of mitosis is basically done. There is a complete set of chromosomes in each end of the cell. However, the chromosomes are still in their condensed form, and in plants and animals there are still no proper nuclei. All of the preparations for mitosis must now be reversed. In the last recognisable stage of mitosis, known as **telophase**, the chromosomes uncoil into their extended working form, the spindle is dismantled and the daughter nuclei form.

The actual division of the cell, or **cytokinesis**, typically occurs at the same time as telophase and it is easy to get the two confused! Mitosis and cytokinesis can in some ways be thought of as interruptions to the real business of being a cell - most normal cellular processes and activities have to be put on hold during division. Most cells waste no time and start to split as soon as the chromosomes are separated in late anaphase.

The way in which cytokinesis occurs depends very much on the structure of the cell. Animal cells, which lack rigid walls, can be just pinched in two. The membranes on either side are pulled together, resulting in the appearance of a cleavage furrow. Obviously the same mechanism would not work in a cell with a rigid cell wall, so plants do it somewhat differently. A structure called the cell plate forms between the daughter nuclei, and this develops into a new wall that divides the daughter cells.

Variations on a theme

The basics of the cell cycle - interphase with DNA replication, mitosis, and cytokinesis, and the movement of chromosomes during mitosis, are common to all eukaryotes. These are the things that it is important for you to learn. Some of the peripheral details that you see in the textbook are more variable, reflecting the enormous diversity of life. For example, plant cells lack centrioles; the nuclear membrane remains intact during mitosis in fungi; and in many organisms mitosis can occur without cytokinesis, resulting in cells with more than one nucleus. Try not to get confused at this stage by these other aspects of cell division.

ACTIVITIES

1. As a means of reinforcing your knowledge of the cell cycle, complete the following table.

What happens to each component?	Phase of the Cell Cycle		
	Interphase	Mitosis	Cytokinesis
• Cell size			
• Chromosomes			
• Nuclei			
• Number of cells			

2. Prepare a simple sketch and write a brief description of what is happening in each of the following stages of mitosis:

- Prophase
- Metaphase
- Anaphase
- Telophase

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LECTURE 2: SEXUAL AND ASEXUAL REPRODUCTION

LECTURE SYNOPSIS

- Prokaryotes such as bacteria reproduce by binary fission.
- In unicellular eukaryotic organisms each cell division generates new organisms. In multicellular eukaryotic organisms the life cycle begins as a single cell (zygote), which divides repeatedly.
- Offspring acquire genes from parents by inheriting chromosomes.
- Trade-offs exist between sexual and asexual reproduction.
- Asexual reproduction involves a single individual parent that produces identical offspring with a complete and identical genome.
  - Low cost of reproduction is offset by absence of genetic variation.
  - Methods and occurrence of asexual reproduction vary across organisms.
- Sexual reproduction
  - Fertilisation and meiosis alternate in life cycle.
  - Fertilisation (syngamy) in plants, animals and some algae involves fusion of two, genetically different, haploid gametes and results in a diploid zygote.
  - The zygote in plants, animals and some algae develops into a diploid organism.
  - Various other sequences of events occur across fungi and many protists.

LEARNING OBJECTIVES

By the end of this lecture you should be able to:

- Explain the difference between asexual and sexual reproduction
- Appreciate the roles of each type of reproduction in the life cycle of an organism
- Discuss the advantages and disadvantages of each type of reproduction

REQUIRED READING

Chapter 18, pages 401-403

KEY TERMS

Haploid	Gamete
Diploid	Zygote
Meiosis	Fertilisation

LECTURE NOTES

The concept of ploidy

Before progressing with a discussion of sexual and asexual reproduction, it is essential to ensure that you understand what is meant by the terms haploid and diploid. This is perhaps easiest to understand in terms of human genetics.

Each of our body cells contains 46 chromosomes. These can be sorted into 23 pairs. The two members of each pair are called **homologous** chromosomes. With the exception of the sex (X and Y) chromosomes, the two members of each homologous pair are the same shape and size, and have genes coding for the same characters at the same positions (loci) along their length. The homologous chromosomes are not identical because they may have different alleles at the same locus - one may code for blue eye colour and one for green, etc. This should be familiar to you from your study of genetics in BIOL 110. For present purposes, the key concept is that each human body cell contains a pair of each type of chromosome.

Organisms with paired chromosomes like this are said to be **diploid**. Another way of looking at it is to say that diploid cells contain two sets of chromosomes (2n). Organisms or cells with only one of each type of chromosome are said to be **haploid**. In humans, sperm and egg cells are haploid and contain only 23 chromosomes - one of each type normally present in human cells. The mention of eggs and sperm should alert you to the fact that the story of sex is all about alternations between haploid and diploid cells.

As an aside, the ploidy, or number of sets of chromosomes, in organisms can differ greatly. For example, although most animals are diploid, in the Hymenoptera (wasps, bees and ants) males are haploid and females diploid. Bananas are triploid (3n) which makes sexual reproduction impossible and is one of the reasons they do not have seeds. Wheat is hexaploid, and contains the chromosomes from three different diploid ancestors added together.

What is asexual reproduction?

Asexual reproduction is reproduction that results in offspring that are genetically identical to the parent organism. Asexual reproduction is very common in unicellular eukaryotes. For example, every time a mitotic cell division occurs in *Paramecium* or *Amoeba* (or any other unicellular organism) two genetically identical daughter organisms are produced.

Asexual reproduction may also occur in many multicellular eukaryotes. There are many ways in which this can be done, but we will look at three common methods.

In **budding** a new individual grows out of the body of a parent. The textbook example is budding in *Hydra* where the daughter polyp buds out of the body wall of the parent. The same basic principle is very common in plants. For example garlic reproduces by forming new bulbs that branch from the base of the plant - these are the familiar garlic cloves used in cooking. This type of asexual reproduction is exploited commercially in production of strawberry runners and propagation of plants by tissue culture, among others.

Spores are produced by many organisms, most conspicuously by fungi. Spores are reproductive cells that can develop directly into a new individual, without the need for fertilisation. The rapid spread of many plant diseases is due to the massive production of asexual spores by the fungi that cause them.

Parthenogenesis is development from an unfertilised egg. It is one of a number of forms of asexual reproduction that result from alterations to normal sexual processes such that genetic exchange does not take place. These are common in plants. However, many animals such as some aphids and nematodes, and even a few lizards, can also reproduce by parthenogenesis.

The pros and cons of asexual reproduction

Asexual reproduction has a number of advantages. It is usually rapid, so that offspring can be produced in a shorter time than by sexual reproduction. The processes involved at the cellular and tissue level are simpler, so less energy and resources are required. And of course, it is not necessary to find a mate. Asexual reproduction is therefore very common in relatively simple organisms that need to increase their populations rapidly in order to exploit new opportunities. For example, when an aphid locates a suitable plant, the population can be built up very quickly by parthenogenesis.

The major disadvantage is a consequence of the lack of genetic variation between parents and offspring. Populations in which all reproduction is asexual have a limited ability to adapt to changing circumstances. For this reason very few eukaryotes rely on asexual reproduction alone, and most are capable of reproducing sexually as well.

Sexual reproduction

In sexual reproduction, the offspring combine genes from two parents. Each offspring can therefore have a new and different combination of genes. Sexual reproduction only occurs in eukaryotes. Some prokaryotes have mechanisms for exchanging genes between individuals, and these are very important in biotechnology, but bacteria do not have sex.

At the core of sexual reproduction are two processes that change the ploidy of cells from diploid to haploid and back again. First is **meiosis**, a modified version of normal cell division that produces haploid daughter cells from a diploid parent cell. We will consider the mechanism of meiosis in the next section. For the time being, remember that meiosis halves the number of chromosomes in the cell. The second process is **fertilisation**, in which two haploid cells combine to produce a diploid cell called a **zygote**. In animals and plants the zygote develops into a new individual by mitotic cell divisions.

A moments reflection will show why it is necessary to have this halving and doubling of chromosome number. As was mentioned before, cells and organisms must have the right number and type of chromosomes. In a reproductive system that combines genes from two parents, the simplest way to ensure a balanced chromosome number is to take equal numbers of chromosomes from each parent. If all of the chromosomes from one parent were added to those of the other parent, the total chromosome number would double in each generation and rapidly become too great. Therefore the chromosome number is halved, usually from diploid to haploid, before cells from the two parents fuse.

Gametes and fertilisation

The haploid cells that fuse to form a zygote are called **gametes**. In humans, the gametes are the direct result of meiotic divisions of diploid cells in the ovary and testis. Human gametes are called sperm and ova (eggs). As you are probably aware, ova are very much larger than sperm, which basically contain only a haploid nucleus and the machinery essential to propel the nucleus to an ovum. Most of the cytoplasm in the zygote comes from the ovum, with some interesting consequences. For example, all of the mitochondria in our bodies are inherited from our mothers. The situation where the gametes are different in size is called **anisogamy** and is very common in complex plants and animals. The larger gamete is usually called female, and the smaller one male.

Isogamy is where the gametes are identical. This is particularly common in unicellular organisms, where the whole organism may serve as a gamete.

Variations in sexual cycles

Meiosis and fertilisation occur in all sexual reproductive cycles, but the timing of these processes in relation to growth of the organism varies. There are three common patterns.

In **animals** most of the life cycle is diploid (Knox p402). Meiosis gives rise to gametes, which fuse without further cell division to give a diploid zygote. This then grows into the new individual.

In **plants** there is an alternation between haploid and diploid generations (Knox p299). In flowering plants the familiar plant is diploid. Meiosis produces haploid cells, which undergo further divisions by mitosis to produce a multicellular, haploid stage. This haploid stage, or gametophyte, eventually produces gametes which fuse to form a zygote. The zygote grows into the diploid stage, or sporophyte. You will learn more about alternation of generations in plants later in the semester.

In most **fungi** most of the life cycle is haploid (Knox p904). Gametes are produced by mitosis from haploid cells. The gametes fuse to form a diploid zygote which undergoes meiosis without further growth. The resulting haploid cells develop into the new organism.

There are some other, even odder, variations! What is common to all of these, and is important to know, is that sexual reproduction involves a halving of chromosome numbers by meiosis, and the fusion of haploid cells from different parents in fertilisation.

Why bother with sex?

Sexual reproduction is complicated and energetically expensive. Despite this, multicellular organisms that never reproduce sexually are extremely uncommon. Sexual reproduction must therefore confer a significant benefit.

The main advantage of sex is that it produces genetic variation among offspring. In particular, it produces new genetic combinations in every generation that can be tested against the environment. This production of new genotypes, some of which may be better adapted than the parents, helps evolution to proceed faster.

Reproductive cycles vary

Asexual reproduction tends to dominate in simple organisms with high population growth rates, while sexual reproduction tends to dominate in more complex organisms.

In some organisms, only asexual reproduction is known. For example, sex has never been observed in amoebae. However, purely asexual organisms are quite uncommon.

In many organisms, such as fungi, most protists and many plants, both sexual and asexual reproduction occur. A typical pattern is that while conditions are favourable for growth most reproduction is asexual. Sexual reproduction, which is slower and more costly, is typically associated with stressful conditions or with a survival phase in the life cycle, such as overwintering.

In most animals and plants, only sexual reproduction occurs. For example, no mammals are known to reproduce asexually. For these organisms the costs of asexual reproduction, in terms of lack of genetic variation, are just too high.

Don't be confused by the distinction between the genetic basis of reproduction (sexual or asexual) and the physical method by which offspring are produced. For example, it is tempting to say that one of the advantages of sexual reproduction in mammals like ourselves is that it provides protection and nourishment for the developing embryo during pregnancy. However, it is conceivable that the same process of pregnancy and placental nourishment could occur parthenogenetically, by development of an unfertilised egg. This is not very different from the parthenogenesis that occurs in some reptiles. The reason why asexual reproduction is not known in mammals almost certainly has a basis in the genetic consequences of this type of reproduction.

ACTIVITIES

1. Compare the features of sexual and asexual reproduction in the following table.

Feature	Sexual	Asexual
Genetic variation		
Energy cost per offspring		
Potential rate of increase		
Number of parents required		

2. How does asexual reproduction occur in potatoes, strawberry, black bread mould (*Rhizopus*), diatoms, planarians, and rotifers? Use the index of your textbook to locate information on organisms that you are not familiar with.

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LECTURE 3: MEIOSIS AND GENETIC VARIABILITY

LECTURE SYNOPSIS

- Meiosis reduces chromosome number from diploid to haploid.
    - Meiosis involves two nuclear divisions.
    - Meiosis I separates homologous chromosomes.
    - Meiosis II separates sister chromatids of each chromosome.
    - Meiosis and cytokinesis result in four haploid cells
- Sexual life cycles produce genetic variation among offspring.
    - Independent segregation of homologous chromosomes during Meiosis I generates different combinations of chromosomes.
    - ‘Crossing-over’ of part(s) of chromatid strands between two, paired homologues during Meiosis I results in new combinations of genes
    - Random fertilisation of gametes leads to unique genetic combinations.
- Sexual reproduction carries a cost of producing gametes required to ensure fertilisation.
- There is a variety of sexual life cycles. Relative duration and importance of diploid and haploid phases varies greatly among groups of organisms.

LEARNING OBJECTIVES

By the end of this lecture you should be able to:

- List the features that distinguish meiosis from mitosis
- Understand the mechanisms of genetic variation in sexual reproduction

REQUIRED READING

Chapter 7, pages 167-171

KEY TERMS

Homologous chromosomes
Synapsis
Chromatids
Crossing-over

LECTURE NOTES

The place of meiosis

The obvious role of meiosis is to halve the number of chromosomes so that when two gametes fuse, the resulting zygote has the correct number of chromosomes. It is therefore crucial to the mechanism of sex. But sexual reproduction is all about genetic variation in populations, and meiosis also has an important role to play in increasing this variation.

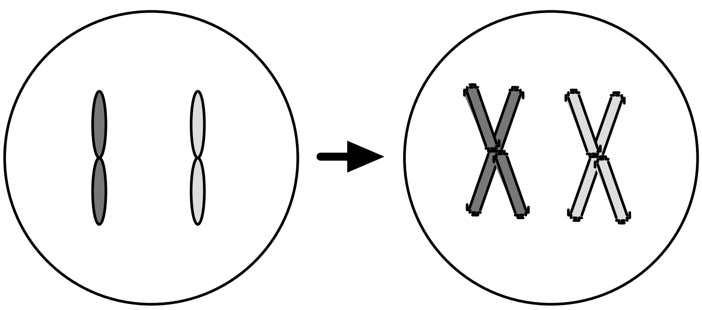
Meiosis presumably evolved from mitosis. Meiotic cell divisions show modifications on the pattern seen in mitosis, especially to:

- Ensure that each member of a pair of homologous chromosomes ends up in different cells
- Allow genes to be swapped between members of a homologous pair.

Meiosis has two rounds of division, and these special modifications occur in the first round of division (Meiosis I).

Homologues and chromatids

In order to understand the process of meiosis, you really do need to know the difference between homologous chromosomes and chromatids.



The diagram represents a cell undergoing DNA replication in interphase. It is a diploid cell, with a chromosome number of 2n = 2. The two chromosomes in the left hand cell are homologous chromosomes. They are the same size and shape, and have genes coding for the same characters at the same positions along their length. However, they are not identical because they can have different alleles of each gene. This has been indicated by shading them differently.

Following DNA replication, each chromosome consists of two identical DNA molecules. In their condensed form, ready for cell division, these can clearly be seen attached to each other. They are called sister chromatids. The chromatids of each chromosome are identical to each other. Chromatids from different chromosomes, even if the chromosomes are homologous, can differ and again this has been indicated by the shading.

In meiosis, the first division separates the homologous chromosomes. At the end of Meiosis I, each chromosome still consists of two chromatids attached to each other. The second division, Meiosis II, separates the chromatids in a way similar to that in mitosis.

Meiosis I

All of the unique features of meiosis occur in the first division, or meiosis I. As with mitosis, the DNA is replicated in the interphase prior to meiosis, and the chromosomes enter mitosis as two sister chromatids joined together.

In the prophase of meiosis I, the chromosomes begin to condense, but the homologous chromosomes line up side-by-side to form tetrads, or groups of 4 chromatids. This process is called **synapsis.** This serves two main functions. The first is to enable the sorting out of the chromosomes so that only one chromosome from each homologous pair goes into each daughter cell. The second is to allow **crossing-over** to occur. Crossing over is when chromatids from homologous chromosomes swap parts of themselves with each other. It is a very important process for enabling genes on the same chromosome to be inherited independently of each other. Formation of tetrads and crossing over is a slow process, and prophase I is by far the longest stage in meiosis.

In metaphase I the chromosomes line up along the metaphase plate. However, in meiosis I the chromosomes are still arranged in their tetrads, with the homologous chromosomes lying side-by-side. Spindle fibres attach each member of a homologous pair to opposite poles of the spindle. Consequently during anaphase I the homologous chromosomes are separated. Each daughter cell receives half of the chromosomes that were present in the parent cell.

Meiosis II

At the end of meiosis I the chromosome number has been halved and the daughter cells are now haploid. However, the chromosomes still consist of two chromatids joined together. Note that the chromatids are now no longer necessarily identical, since crossing over may have occurred.

The second round of division in meiosis proceeds in the same way as mitosis. Sister chromatids are pulled to opposite poles of the cell, resulting in daughter cells with each chromosome again consisting of a single DNA molecule.

Comparing meiosis and mitosis

It is very easy to get the terms mitosis and meiosis confused! Try hard to sort them out. Understanding the distinction is fundamental to reproductive biology and genetics of all eukaryotic organisms.

Mitosis	Meiosis
Single round of division	Two rounds of division
2 daughter cells, of same ploidy as parent	4 haploid daughter cells from a diploid parent
Daughter cells genetically identical	Daughter cells genetically different from each other
May occur throughout the body of multicellular organisms	Only occurs in specialised sex cells in multicellular organisms
Function: growth and repair in multicellular organisms, asexual reproduction in unicellular organisms	Function: production of haploid gametes or haploid generation in sexual life cycles

Sources of genetic variation in meiosis

Meiosis contributes two main sources of genetic variation in sexual reproduction.

Independent assortment of homologous chromosomes. This means that gametes receive a random combination of maternal and paternal chromosomes.

Crossing-over enables combining of maternal and paternal genes on the same chromosome.

A third source of variation comes from **random fertilisation**, in which a gamete produced by one parent (for example, an egg) can be fertilised by any of the gametes produced by the other parent (for example, sperm).

ACTIVITIES

Complete the following table. Illustrate each stage or process with a sketch in the left hand column.

	Meiosis starts with a diploid cell
	Crossing-over occurs during Prophase I
	During Meiosis I, the ____________________ are separated
	The products of Meiosis I are
	During Meiosis II, the _____________________ are separated
	The products of Meiosis II are

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SAMPLE EXAMINATION QUESTIONS

Plan an answer to the following questions. You might like to begin by listing or mind mapping relevant information and then drafting 1-2 short paragraphs plus a diagram if appropriate. In an exam you would be allowed about 5 minutes for each answer.

a). Explain the three main phases of the cell cycle with the aid of one or more diagrams.

b). Give details of the main events in the process of mitosis.

c). List and briefly describe the ways in which meiosis differs from mitosis.

d). Differentiate between the three sources of genetic variation in sexual reproduction.

e) Define asexual reproduction and give an example of how it might occur in plants or animals

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Next topic