Chapter 11

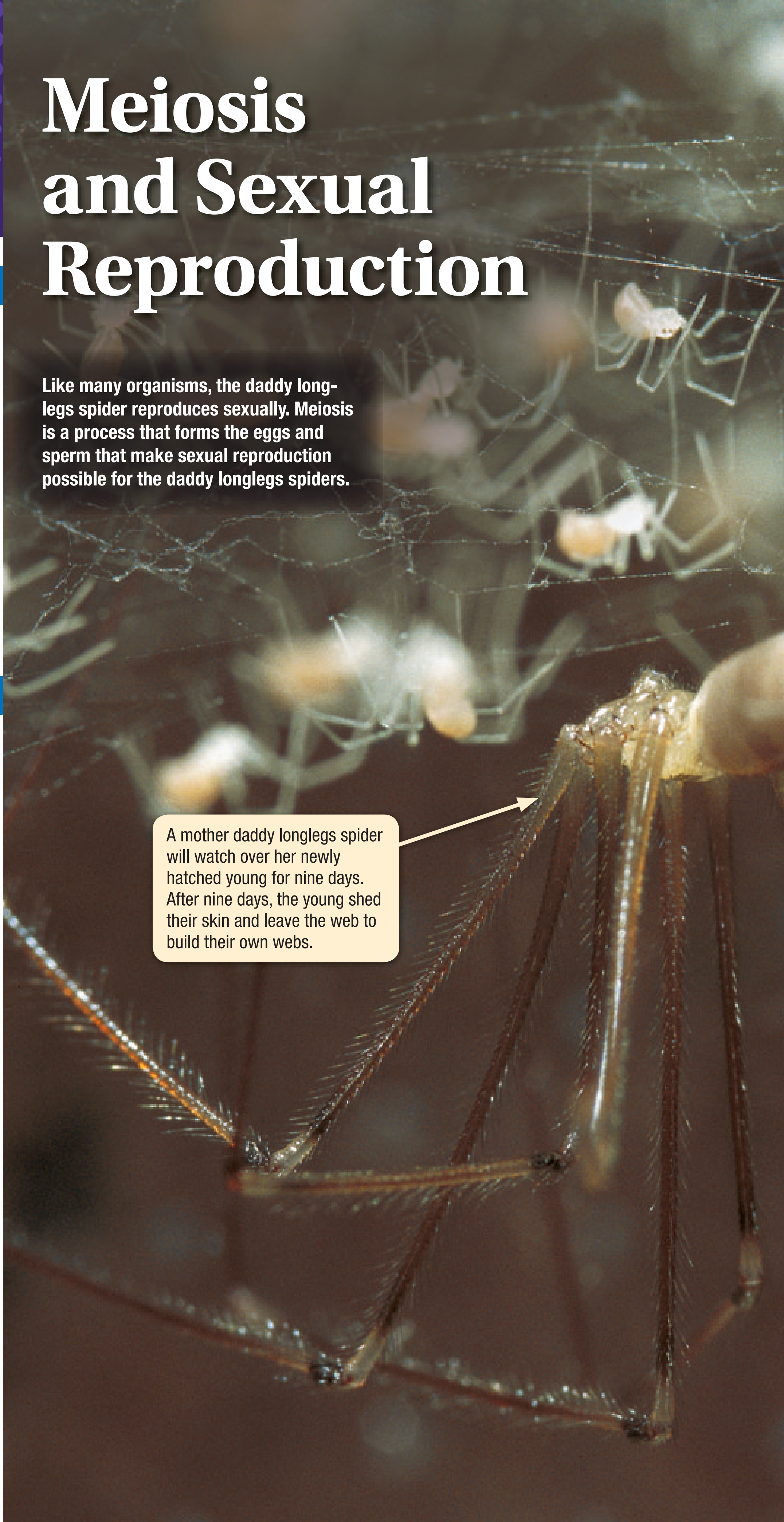
Meiosis and Sexual Reproduction

Preview

Why It Matters

You know that in sexual reproduction, an egg and a sperm combine to form a new organism. But how are eggs and sperm produced? In this chapter, you will learn about a special type of cell division called *meiosis.*

Like many organisms, the daddy long-legs spider reproduces sexually. Meiosis is a process that forms the eggs and sperm that make sexual reproduction possible for the daddy longlegs spiders.



A mother daddy longlegs spider will watch over her newly hatched young for nine days. After nine days, the young shed their skin and leave the web to build their own webs.

Section 1

Reproduction

Key Ideas	Key Terms	Why It Matters
In asexual reproduction, how does the offspring compare to the parent? In sexual reproduction, how does the offspring compare to the parent? Why are chromosomes important to an organism?	gamete zygote diploid haploid homologous chromosomes	Living organisms produce offspring. How closely the offspring resemble their parents depends on how the organism reproduces.

Reproduction is the process of producing offspring. Some offspring are produced by two parents, and others are produced by just one parent. Some organisms look exactly like their parents, and others look very similar. Whether an organism is identical or similar to its parent is determined by the way that the organism reproduces.

Asexual Reproduction

In *asexual reproduction*, a single parent passes a complete copy of its genetic information to each of its offspring. **An individual formed by asexual reproduction is genetically identical to its parent.**

Prokaryotes reproduce asexually by a kind of cell division called *binary fission.* Many unicellular eukaryotes also reproduce asexually. Amoebas reproduce by splitting into two or more individuals of about equal size. Some multicellular eukaryotes, such as starfish, go through fragmentation. *Fragmentation* is a kind of reproduction in which the body breaks into several pieces. Some or all of these fragments regrow missing parts and develop into complete adults.

Other animals, such as the hydra shown in **Figure 1,** go through *budding.* In budding, new individuals split off from existing ones. Some plants, such as potatoes, can form whole new plants from parts of stems. Other plants can reproduce from roots or leaves. Some crustaceans, such as water fleas, reproduce by parthenogenesis. *Parthenogenesis* is a process in which a female makes a viable egg that grows into an adult without being fertilized by a male.

Reading Check *What is fragmentation? (See the Appendix for answers to Reading Checks.)*

Figure 1 This hydra is in the process of reproducing asexually. The smaller hydra budding from the parent is genetically identical to the parent.

gamete (GAM eet) a haploid reproductive cell that unites with another haploid reproductive cell to form a zygote

zygote (ZIE GOHT) the cell that results from the fusion of gametes

diploid a cell that contains two haploid sets of chromosomes

haploid describes a cell, nucleus, or organism that has only one set of unpaired chromosomes

homologous chromosomes (hoh MAHL uh guhs) chromosomes that have the same sequence of genes, that have the same structure, and that pair during meiosis

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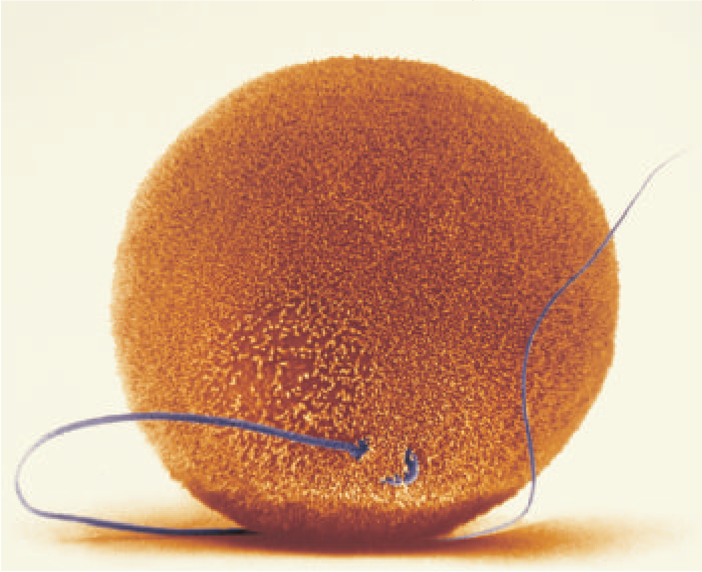
Figure 2 Two gametes, an egg and a sperm, combine during fertilization to form a zygote. **What types of cells produce gametes?**



Sexual Reproduction

Most eukaryotic organisms reproduce sexually. **In *sexual reproduction*, two parents give genetic material to produce offspring that are genetically different from their parents.** Each parent produces a reproductive cell, called a **gamete.** A gamete from one parent fuses with a gamete from the other parent, as **Figure 2** shows. The resulting cell, called a **zygote,** has a combination of genetic material from both parents. This process is called *fertilization*. Because both parents give genetic material, the offspring has traits of both parents but is not exactly like either parent.

Germ Cells and Somatic Cells Recall that the cells of a multicellular organism are often specialized for certain functions. Muscle cells, for example, contract and move your body. Cells that are specialized for sexual reproduction are called *germ cells.* Only germ cells can produce gametes. Other body cells are called *somatic cells.* Somatic cells do not participate in sexual reproduction.

Advantages of Sexual Reproduction Asexual reproduction is the simplest, most efficient method of reproduction. Asexual reproduction allows organisms to produce many offspring in a short period of time without using energy to make gametes or to find a mate. But the genetic material of these organisms varies little between individuals, so they may be at a disadvantage in a changing environment. Sexual reproduction, in contrast, produces genetically diverse individuals. A population of diverse organisms is more likely to have some individuals that survive a major environmental change.

Chromosome Number

Genes are located on chromosomes. **Each chromosome has thousands of genes that play an important role in determining how an organism develops and functions.** Each species has a characteristic number of chromosomes. As shown in **Figure 3,** mosquitoes have only 6 chromosomes in each cell. Chimpanzees have 48 chromosomes in each cell. Some ferns have more than 500! An organism must have exactly the right number of chromosomes. If an organism has too many or too few chromosomes, the organism may not develop and function properly.

In humans, each cell has two copies of 23 chromosomes for a total of 46. When fertilization happens, two cells combine to form a zygote, which still has only 46 chromosomes. Why is the number the same? The gametes that form a zygote have only *one* copy of each chromosome, or one set of 23 chromosomes. This reduction of chromosomes in gametes keeps the chromosome number of human somatic cells at a constant 46.

Reading Check ***What kind of cells do germ cells produce?***

Haploid and Diploid Cells A cell, such as a somatic cell, that has two sets of chromosomes is **diploid.** A cell is **haploid** if it has one set of chromosomes. Gametes are haploid cells. The symbol n is used to represent the number of chromosomes in one set. Human gametes have 23 chromosomes, so $n = 23$. The diploid number in somatic cells is written as $2n$. Human somatic cells have 46 chromosomes ($2n = 46$).

Homologous Chromosomes Each diploid cell has pairs of chromosomes made up of two homologous chromosomes. **Homologous chromosomes** are chromosomes that are similar in size, in shape, and in kinds of genes that they contain. Each chromosome in a homologous pair comes from one of the two parents. In humans, one set of 23 chromosomes comes from the mother, and one set comes from the father. Homologous chromosomes can carry different forms of genes. For example, flower color in peas is determined by a gene on one of its chromosomes. The form of this gene can be white or purple. The cells of each pea plant will have two flower-color genes, one on each of the chromosomes that carry the flower-color gene. Both could be genes for white flower color, or both could be genes for purple flower color. Or one gene could be for white color, and the other could be for purple color.

Autosomes and Sex Chromosomes *Autosomes* are chromosomes with genes that do not determine the sex of an individual. *Sex chromosomes* have genes that determine the sex of an individual. In humans and many other organisms, the two sex chromosomes are referred to as the *X* and *Y chromosomes*. The genes that cause a zygote to develop into a male are located on the Y chromosome. Human males have one X chromosome and one Y chromosome (XY), and human females have two X chromosomes (XX).

Chromosome Number of Various Organisms

Organism	Number ($2n$) of chromosomes
Penicillium	1–4
Saccharomyces (yeast)	16
Mosquito	6
Housefly	12
Garden pea	14
Corn	20
Fern	480–1,020
Frog	26
Human	46
Orangutan	48
Dog	78

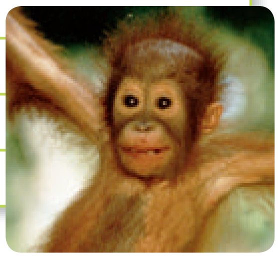


Figure 3
Different species have different numbers of chromosomes.

READING TOOLBOX

Key-Term Fold On the back of your key-term fold, write a definition in your own words for the key terms in this section.

Section 1 Review

KEY IDEAS

1. **Compare** the offspring in asexual reproduction with the parent.
2. **Describe** how the offspring in sexual reproduction compares genetically with its parent.
3. **Compare** the number of sets of chromosomes between a haploid cell and a diploid cell.
4. **Explain** why chromosomes are important for organisms.

CRITICAL THINKING

5. **Inferring Relationships** Why are haploid cells important in sexual reproduction?
6. **Forming Reasoned Opinions** Do you agree or disagree that homologous chromosomes occur in gametes? Explain.

METHODS OF SIENCE

7. **Evaluating Hypotheses** A student states that organisms that reproduce asexually are at a disadvantage in a stable environment. If you agree with this hypothesis, name one or more of its strengths. If you disagree, name one or more of its weaknesses.

Section 2

Meiosis

Key Ideas	Key Terms	Why It Matters
❯ What occurs during the stages of meiosis? ❯ How does the function of mitosis differ from the function of meiosis? ❯ What are three mechanisms of genetic variation?	meiosis crossing-over independent assortment	Meiosis allows genetic information from two parents to combine to form offspring that are different from both parents.

Most cells that divide and produce new cells form two offspring cells that have the same number of chromosomes as the parent cell. How do haploid gametes form from a diploid germ cell? **Meiosis** is a form of cell division that produces daughter cells with half the number of chromosomes that are in the parent cell.

Stages of Meiosis

Before meiosis begins, the chromosomes in the original cell are copied. Meiosis involves two divisions of the nucleus—meiosis I and meiosis II. ❯ **During meiosis, a diploid cell goes through two divisions to form four haploid cells.** In meiosis I, homologous chromosomes are separated. In meiosis II, the sister chromatids of each homologue are separated. As a result, four haploid cells are formed from the original diploid cell. **Figure 4** illustrates the steps of meiosis.

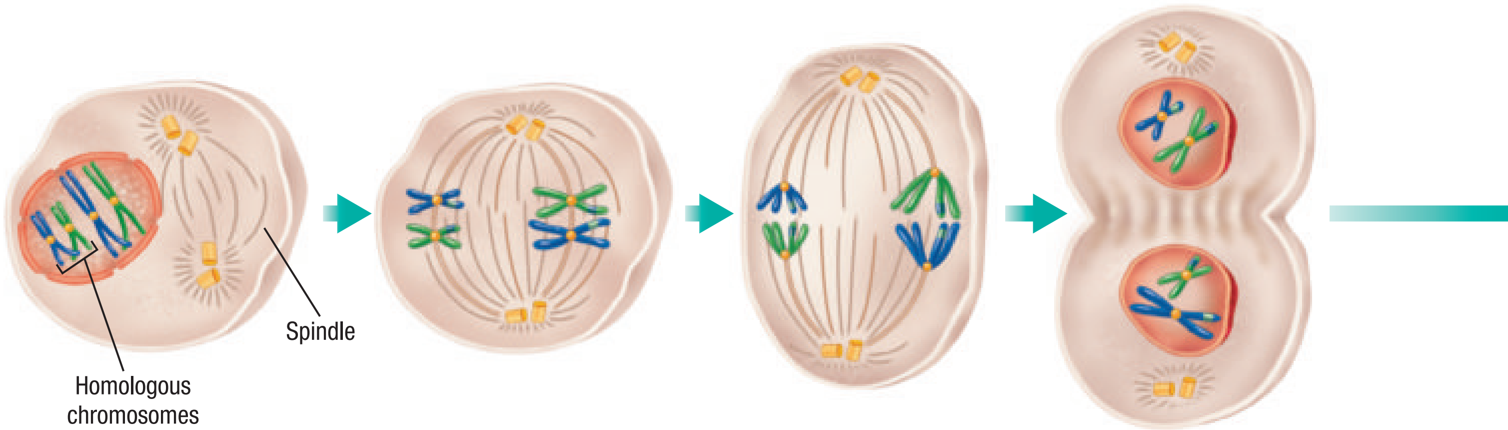
Stages of Meiosis I

1 Prophase I Chromosomes condense. The nuclear envelope breaks down.

2 Metaphase I Pairs of homologous chromosomes move to the cell's equator.

3 Anaphase I Homologous chromosomes move to the cell's opposite poles.

4 Telophase I Chromosomes gather at the poles. The cytoplasm divides.



Meiosis I Meiosis begins with a diploid cell that has copied its chromosomes. The first phase is prophase I. **1** During prophase I, the chromosomes condense, and the nuclear envelope breaks down. Homologous chromosomes pair. Chromatids exchange genetic material in a process called **crossing-over.** **2** In metaphase I, the spindle moves the pairs of homologous chromosomes to the equator of the cell. The homologous chromosomes remain together. **3** In anaphase I, the homologous chromosomes separate. The spindle fibers pull the chromosomes of each pair to opposite poles of the cell. But the chromatids do not separate at their centromeres. Each chromosome is still made of two chromatids. The genetic material, however, has recombined. **4** During telophase I, the cytoplasm divides (cytokinesis), and two new cells are formed. Both cells have one chromosome from each pair of homologous chromosomes.

Meiosis II Meiosis II begins with the two cells formed at the end of telophase I of meiosis I. The chromosomes are not copied between meiosis I and meiosis II. **5** In prophase II, new spindles form. **6** During metaphase II, the chromosomes line up along the equators and are attached at their centromeres to spindle fibers. **7** In anaphase II, the centromeres divide. The chromatids, which are now called *chromosomes,* move to opposite poles of the cell. **8** During telophase II, a nuclear envelope forms around each set of chromosomes. The spindle breaks down, and the cell goes through cytokinesis. The result of meiosis is four haploid cells.

Reading Check ***In what phase of meiosis is genetic material exchanged?***

meiosis a process in cell division during which the number of chromosomes decreases to half the original number by two divisions of the nucleus, which results in the production of sex cells (gametes or spores)

crossing-over the exchange of genetic material between homologous chromosomes during meiosis

Figure 4 During meiosis, four haploid cells are produced from a diploid cell. ***What is the difference between anaphase I and anaphase II?***

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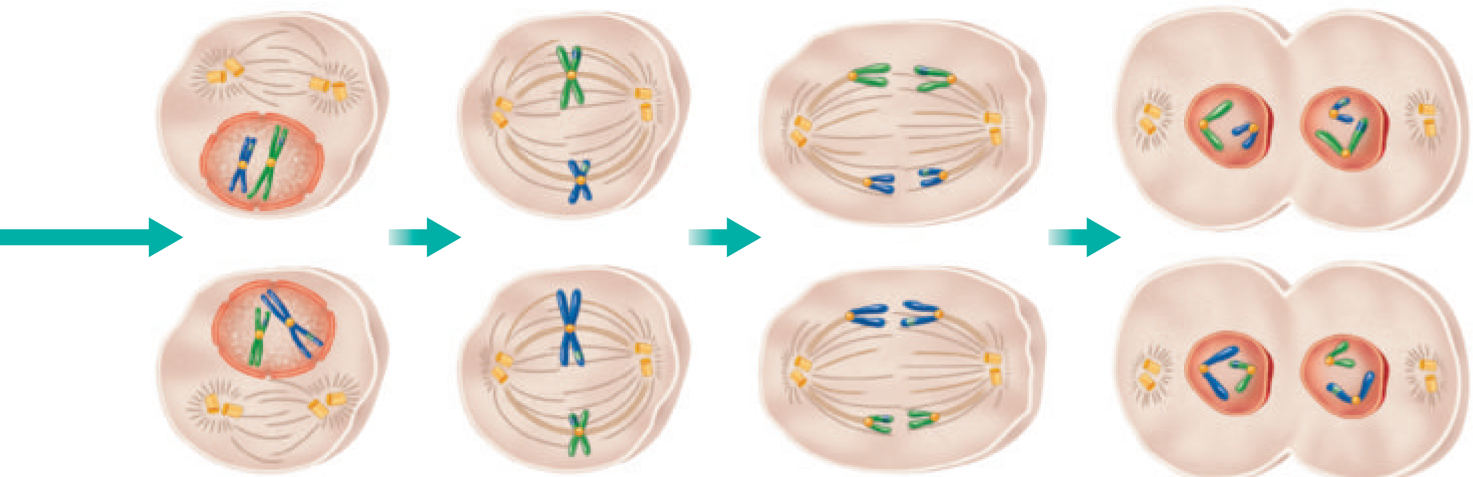
Stages of Meiosis II

5 Prophase II A new spindle forms around the chromosomes.

6 Metaphase II Chromosomes line up at the equators.

7 Anaphase II Centromeres divide, and chromatids move to opposite poles.

8 Telophase II A nuclear envelope forms around each set of chromosomes. The cells divide.



Comparing Mitosis and Meiosis

The processes of mitosis and meiosis are similar but meet different needs and have different results. **Mitosis makes new cells that are used during growth, development, repair, and asexual reproduction. Meiosis makes cells that enable an organism to reproduce sexually and happens only in reproductive structures.** Mitosis produces two genetically identical diploid cells. In contrast, meiosis produces four genetically different haploid cells. The haploid cells produced by meiosis contain half the genetic information of the parent cell. When two such cells, often an egg cell and a sperm cell, combine, the resulting zygote has the same number of chromosomes as each of the parents' cells.

If you compare meiosis and mitosis, as shown in **Figure 5**, you may think that they are alike. For example, in metaphase of mitosis and metaphase I of meiosis, the chromosomes move to the equator. However, there is a major difference that happens in an earlier stage.

In prophase I of meiosis, every chromosome pairs with its homologue. A pair of homologous chromosomes is called a *tetrad.* As the tetrads form, different homologues exchange parts of their chromatids in the process of crossing-over. The pairing of homologous chromosomes and the crossing-over do not happen in mitosis. Therefore, a main difference between meiosis and mitosis is that in meiosis, genetic information is rearranged. The rearranging of genetic information leads to genetic variation in offspring. Crossing-over is one of several processes that lead to genetic variation.

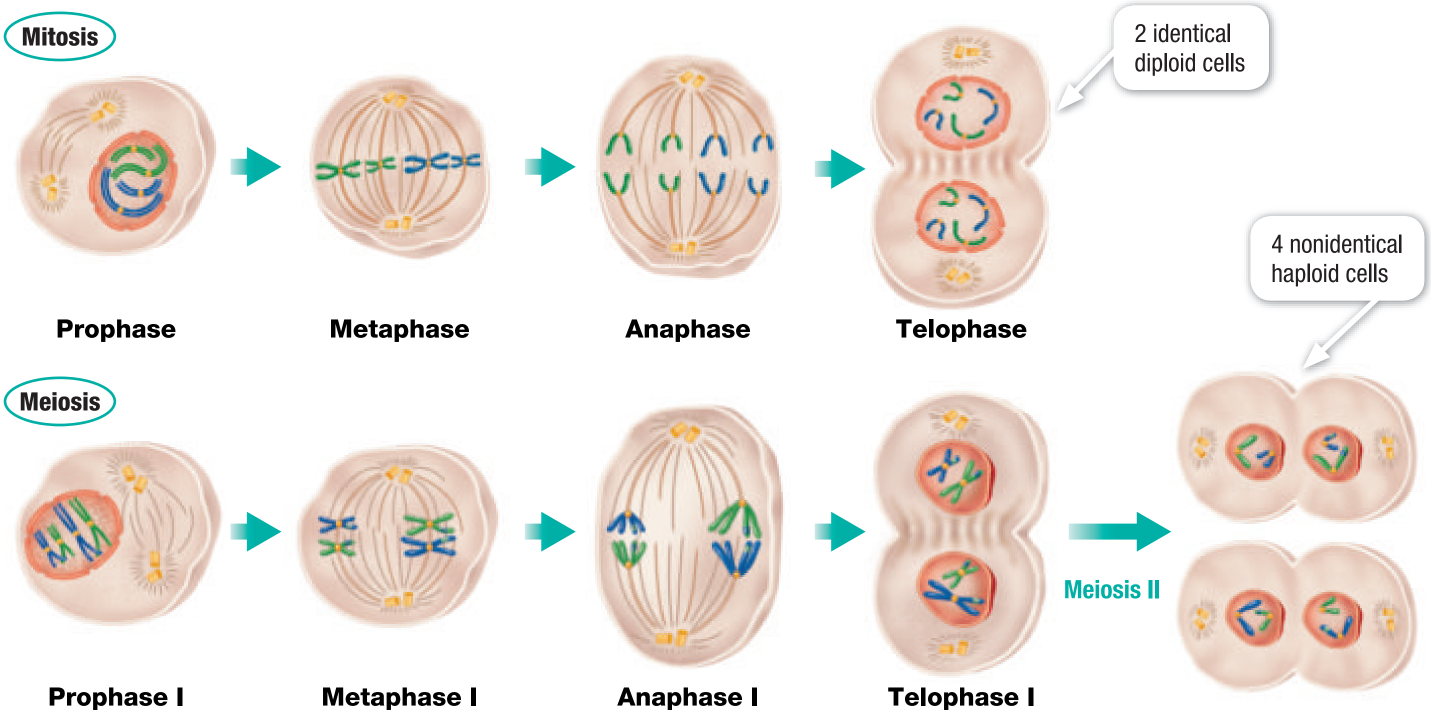
Reading Check ***How are cells formed by mitosis different from cells formed by meiosis in relation to number of chromosomes?***

READING TOOLBOX

Comparisons Write two sentences that compare and two sentences that contrast meiosis and mitosis.

Figure 5 Mitosis produces two diploid daughter cells that are identical to the parent cell. Meiosis produces four haploid cells from a diploid cell. *What is the difference between anaphase in mitosis and anaphase I in meiosis I?*

Comparing Mitosis and Meiosis



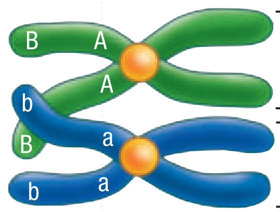
Hands On

QuickLab

30 min

Crossing-Over Model

You can use paper strips and pencils to model the process of crossing-over.



Procedure

1. Use a **colored pencil** to write "A" and "B" on **two paper strips.** These two strips will represent one of the two homologous chromosomes shown.
2. Use a **second colored pencil** to write "a" and "b" on **two paper strips**. These two strips will represent the second homologous chromosome shown.
3. **CAUTION: Handle scissors with care.** Use your chromosome models, **scissors,** and **tape** to demonstrate crossing-over between two chromatids.

Analysis

1. **Determine** what the letters *A, B, a,* and *b* represent.
2. **Making Inferences** Explain why the chromosomes that you made are homologous.
3. **Compare** the number of different types of chromatids (combinations of *A, B, a,* and *b*) before crossing-over with the number after crossing-over.
4. CRITICAL THINKING **Analyzing Information** How does crossing-over relate to genetic recombination?

Genetic Variation

Genetic variation is advantageous for a population. Genetic variation can help a population survive a major environmental change. For example, in the Arctic, if temperatures drop below average, those polar bears with genes that make thicker fur will survive. Polar bears without the genes for thicker fur may die out. The polar bears with the genes for thicker fur reproduce, and the population grows. Now, suppose that all of the individuals in the population have the same genes, but none of the genes are for thicker fur. What do you think will happen if the temperature drops below average? The entire population of polar bears may die out.

Genetic variation is made possible by sexual reproduction. In sexual reproduction, existing genes are rearranged. Meiosis is the process that makes the rearranging of genes possible. Fusion of haploid cells from two different individuals adds further variation. **› Three key contributions to genetic variation are crossing-over, independent assortment, and random fertilization.**

Crossing-Over During prophase I, homologous chromosomes line up next to each other. Each homologous chromosome is made of two sister chromatids attached at the centromere. Crossing-over happens when one arm of a chromatid crosses over the arm of the other chromatid, as illustrated in the QuickLab. The chromosomes break at the point of the crossover, and each chromatid re-forms its full length with the piece from the other chromosome. Thus, the sister chromatids of a homologous chromosome no longer have identical genetic information.

› Reading Check *How can crossing-over increase genetic variation?*

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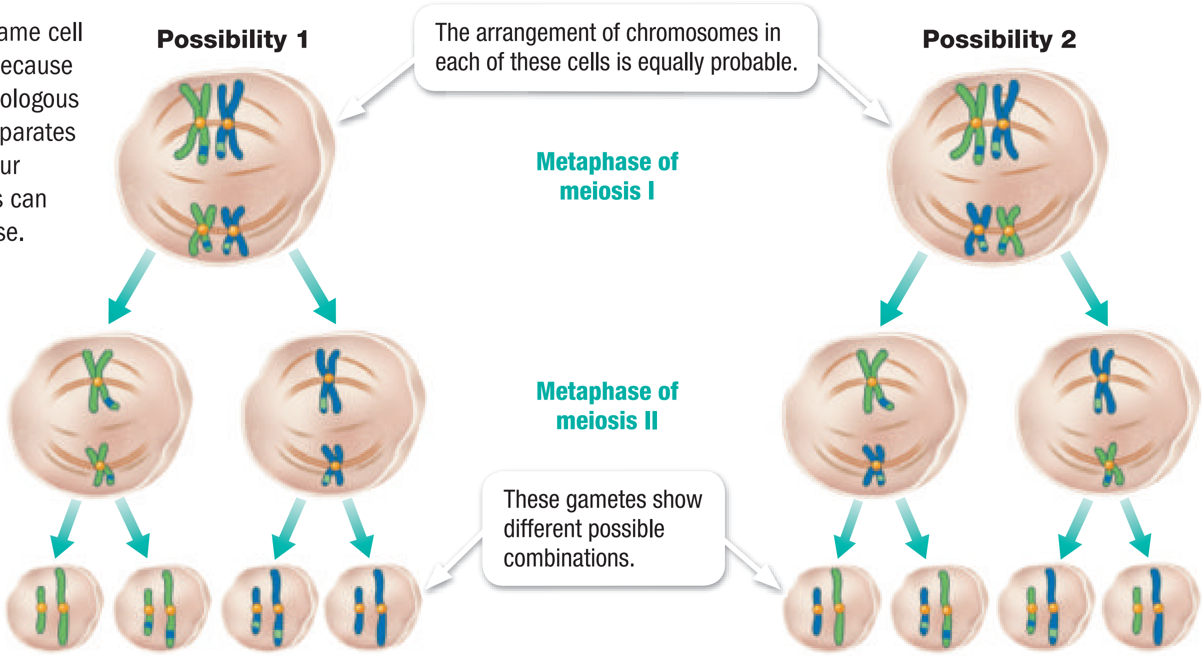
ACADEMIC VOCABULARY

exist to occur or be present

Figure 6 The same cell is shown twice. Because each pair of homologous chromosomes separates independently, four different gametes can result in each case.



independent assortment the random distribution of the pairs of genes on different chromosomes to the gametes

Independent Assortment During metaphase I, homologous pairs of chromosomes line up at the equator of the cell. The two pairs of chromosomes can line up in either of two equally probable ways. This random distribution of homologous chromosomes during meiosis is called **independent assortment.** The four haploid cells formed in possibility 1 in **Figure 6** have entirely different combinations of chromosomes than do the four cells made in possibility 2.

In humans, each gamete receives one chromosome from each of 23 pairs of homologous chromosomes. Each of the 23 pairs of chromosomes separates independently. Thus, 2^{23} (about 8 million) gametes with different gene combinations can be made from one original cell.

Random Fertilization Fertilization is a random process that adds genetic variation. The zygote that forms is made by the random joining of two gametes. Because fertilization of an egg by a sperm is random, the number of possible outcomes is *squared.* In humans, the possibility is $2^{23} \times 2^{23}$, or 64 trillion, different combinations!

Section 2 Review

KEY IDEAS

1. **Summarize** the different phases of meiosis.
2. **Explain** how the function of meiosis differs from the function of mitosis.
3. **Describe** three mechanisms of genetic variation.

CRITICAL THINKING

4. **Comparing Functions** Compare the processes of crossing-over and independent assortment. How does each contribute to genetic variation?
5. **Inferring Conclusions** Why might sexual reproducers better adapt to a changing environment than asexual reproducers?

ALTERNATIVE ASSESSMENT

6. **Word Problem** If one cell in a dog ($2n = 78$) undergoes meiosis and another cell undergoes mitosis, how many chromosomes will each resulting cell contain?

Section 3

Multicellular Life Cycles

Key Ideas	Key Terms	Why It Matters
What is a diploid life cycle? What is a haploid life cycle? What is alternation of generations?	life cycle sperm ovum	Some life cycles are mainly diploid, others are mainly haploid, and still others alternate between haploid and diploid phases.

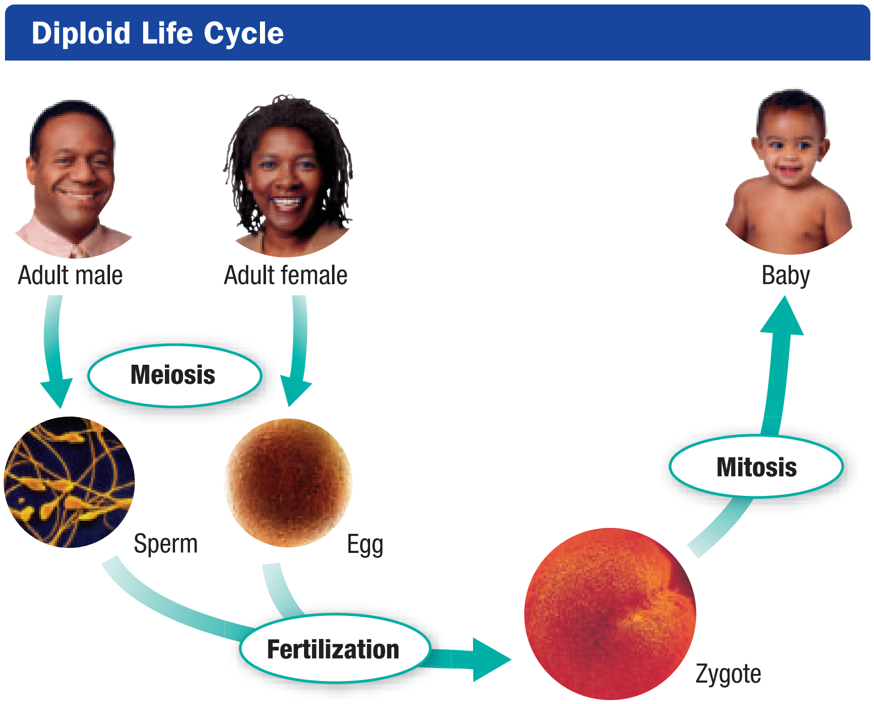
All of the events in the growth and development of an organism until the organism reaches sexual maturity are called a **life cycle.** All organisms that reproduce sexually have both diploid stages and haploid stages.

Diploid Life Cycle

Most animals have a diploid life cycle. **Figure 7** illustrates this type of life cycle. Most of the life cycle is spent in the diploid state. All of the cells except the gametes are diploid.

A diploid germ cell in a reproductive organ goes through meiosis and forms gametes. The gametes, the sperm and the egg, join during fertilization. The result is a diploid zygote. This single diploid cell goes through mitosis and eventually gives rise to all of the cells of the adult, which are also diploid. **In diploid life cycles, meiosis in germ cells of a multicellular diploid organism results in the formation of haploid gametes.**

Figure 7 Humans and most other animals have a life cycle dominated by a diploid individual. ***What are the only haploid cells in a diploid life cycle?***



life cycle all of the events in the growth and development of an organism until the organism reaches sexual maturity

sperm the male gamete (sex cell)

ovum a mature egg cell

Meiosis and Gamete Formation

Male animals produce gametes called **sperm.** As **Figure 8** illustrates, a diploid germ cell goes through meiosis I. Two cells are formed, each of which goes through meiosis II. The result is four haploid cells. The four cells change in form and develop a tail to form four sperm.

Female animals produce gametes called eggs, or ova (singular, **ovum**). A diploid germ cell begins to divide by meiosis. Meiosis I results in the formation of two haploid cells that have unequal amounts of cytoplasm. One of the cells has nearly all of the cytoplasm. The other cell, called a *polar body,* is very small and has a small amount of cytoplasm. The polar body may divide again, but its offspring cells will not survive. The larger cell goes through meiosis II, and the division of the cell's cytoplasm is again unequal. The larger cell develops into an ovum. The smaller cell, the second polar body, dies. Because of its larger share of cytoplasm, the mature ovum has a rich storehouse of nutrients. These nutrients nourish the young organism that develops if the ovum is fertilized.

Reading Check *How many gametes are formed from one female germ cell?*

Data QuickLab 15 min

Chromosome Combinations

When a sperm and egg fuse, two sets of chromosomes are combined. In this lab, you will model this cross between two sets of chromosomes.

Procedure

1. **Write** "F1F2 X M1M2" on a sheet of paper. F1 and F2 represent the father's chromosomes. M1 and M2 represent the mother's chromosomes.
2. **Determine** all of the possible chromosome combinations in the zygote that forms from the fusion of the gametes with the chromosomes that you wrote in step 1.

Analysis

1. **Calculate** the number of chromosome combinations that are possible in the zygote.
2. CRITICAL THINKING **Analyzing Data** List all of the possible chromosome combinations.

Figure 8 Meiosis of diploid germ cells results in haploid gametes.

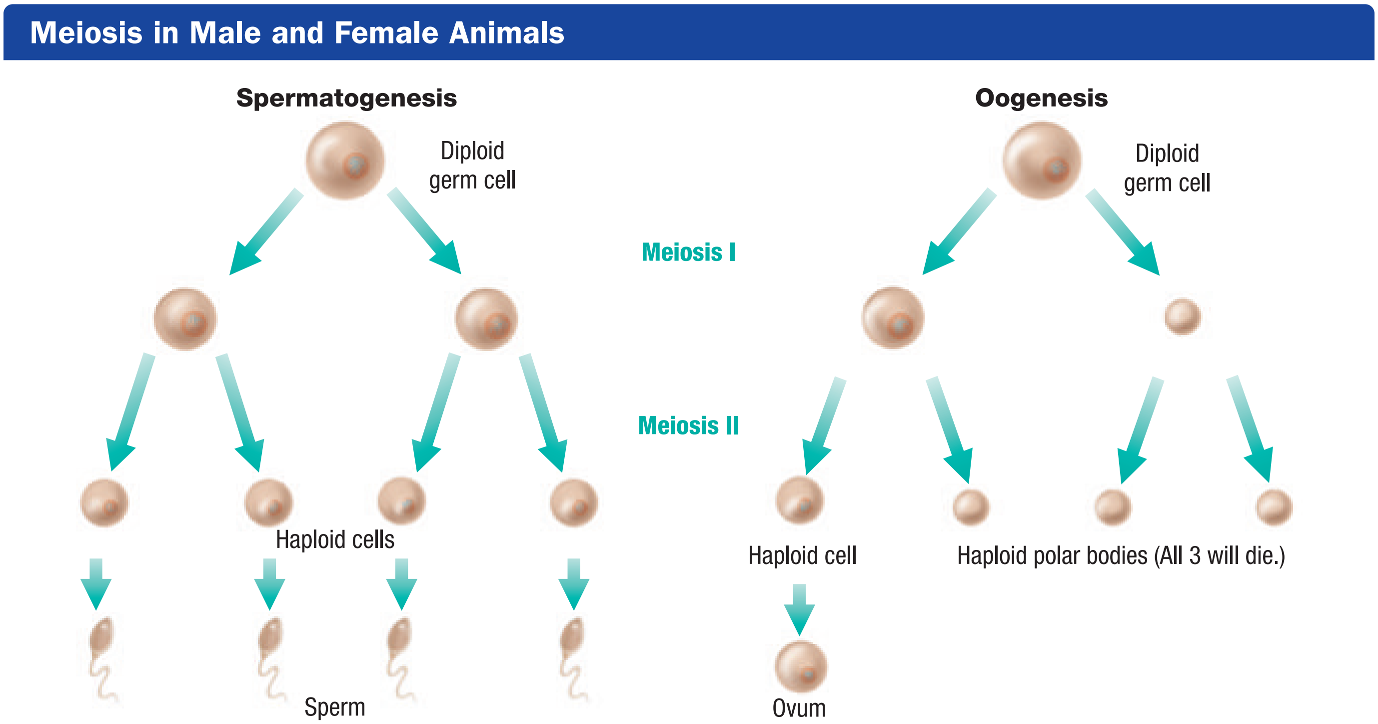
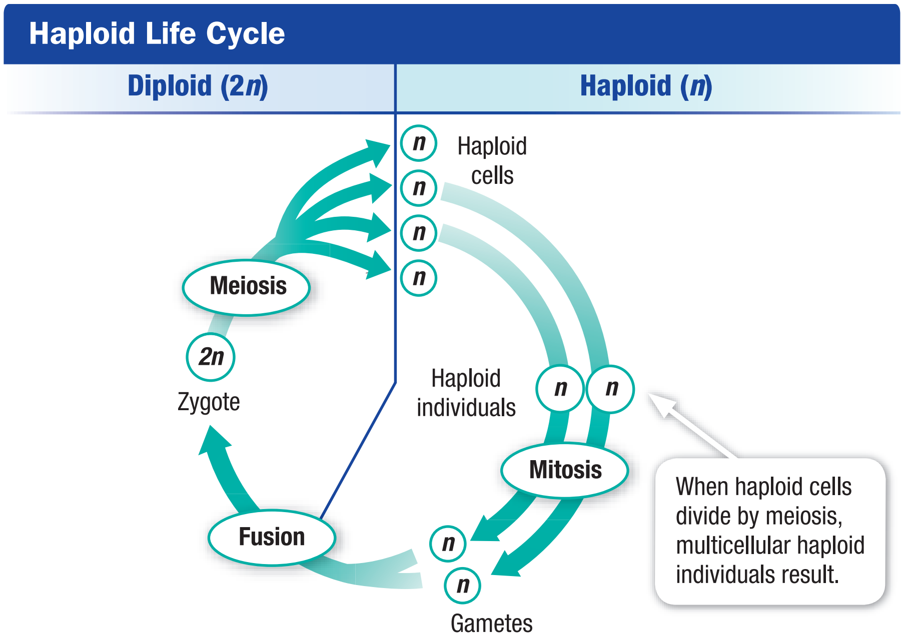


Figure 9 Some organisms, such as fungi, have haploid cells as a major portion of their life cycles.



Haploid Life Cycle

The haploid life cycle, shown in **Figure 9,** happens in most fungi and some protists. Haploid stages make up the major part of this life cycle. The zygote, the only diploid structure, goes through meiosis immediately after it is formed and makes new haploid cells. The haploid cells divide by mitosis and give rise to multicellular haploid individuals. **In haploid life cycles, meiosis in a diploid zygote results in the formation of the first cell of a multicellular haploid individual.**

READING TOOLBOX

Two-column notes Use two-column notes to summarize the stages and details of the haploid life cycle.

Alternation of Generations

Plants and most multicellular protists have a life cycle that alternates between a haploid phase and a diploid phase called *alternation of generations*. In plants, the multicellular diploid phase in the life cycle is called a *sporophyte*. Spore-forming cells in the sporophyte undergo meiosis and produce spores. A spore forms a multicellular gametophyte. The *gametophyte* is the haploid phase that produces gametes by mitosis. The gametes fuse and give rise to the diploid phase.

Section 3 Review

KEY IDEAS

1. **Summarize** the process in a diploid life cycle.
2. **Describe** what happens in a haploid life cycle.
3. **Describe** what happens to the polar bodies formed during meiosis of a female diploid cell in animal.
4. **Explain** the alternation of generations life cycle.

CRITICAL THINKING

5. **Evaluating Processes** How does the formation of sperm through meiosis of a diploid germ cell differ from the formation of an ovum from a diploid germ cell?
6. **Analyzing Information** What type of cell or structure is the first stage of every sexual life cycle?

WRITING IN SCIENCE

7. **Lesson Plan** Write a lesson plan that you can use to teach a classmate the difference between a haploid and a diploid life cycle. In your own words, write a summary of each. Include diagrams with your explanation.

Chapter 11

Summary

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SUPER SUMMARY
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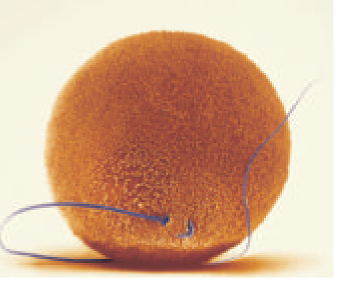
Key Ideas	Key Terms

1 Reproduction

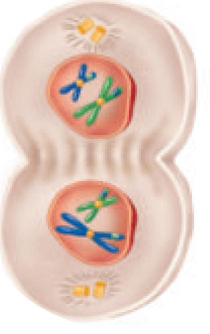


- An individual formed by asexual reproduction is genetically identical to its parent.
- In sexual reproduction, two parents give genetic material to produce offspring that are genetically different from their parents.
- Each chromosome has thousands of genes that play an important role in determining how an organism develops and functions.

Key Terms: **gamete** (248), **zygote** (248), **diploid** (249), **haploid** (249), **homologous chromosomes** (249)

2 Meiosis

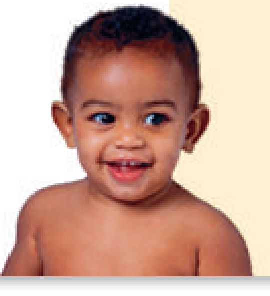
- During meiosis, a diploid cell goes through two divisions to form four haploid cells.
- Mitosis produces cells that are used during growth, development, repair, and asexual reproduction. Meiosis makes cells that enable an organism to reproduce sexually and it only happens in reproductive structures.
- Three key contributions to genetic variation are crossing-over, independent assortment, and random fertilization.



Key Terms: **meiosis** (250), **crossing-over** (251), **independent assortment** (254)

3 Multicellular Life Cycles

- In diploid life cycles, meiosis in germ cells of a multicellular diploid organism results in the formation of haploid gametes.
- In haploid life cycles, meiosis in a diploid zygote results in the formation of the first cell of a multicellular haploid individual.
- Plants and most multicellular protists have a life cycle that alternates between a haploid phase and a diploid phase called *alternation of generations*.



Key Terms: **life cycle** (256), **sperm** (257), **ovum** (257)