4.3 Sexual Reproduction: Adding Variety

In sharp contrast to asexual reproduction, sexual reproduction produces genetic variety. Whereas offspring produced by asexual reproduction are genetic clones of the parent, offspring produced by sexual reproduction inherit genetic information from two parents. Each parent contributes a copy of half of its genetic information. This process of combining genetic information from two individuals results in offspring that differ genetically from their parents and from each other.

gamete a sex cell; includes sperm cells in males and egg cells in females

fertilization the formation of a zygote by the joining together, or fusion, of two gametes

zygote a cell produced by the fusion of two gametes

Sexual reproduction involves two key processes. The first is the formation of haploid sex cells, or **gametes**, which contain genetic information from the parents. The second process is **fertilization**, which occurs when two sex cells join to produce a **zygote**—the first cell of a new individual.

Modes of Sexual Reproduction

The sex cells of different organisms vary considerably in size, shape, and mobility. Most species produce two different types of sex cells. In animals, the reproductive organs that produce sex cells are the testes (which produce sperm cells) and the ovaries (which produce egg cells, or **ova**) (**Figure 1**).

ova female sex cells (egg cells)

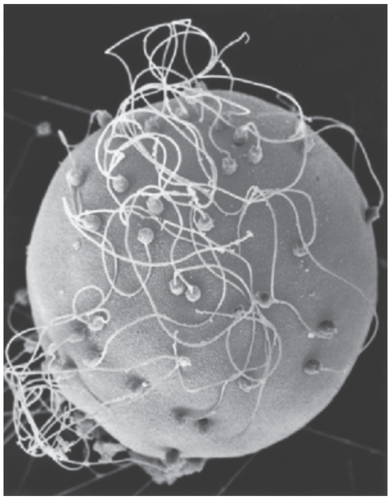


Figure 1 Sperm cells are able to swim using one or more flagella. Here many sperm can be seen surrounding the much larger egg cell, or ovum.

While simple plants like mosses and ferns also produce sperm, the male gametes of higher plants are contained within pollen grains. The sex cells of higher plants are produced in specialized sex organs called cones and flowers.

Many species have distinct male and female individuals—each possessing only one type of sex organ and the ability to produce only one kind of sex cell. Other species are hermaphroditic, meaning that they are composed of individuals that produce both male and female gametes. Fertilization strategies can be highly variable. **Table 1** highlights some of the diversity in sexual reproduction.

Table 1 Sexual Gametes and Fertilization Methods in Various Organisms

Organism	Types of individuals and gametes	Fertilization method
bread mould fungus	• "+" and "−" individuals produce similar-looking gametes where they come in contact	Gametes fuse, forming a zygote.
willow tree	• Separate male and female trees • Male pollen grains and female eggs	Insects pollinate "pussy willow" flowers.
giant clam	• Young clams are males and change to females as they mature. • Sperm and egg cells	External fertilization. All individuals in an area simultaneously release their sex cells into the open water.
earthworm	• Hermaphrodites with both sperm and eggs	Internal fertilization. Two worms exchange sperm, fertilizing each other's eggs.
parrot fish	• Separate males and females. • Fish can change sexes. • Sperm and egg cells	External fertilization. Sperm are released over eggs in water.
Canada goose	• Separate sexes • Sperm and egg cells	Internal fertilization

While types of individuals and methods of fertilization are highly variable across the kingdoms of life, the formation of gametes is less so. Most sexually reproducing eukaryotes produce specialized sex cells using a very similar process. In the remainder of this section, we will examine the formation of sex cells and the processes that influence and determine their genetic contents.

Meiosis

Sexual reproduction depends on **meiosis**, the process in which haploid gametes are formed. Meiosis involves two stages of cell division that have phases similar to those in mitosis. In mitosis, the chromosome number of the daughter cells is the same as that of the parent cell. In meiosis, the chromosome number of the daughter cells is half that of the parent cell. For example, a human cell containing 46 chromosomes that undergoes meiosis will produce gametes that each have 23 chromosomes. Since these gametes have only one set of chromosomes, they are haploid. The number of chromosomes in a gamete is called the haploid number, or n; the number of chromosomes in body cells is twice the haploid number and (with the exception of species exhibiting polyploidy) is called the diploid number, or $2n$. In humans, the haploid chromosome number is 23 and the diploid chromosome number is 46. Humans are a diploid species.

The result of sexual reproduction is that offspring receive genetic material from each parent in the form of haploid gametes. When combined, two gametes produce a zygote that contains one complete set of chromosomes (**Figure 2**).

What may surprise you is that you receive a nearly complete set of genetic instructions from each of your parents. Rather than contributing information for one half of your genes, each parent contributes a copy of virtually every gene. You receive one version from your father and one version from your mother. For example, both of your parents give you a gene containing information for eye colour. That information might be the same—instructions for blue eyes from both parents—but it could also be different—brown eye information from one parent and blue eye information from the other parent. In this way, each parent contributes one version of genetic information for each corresponding gene. Each of the 23 chromosomes you receive from your father is matched by 23 chromosomes from your mother. The paired chromosomes are called homologous chromosomes. With the exception of a pair of special sex chromosomes, which we will examine later, **homologous chromosomes** are similar in size and shape and carry genetic information for the same genes (**Figure 3**).

Fertilization occurs when a haploid sperm cell ($n = 23$) unites with a haploid egg cell ($n = 23$) to form a diploid zygote ($2n = 46$). The zygote then begins a process of ongoing growth, mitotic cellular division, and cell specialization that will ultimately produce a mature multicellular individual.

meiosis a two-stage cell division in which the resulting daughter cells have half the number of chromosomes as the parent cell; results in the formation of gametes or spores

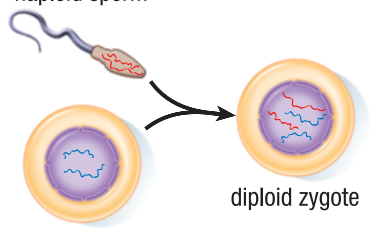


Figure 2 Fertilization results in a zygote that has two sets ($2n$) of chromosomes—one set from each parent.

homologous chromosomes matching pairs of chromosomes, similar in size and carrying information for the same genes

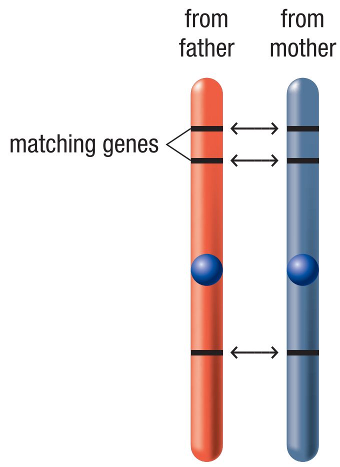


Figure 3 Homologous chromosomes carry information for the same genes.

Stages of Meiosis

Meiosis involves two divisions that produce four haploid cells. Meiosis I, the first division, is often described as a reduction division because the diploid, or $2n$, chromosome number is reduced by half to the haploid, or n, chromosome number. This reduction in chromosome number is a key distinguishing feature of meiosis. In the second division, meiosis II, the number of chromosomes is unchanged, but the total number of cells increases to four (**Figure 4**).

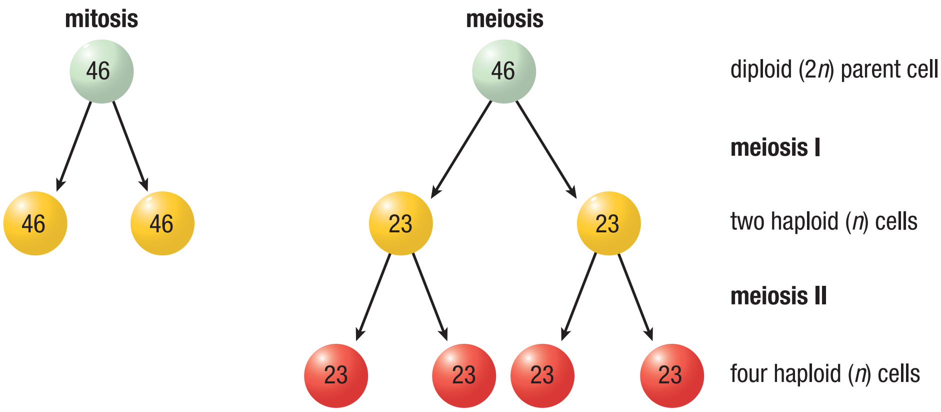


Figure 4 In mitosis, a single division results in two daughter cells with the same number of chromosomes as the original parent cell. Meiosis involves two division stages resulting in four daughter cells—each with half the number of chromosomes of the original parent cell.

MEIOSIS I

As in mitosis, DNA replication in meiosis occurs during interphase (prior to the start of meiosis). At the beginning of prophase I, the chromosomes start to shorten and thicken. Each chromosome has been replicated during interphase and now consists of two sister chromatids joined at the centromere. The nuclear membrane begins to dissolve, the centrioles separate and move to opposite poles of the cell, and spindle fibres form.

As prophase I continues, the chromosomes come together in homologous pairs. Each chromosome of the pair is composed of a pair of sister chromatids. The whole structure is then referred to as a **tetrad** because each pair of chromosomes is composed of four chromatids. Each sister chromatid intertwines with a sister chromatid from its matching homologous chromosome, a process called **synapsis** (**Figure 5**).

tetrad a pair of homologous chromosomes, each with two sister chromatids

synapsis the physical pairing up of homologous chromosomes during prophase I of meiosis

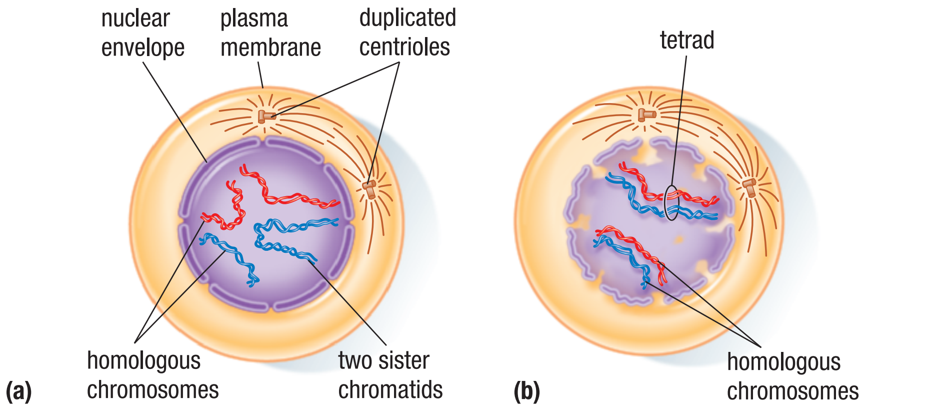


Figure 5 (a) By the end of interphase, chromosomes have been replicated. (b) In early prophase, the two pairs of homologous chromosomes in this diploid ($2n = 4$) cell have formed tetrads.

As prophase continues (**Figure 6(a)**), it is common for the intertwined chromatids from different chromosomes to break and reattach to each other—exchanging sections in a process called **crossing over**. Crossing over results in the recombination (mixing) of genetic information between non-sister chromatids of a homologous pair (**Figure 7**, next page).

crossing over the exchange of chromosome segments between homologous pairs during synapsis

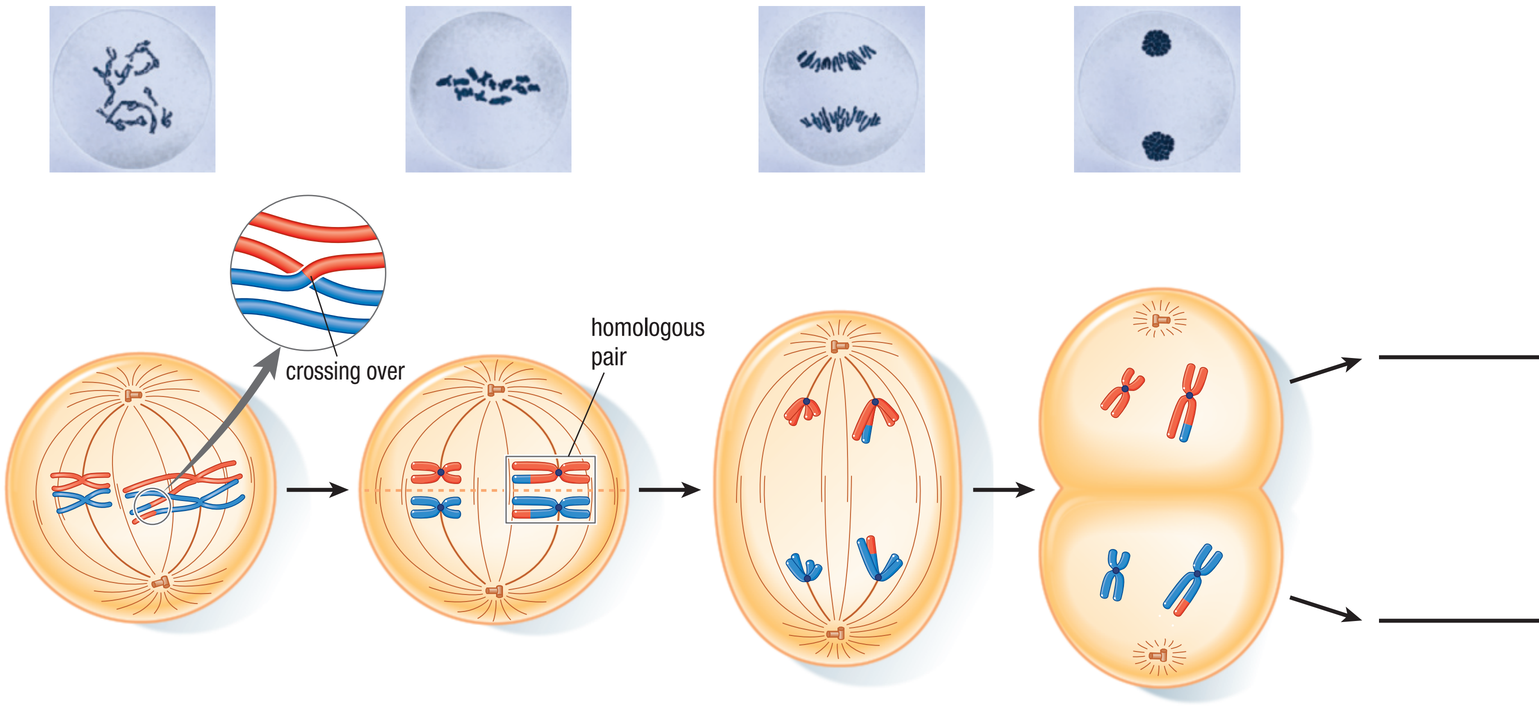


Figure 6 (a) The first meiotic division is characterized by the division of homologous chromosomes. (This diagram has been simplified to show only four chromosomes.)

During metaphase I, the tetrads (made up of pairs of homologous chromosomes) migrate toward the centre of the cell and align their centromeres across the middle of the cell.

In anaphase I, homologous chromosomes move to opposite poles of the cell. At this point in meiosis, reduction division occurs. *Only one chromosome from each homologous pair will be found in each new daughter cell.* Each chromosome in the new cells consists of two sister chromatids.

In telophase I, nuclear membranes begin to form around the chromosomes at each end of the cell and the cell begins to divide. Unlike in mitosis, the chromosomes in the two nuclei are not identical with respect to their gene content. Each daughter nucleus receives only one member of each original chromosome pair. These cells are now haploid—containing only *n* chromosomes—and are ready to begin the second stage of meiosis.

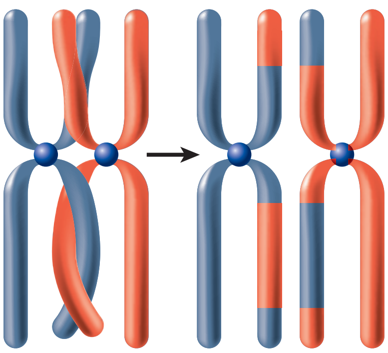


Figure 7 During synapsis, crossing over occurs and non-sister chromatids exchange segments. This results in the recombination of genetic information. For simplicity, synapsis and crossing over are shown for only two chromatids.

MEIOSIS II

Meiosis II usually begins immediately after telophase I and the first cell division (**Figure 6(b)**). Each haploid daughter cell contains one set of chromosomes. The chromosomes still consist of two sister chromatids. As a result of crossing over events, the sister chromatids are no longer identical. Note that there is no duplication of DNA between meiosis I and meiosis II.

Prophase II signals the beginning of the second division. During this stage, the nuclear membrane dissolves and the spindle fibres begin to form.

Metaphase II is identified by the arrangement of the chromosomes, each with two sister chromatids, across the middle of the cell. The sister chromatids remain attached by their centromeres.

In anaphase II, sister chromatids separate and move to opposite poles of the cell. The nuclear membrane begins to form around the chromatids, now called chromosomes.

The cells then enter telophase II, the final stage of meiosis II. During this stage, the second nuclear division is completed and the second division of cytoplasm follows.

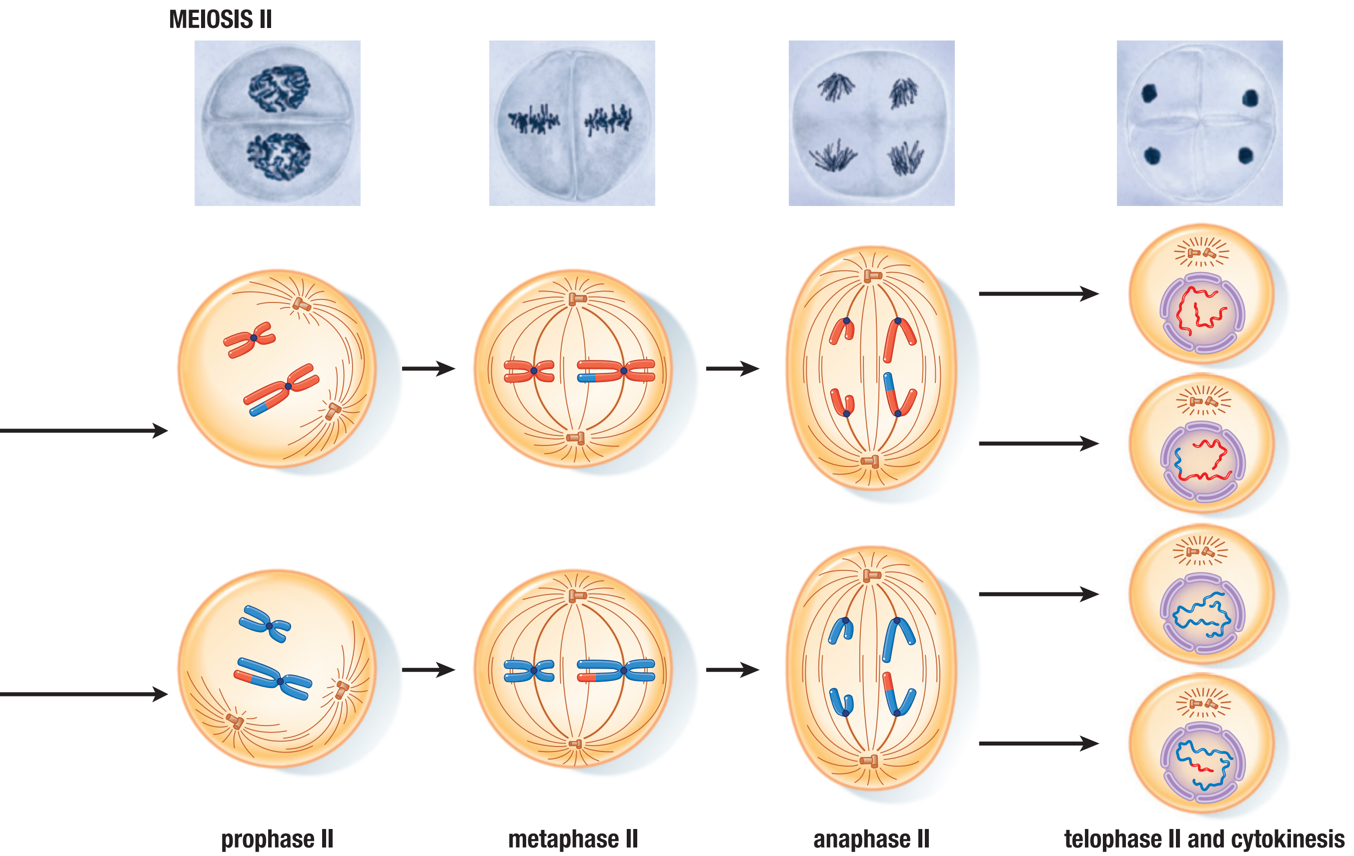


Figure 6 (b) The second meiotic division is characterized by the division of sister chromatids.

Investigation 4.3.1

Observing Meiosis (page 171)
Now that you have read about the steps involved in meiosis, you can complete Investigation 4.3.1.

In this observational study you will observe cells in the process of meiosis. You will identify the stages of meiosis and document your findings with proper biological drawings.

Four haploid daughter cells (gametes) have been produced. The recombination of genetic information that occurs during the crossing over stage of meiosis produces gametes (sex cells) that are genetically different from one another.

Random Assortment of Homologous Chromosomes

During meiosis I, homologous chromosomes pair up during prophase I and metaphase I. They are then separated from each other during anaphase I. Each daughter cell is now haploid, having received only one chromosome from each pair. When this happens, the chromosomes in each pair are assorted independently. In other words, a daughter cell can receive either chromosome of each homologous pair—this is called random assortment.

Carefully examine the four chromosome arrangements illustrated in **Figure 8**. They represent four ways in which three pairs of homologous chromosomes might be arranged during metaphase I and then separated during anaphase I. If you imagine each of these arrangements undergoing anaphase with the three chromosomes on the top moving to one pole of the cell and the three chromosomes on the bottom moving to the opposite pole of the cell, you can see that there are eight different possible combinations of chromosomes for a daughter cell. Each of these arrangements will contain one chromosome from each of the three original homologous pairs.

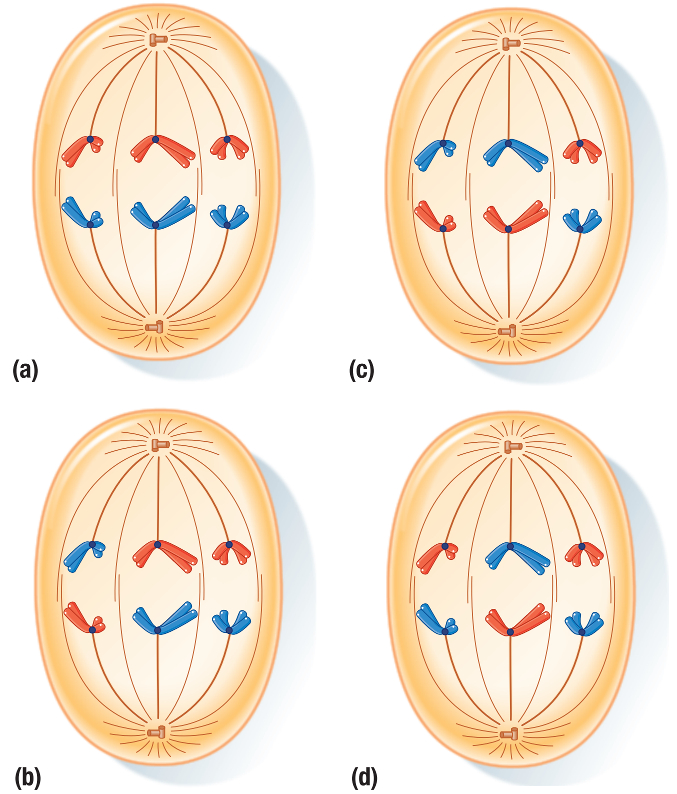


Figure 8 Four possible arrangements of three homologous pairs can occur during metaphase I. Separation during anaphase results in eight possible assortments of chromosomes in the daughter cells. Each arrangement is equally likely.

The number of possible combinations of chromosomes depends on the number of chromosome pairs. For any diploid ($2n$) organism, the number of combinations is 2^n. With three pairs of chromosomes, the number of possible combinations is $2^3 = 8$. If there are 23 pairs of chromosomes, as in humans, the number of possible combinations is $2^{23} = 8\,388\,608$!

This variation among sex cells does not include the added variation that results from crossing over. If you have ever wondered why no two people are exactly alike—even two siblings—you now have your answer!

Mini Investigation

Modelling Meiosis

Skills Menu: Performing, Observing, Analyzing, Communicating — SKILLS HANDBOOK A2.1

In this activity, you will use "pop-it" beads to represent homologous chromosomes and to model the key steps of meiosis.

Equipment and Materials: 42 red pop-it beads; 42 yellow pop-it beads; 4 twist-ties

1. Make two strings of 12 yellow pop-it beads and two strings of 9 yellow pop-it beads.
2. Use a twist tie to join the two yellow 12-bead strands together between the third and fourth beads.
3. Use a twist tie to join the two yellow 9-bead strands together between the fourth and fifth beads (**Figure 9**).
4. Make matching versions of these chromosomes using the red beads.

Figure 9

5. Arrange the pairs of "homologous chromosomes" side by side across the middle of your desk.
6. Perform one or two crossing over events of your choosing between non-sister chromatids.
7. Model anaphase I by separating each homologous pair—moving them to opposite ends of your desk.
8. Model anaphase II by undoing the twist-ties and separating the sister chromatids into separate locations on your desk. Each location should have one long and one short "chromosome."

A. Was your initial cell a diploid or a haploid cell? How could you tell? T/I

B. What was *n* for these cells? T/I

C. What event in meiosis was represented in Step 6? T/I

D. What was the order and sequence of red and yellow beads in each of your four "gametes"? T/I

Gametogenesis

In animals, meiosis takes place in the testes and ovaries. The formation of sex cells in meiosis is called **gametogenesis**. Sex cells contain the haploid number of chromosomes and are produced by meiosis. The production of sperm cells is called **spermatogenesis**, whereas the production of egg cells (ova) is called **oogenesis**. Although human male and female gametes both follow the general process of meiosis, some differences do exist.

In oogenesis, the cytoplasm of the female gametes does not divide equally during each of the two cell divisions of meiosis (**Figure 10**). Instead, one of the daughter cells receives most of the cytoplasm. The other cells, called polar bodies, die, and the final product of oogenesis is a single ovum (egg cell). In spermatogenesis, the cytoplasm is divided equally during each cell division, resulting in the formation of four equal-sized sperm cells. Each of the four sperm cells is small in size and streamlined for maximum motility.

gametogenesis the production of gametes (sex cells) in animals

spermatogenesis the production of mature sperm cells

oogenesis the production of mature egg cells

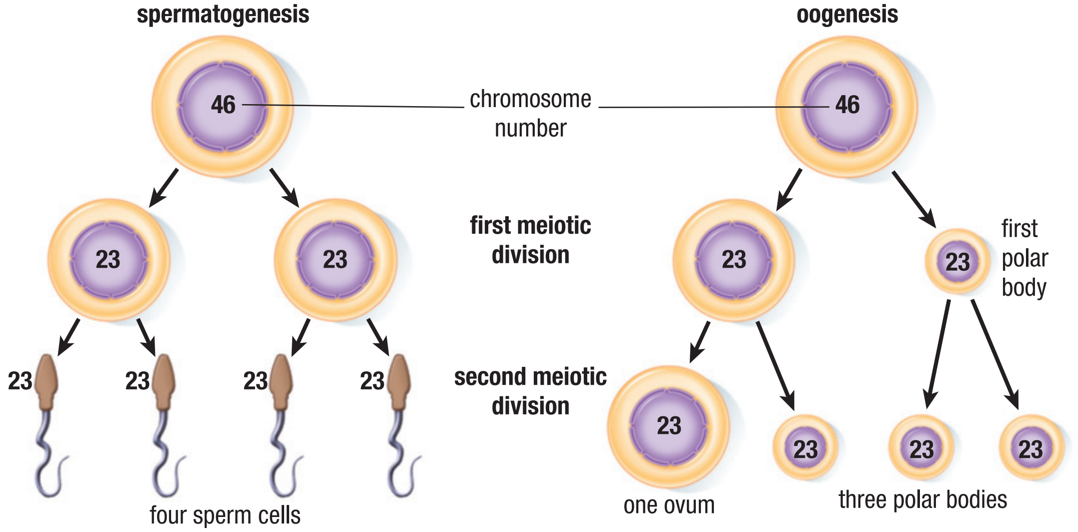


Figure 10 Spermatogenesis and oogenesis

Why are there differences between male and female gametes? Mature sperm cells must be able to swim to an egg cell in order to fertilize it. Sperm cells must be highly motile; being large and heavy would slow them down. In contrast, egg cells do not need to be motile; it is more advantageous for them to contain a large supply of nutrients in their cytoplasm. Egg cells use the nutrients and organelles carried in the cytoplasm to fuel future cell divisions in the event that the egg cell becomes fertilized.

Males produce many more sex cells than females. Once they reach sexual maturity, male humans, for example, can produce hundreds of millions of sperm cells every day. Only a few weeks after a female mammal is born, all of her potential egg cells stop developing at the end of prophase I. When she reaches sexual maturity, some of these cells go on to complete meiosis. In an entire lifetime, a female human produces between 400 and 500 eggs.

KARYOTYPES

During stages of cell division, chromosomes can be stained, viewed, and photographed under a microscope (**Figure 11(a)**). Doing this allows scientists to count, compare, and arrange the chromosomes according to their size and type. A picture of chromosomes that have been arranged according to number, size, shape, or some other characteristic is called a **karyotype** (**Figure 11(b)**).

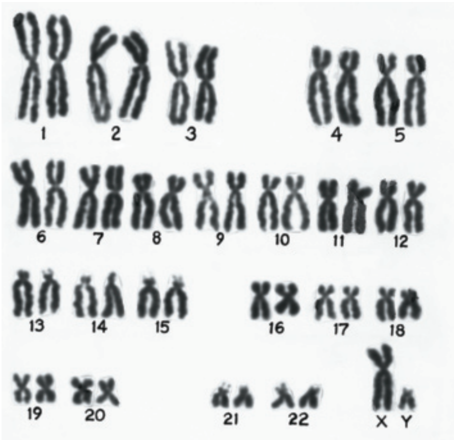
karyotype the chromosomes of an individual that have been sorted and arranged according to size and type

WEB LINK

To gain further practice in constructing and interpreting karyotypes,

GO TO NELSON SCIENCE

(a)



(b)

Figure 11 (a) After all chromosomes from a single human cell are stained and photographed, (b) they can be arranged into a karyotype based on their characteristics.

Sex Chromosomes and Sex Determination

Many eukaryotic organisms, including most animals, have at least one pair of chromosomes that differ between the males and females of that species. In most mammals, for example, **sex chromosomes** consist of a matching pair of homologous chromosomes in females and a partially matching pair in males (**Figure 12**). In males, one chromosome is much smaller than the other. The larger of the two chromosomes is a homologue to the sex chromosomes in the female.

sex chromosomes chromosomes that differ in males and females of the same species; the combination of sex chromosomes determines the sex of the offspring

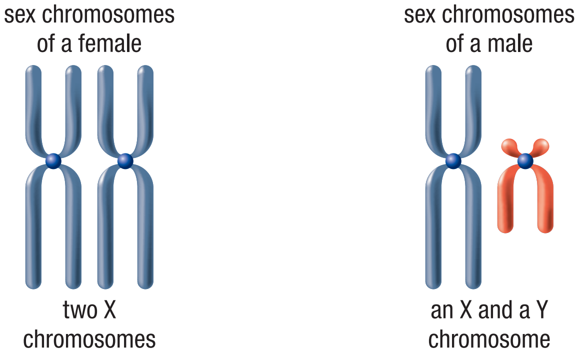


Figure 12 Sex chromosomes of a female and of a male

The larger type of chromosome is called an X chromosome, while the smaller chromosome is called a Y chromosome. Although they differ dramatically in size, parts of the X and the Y chromosomes contain matching regions that enable them to undergo synapsis and behave as a homologous pair during meiosis. Chromosomes that are not sex chromosomes are referred to as **autosomes**.

autosomes non-sex chromosomes

This pattern of XX sex chromosomes in females and XY sex chromosomes in males is referred to as the XX/XY sex-determination system. This system occurs in humans and almost all other mammals. Individuals that inherit an X chromosome from their father and an X chromosome from their mother develop into females. Individuals that inherit a Y chromosome from their father and an X chromosome from their mother develop into males.

The XX/XY system is only one of many systems used by living things to determine the sex of the offspring. In many reptiles, for example, the gender of the offspring is determined by the temperature of the eggs during incubation. In some fish species, offspring are born female and become male, while in others, they are born male and become female. **Table 2** outlines some different animal sex-determination systems.

Table 2 Common Sex-Determination Mechanisms in the Animal Kingdom

Sex determination	Examples	Description
XX/XY	mammals, some insects	XX females, XY males
ZW/ZZ	birds	ZW females, ZZ males
temperature	turtles, crocodiles	If the eggs are kept relatively warm, most or all eggs hatch as females. If the eggs are kept relatively cool, most or all eggs hatch as males.
age	some fish, some mollusks	All young are born male. As they become older and larger, they change into females.
social structure	some fish	All young fish are females. When the dominant male fish dies, a large female changes into a male.
fertilization—haploid/diploid	bees, ants, wasps	Fertilized eggs ($2n$) become females. Unfertilized eggs (n) become males.
infection	some insects	Variable. In one form, infected individuals develop into females.
none	earthworms and other hermaphroditic organisms	All individuals have both male and female reproductive organs.

4.3 Summary

- Sexual reproduction produces genetically variable offspring by combining the genetic information from two parents.
- During meiosis I, chromosomes exchange genetic information, known as crossing over, during prophase I.
- Homologous chromosomes are assorted independently of other pairs.
- The formation of genetically variable sex cells in meiosis II is called gametogenesis.
- There are many different sex-determination systems in living things.
- Mammals have X and Y sex chromosomes and use an XX/XY system for female/male sex determination.

UNIT TASK BOOKMARK

What evidence suggests that the disorder you are investigating is genetic? How does meiosis account for the fact that not all offspring inherit the same disorder?

4.3 Questions

1. Not all species have distinct males and females. Describe the male and female relationships and fertilization methods in
   (a) giant clams
   (b) honeybees
   (c) earthworms
   (d) parrot fish K/U
2. Use a format of your choice to compare mitosis and meiosis. You may choose a graphical organizer or a table. You could also create a song or skit to highlight key similarities and differences. K/U C
3. How do each of the following contribute to genetic variation in offspring? K/U
   (a) Crossing over
   (b) Random assortment of homologous chromosomes
   (c) Fertilization
4. Prior to crossing over, in what ways are homologous chromosomes similar? In what ways do they differ? K/U
5. Individuals inherit a complete set of genetic instructions from each parent. Explain how this occurs. K/U
6. Describe what happens to chromosomes in each of the following phases of meiosis: K/U
   (a) prophase I
   (b) anaphase I
   (c) anaphase II
7. Copy and complete **Table 3**. K/U T/I C
   (a) Compare the chromosome number in the organisms before, during, and at the end of meiosis.
   (b) Indicate whether the chromosome number is haploid or diploid.
8. At what point in meiosis do cells change from being diploid to being haploid? K/U
9. How many different arrangements of chromosomes are possible in gametes if the cell at the beginning of meiosis has 10 chromosomes? K/U
10. Use a Venn diagram to compare spermatogenesis and oogenesis. K/U C
11. How can it be beneficial for an organism to produce only one large egg cell during oogenesis and have three polar bodies that die? In contrast, how can it be beneficial for males to produce very large numbers of very small sperm? K/U
12. Sex-determination systems are extremely diverse. Conduct Internet research to investigate and describe sex-determination in the green spoonworm (*Bonellia viridis*). T/I
13. At the beginning of this chapter, you performed a Mini Investigation called Variability—It's a Coin Toss. Review the results of this activity. T/I
    (a) How did the activity model the process of random chromosome assortment that occurs during meiosis I?
    (b) How many homologous pairs of chromosomes did the investigation model?
    (c) If a cell had the same number of homologous chromosomes, how many different sex cells are possible?

GO TO NELSON SCIENCE

Table 3

	Human	Earthworm	Hedgehog	Broccoli
Before Meiosis				
chromosome number (haploid or diploid)	46	?	?	?
number of pairs of homologous chromosomes	?	?	45	?
After Meiosis I				
chromosome number (haploid or diploid)	?	18	?	?
After Meiosis II				
chromosome number (haploid or diploid)	?	?	?	9
number of pairs of homologous chromosomes	0	?	?	?