Chapter 13

Meiosis and Sexual Life Cycles

Lecture Outline

Overview

- Living organisms are distinguished by their ability to reproduce their own kind.
- Offspring resemble their parents more than they do less closely related individuals of the same species.
- The transmission of traits from one generation to the next is called heredity or inheritance.
- However, offspring differ somewhat from parents and siblings, demonstrating variation.
- Farmers have bred plants and animals for desired traits for thousands of years, but the mechanisms of heredity and variation eluded biologists until the development of genetics in the 20th century.
- Genetics is the scientific study of heredity and variation.

A. The Basis of Heredity

1. Offspring acquire genes from parents by inheriting chromosomes.

- Parents endow their offspring with coded information in the form of genes.
  - Your genome is comprosed of the tens of thousands of genes that you inherited from your mother and your father.
- Genes program specific traits that emerge as we develop from fertilized eggs into adults.
- Genes are segments of DNA. Genetic information is transmitted as specific sequences of the four deoxyribonucleotides in DNA.
  - This is analogous to the symbolic information of language in which words and sentences are translated into mental images.
  - Cells translate genetic "sentences" into freckles and other features with no resemblance to genes.
- Most genes program cells to synthesize specific enzymes and other proteins whose cumulative action produces an organism's inherited traits.
- The transmission of hereditary traits has its molecular basis in the precise replication of DNA.
  - This produces copies of genes that can be passed from parents to offspring.
- In plants and animals, sperm and ova (unfertilized eggs) transmit genes from one generation to the next.
- After fertilization (fusion of a sperm cell and an ovum), genes from both parents are present in the nucleus of the fertilized egg, or zygote.
- Almost all the DNA in a eukaryotic cell is subdivided into chromosomes in the nucleus.
  - Tiny amounts of DNA are also found in mitochondria and chloroplasts.

- Every living species has a characteristic number of chromosomes.
  - Humans have 46 chromosomes in almost all of their cells.
- Each chromosome consists of a single DNA molecule associated with various proteins.
- Each chromosome has hundreds or thousands of genes, each at a specific location, its **locus.**

2. Like begets like, more or less: a comparison of asexual and sexual reproduction.

- Only organisms that reproduce asexually can produce offspring that are exact copies of themselves.
- In **asexual reproduction,** a single individual is the sole parent to donate genes to its offspring.
  - Single-celled eukaryotes can reproduce asexually by mitotic cell division to produce two genetically identical daughter cells.
  - Some multicellular eukaryotes, like *Hydra*, can reproduce by budding, producing a mass of cells by mitosis.
- An individual that reproduces asexually gives rise to a **clone,** a group of genetically identical individuals.
  - Members of a clone may be genetically different as a result of mutation.
- In **sexual reproduction,** two parents produce offspring that have unique combinations of genes inherited from the two parents.
- Unlike a clone, offspring produced by sexual reproduction vary genetically from their siblings and their parents.

B. The Role of Meiosis in Sexual Life Cycles

- A **life cycle** is the generation-to-generation sequence of stages in the reproductive history of an organism.
  - It starts at the conception of an organism and continues until the organism produces its own offspring.

1. Human cells contain sets of chromosomes.

- In humans, each **somatic cell** (all cells other than sperm or ovum) has 46 chromosomes.
  - Each chromosome can be distinguished by size, position of the centromere, and pattern of staining with certain dyes.
- Images of the 46 human chromosomes can be arranged in pairs in order of size to produce a **karyotype** display.
  - The two chromosomes comprising a pair have the same length, centromere position, and staining pattern.
  - These **homologous chromosome** pairs carry genes that control the same inherited characters.
- Two distinct **sex chromosomes,** the X and the Y, are an exception to the general pattern of homologous chromosomes in human somatic cells.
- The other 22 pairs are called **autosomes.**
- The pattern of inheritance of the sex chromosomes determines an individual's sex.
  - Human females have a homologous pair of X chromosomes (XX).
  - Human males have an X and a Y chromosome (XY).
- Only small parts of the X and Y are homologous.

- Most of the genes carried on the X chromosome do not have counterparts on the tiny Y.
- The Y chromosome also has genes not present on the X.

- The occurrence of homologous pairs of chromosomes is a consequence of sexual reproduction.
- We inherit one chromosome of each homologous pair from each parent.
  - The 46 chromosomes in each somatic cell are two sets of 23, a maternal set (from your mother) and a paternal set (from your father).
- The number of chromosomes in a single set is represented by *n*.
- Any cell with two sets of chromosomes is called a **diploid cell** and has a diploid number of chromosomes, abbreviated as *2n*.
- Sperm cells or ova **(gametes)** have only one set of chromosomes—22 autosomes and an X (in an ovum) and 22 autosomes and an X or a Y (in a sperm cell).
- A gamete with a single chromosome set is **haploid,** abbreviated as *n*.
- Any sexually reproducing species has a characteristic haploid and diploid number of chromosomes.
  - For humans, the haploid number of chromosomes is 23 ($n = 23$), and the diploid number is 46 ($2n = 46$).

2. Let's discuss the role of meiosis in the human life cycle.

- The human life cycle begins when a haploid sperm cell fuses with a haploid ovum.
- These cells fuse **(syngamy),** resulting in **fertilization**.
- The fertilized egg **(zygote)** is diploid because it contains two haploid sets of chromosomes bearing genes from the maternal and paternal family lines.
- As an organism develops from a zygote to a sexually mature adult, mitosis generates all the somatic cells of the body.
  - Each somatic cell contains a full diploid set of chromosomes.
- Gametes, which develop in the gonads (testes or ovaries), are *not* produced by mitosis.
  - If gametes were produced by mitosis, the fusion of gametes would produce offspring with four sets of chromosomes after one generation, eight after a second, and so on.
- Instead, gametes undergo the process of **meiosis** in which the chromosome number is halved.
  - Human sperm or ova have a haploid set of 23 different chromosomes, one from each homologous pair.
- Fertilization restores the diploid condition by combining two haploid sets of chromosomes.

3. Organisms display a variety of sexual life cycles.

- Fertilization and meiosis alternate in all sexual life cycles.
- However, the timing of meiosis and fertilization does vary among species.
- These variations can be grouped into three main types of life cycles.
- In most animals, including humans, gametes are the only haploid cells.
  - Gametes do not divide but fuse to form a diploid zygote that divides by mitosis to produce a multicellular organism.
- Plants and some algae have a second type of life cycle called **alternation of generations.**
  - This life cycle includes two multicellular stages, one haploid and one diploid.

- The multicellular diploid stage is called the **sporophyte.**
- Meiosis in the sporophyte produces haploid **spores** that develop by mitosis into the haploid **gametophyte** stage.
- Gametes produced via mitosis by the gametophyte fuse to form the zygote, which grows into the sporophyte by mitosis.

- Most fungi and some protists have a third type of life cycle.
  - Gametes fuse to form a zygote, which is the only diploid phase.
  - The zygote undergoes meiosis to produce haploid cells.
  - These haploid cells grow by mitosis to form the haploid multicellular adult organism.
  - The haploid adult produces gametes by mitosis.
- Note that either haploid or diploid cells can divide by mitosis, depending on the type of life cycle. However, only diploid cells can undergo meiosis.
- Although the three types of sexual life cycles differ in the timing of meiosis and fertilization, they share a fundamental feature: each cycle of chromosome halving and doubling contributes to genetic variation among offspring.

4. Meiosis reduces the chromosome number from diploid to haploid.

- Many steps of meiosis resemble steps in mitosis.
  - Both are preceded by the replication of chromosomes.
- However, in meiosis, there are two consecutive cell divisions, **meiosis I** and **meiosis II,** resulting in four daughter cells.
  - The first division, meiosis I, separates homologous chromosomes.
  - The second, meiosis II, separates sister chromatids.
- The four daughter cells have only half as many chromosomes as the parent cell.
- Meiosis I is preceded by **interphase,** in which the chromosomes are replicated to form sister chromatids.
  - These are genetically identical and joined at the centromere.
  - The single centrosome is replicated, forming two centrosomes.
- Division in meiosis I occurs in four phases: prophase I, metaphase I, anaphase I, and telophase I.

Prophase I

- Prophase I typically occupies more than 90% of the time required for meiosis.
- During prophase I, the chromosomes begin to condense.
- Homologous chromosomes loosely pair up along their length, precisely aligned gene for gene.
  - In crossing over, DNA molecules in nonsister chromatids break at corresponding places and then rejoin the other chromatid.
  - In synapsis, a protein structure called the synaptonemal complex forms between homologues, holding them tightly together along their length.
  - As the synaptonemal complex disassembles in late prophase, each chromosome pair becomes visible as a **tetrad,** or group of four chromatids.
  - Each tetrad has one or more **chiasmata,** sites where the chromatids of homologous chromosomes have crossed and segments of the chromatids have been traded.

- Spindle microtubules form from the centrosomes, which have moved to the poles.
- The breakdown of the nuclear envelope and nucleoli take place.
- Kinetochores of each homologue attach to microtubules from one of the poles.

Metaphase I

- At metaphase I, the tetrads are all arranged at the metaphase plate, with one chromosome facing each pole.
  - Microtubules from one pole are attached to the kinetochore of one chromosome of each tetrad, while those from the other pole are attached to the other.

Anaphase I

- In anaphase I, the homologous chromosomes separate. One chromosome moves toward each pole, guided by the spindle apparatus.
- Sister chromatids remain attached at the centromere and move as a single unit toward the pole.

Telophase I and cytokinesis

- In telophase I, movement of homologous chromosomes continues until there is a haploid set at each pole.
  - Each chromosome consists of two sister chromatids.
- Cytokinesis usually occurs simultaneously, by the same mechanisms as mitosis.
  - In animal cells, a cleavage furrow forms. In plant cells, a cell plate forms.
- No chromosome replication occurs between the end of meiosis I and the beginning of meiosis II, as the chromosomes are already replicated.

Meiosis II

- Meiosis II is very similar to mitosis.
  - During prophase II, a spindle apparatus forms and attaches to kinetochores of each sister chromatid.
    - Spindle fibers from one pole attach to the kinetochore of one sister chromatid, and those of the other pole attach to kinetochore of the other sister chromatid.
- At metaphase II, the sister chromatids are arranged at the metaphase plate.
  - Because of crossing over in meiosis I, the two sister chromatids of each chromosome are no longer genetically identical.
  - The kinetochores of sister chromatids attach to microtubules extending from opposite poles.
- At anaphase II, the centomeres of sister chromatids separate and two newly individual chromosomes travel toward opposite poles.
- In telophase II, the chromosomes arrive at opposite poles.
  - Nuclei form around the chromosomes, which begin expanding, and cytokinesis separates the cytoplasm.
- At the end of meiosis, there are four haploid daughter cells.

5. There are key differences between mitosis and meiosis.

- Mitosis and meiosis have several key differences.

- The chromosome number is reduced from diploid to haploid in meiosis but is conserved in mitosis.
- Mitosis produces daughter cells that are genetically identical to the parent and to each other.
- Meiosis produces cells that are genetically distinct from the parent cell and from each other.

- Three events, unique to meiosis, occur during the first division cycle.
  1. During prophase I of meiosis, replicated homologous chromosomes line up and become physically connected along their lengths by a zipperlike protein complex, the synaptonemal complex, in a process called synapsis. Genetic rearrangement between nonsister chromatids called crossing over also occurs. Once the synaptonemal complex is disassembled, the joined homologous chromosomes are visible as a tetrad. X-shaped regions called chiasmata are visible as the physical manifestation of crossing over. Synapsis and crossing over do not occur in mitosis.
  2. At metaphase I of meiosis, homologous pairs of chromosomes align along the metaphase plate. In mitosis, individual replicated chromosomes line up along the metaphase plate.
  3. At anaphase I of meiosis, it is homologous chromosomes, not sister chromatids, that separate and are carried to opposite poles of the cell. Sister chromatids of each replicated chromosome remain attached. In mitosis, sister chromatids separate to become individual chromosomes.
- Meiosis I is called the *reductional division* because it halves the number of chromosome sets per cell—a reduction from the diploid to the haploid state.
- The sister chromatids separate during the second meiosis division, meiosis II.

C. Origins of Genetic Variation

- What is the origin of genetic variation?
- Mutations are the original source of genetic diversity.
- Once different versions of genes arise through mutation, reshuffling during meiosis and fertilization produce offspring with their own unique set of traits.

1. Sexual life cycles produce genetic variation among offspring.

- The behavior of chromosomes during meiosis and fertilization is responsible for most of the variation that arises in each generation.
- Three mechanisms contribute to genetic variation:
  1. Independent assortment of chromosomes.
  2. Crossing over.
  3. Random fertilization.
- **Independent assortment of chromosomes** contributes to genetic variability due to the random orientation of homologous pairs of chromosomes at the metaphase plate during meiosis I.
  - There is a fifty-fifty chance that a particular daughter cell of meiosis I will get the maternal chromosome of a certain homologous pair and a fifty-fifty chance that it will receive the paternal chromosome.
- Each homologous pair of chromosomes segregates independently of the other homologous pairs during metaphase I.

- Therefore, the first meiotic division results in independent assortment of maternal and paternal chromosomes into daughter cells.
- The number of combinations possible when chromosomes assort independently into gametes is 2^n, where n is the haploid number of the organism.
  - If $n = 3$, there are $2^3 = 8$ possible combinations.
  - For humans with $n = 23$, there are 2^{23}, or more than 8 million possible combinations of chromosomes.
- **Crossing over** produces **recombinant chromosomes,** which combine genes inherited from each parent.
- Crossing over begins very early in prophase I as homologous chromosomes pair up gene by gene.
- In crossing over, homologous portions of two nonsister chromatids trade places.
  - For humans, this occurs an average of one to three times per chromosome pair.
- Recent research suggests that, in some organisms, crossing over may be essential for synapsis and the proper assortment of chromosomes in meiosis I.
- Crossing over, by combining DNA inherited from two parents into a single chromosome, is an important source of genetic variation.
- At metaphase II, nonidentical sister chromatids sort independently from one another, increasing by even more the number of genetic types of daughter cells that are formed by meiosis.
- The **random nature of fertilization** adds to the genetic variation arising from meiosis.
- Any sperm can fuse with any egg.
  - The ovum is one of more than 8 million possible chromosome combinations.
  - The successful sperm is one of more than 8 million possibilities.
  - The resulting zygote could contain any one of more than 70 trillion possible combinations of chromosomes.
  - Crossing over adds even more variation to this.
- Each zygote has a unique genetic identity.
- The three sources of genetic variability in a sexually reproducing organism are:
  1. Independent assortment of homologous chromosomes during meiosis I and of nonidentical sister chromatids during meiosis II.
  2. Crossing over between homologous chromosomes during prophase I.
  3. Random fertilization of an ovum by a sperm.
- All three mechanisms reshuffle the various genes carried by individual members of a population.

2. Evolutionary adaptation depends on a population's genetic variation.

- Darwin recognized the importance of genetic variation in evolution.
  - A population evolves through the differential reproductive success of its variant members.
  - Those individuals best suited to the local environment leave the most offspring, transmitting their genes in the process.
- This natural selection results in adaptation, the accumulation of favorable genetic variations.

- If the environment changes or a population moves to a new environment, new genetic combinations that work best in the new conditions will produce more offspring, and these genes will increase.
  - The formerly favored genes will decrease.
- Sex and mutation continually generate new genetic variability.
- Although Darwin realized that heritable variation makes evolution possible, he did not have a theory of inheritance.
- Gregor Mendel, a contemporary of Darwin's, published a theory of inheritance that supported Darwin's theory.
  - However, this work was largely unknown until 1900, after Darwin and Mendel had both been dead for more than 15 years.