8 Cellular Reproduction: Cells from Cells

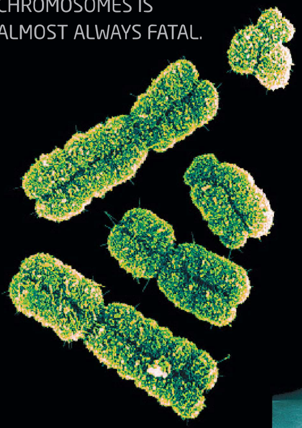
CHAPTER CONTENTS

Why Cellular Reproduction Matters

About 9 months before you were born, you were just a single cell. From that microscopic beginning, every cell in your body was created through cell reproduction. Even today, millions of cells are reproducing themselves in your body every second—and errors in the process can be deadly.

IF STRETCHED OUT, THE DNA IN ANY ONE OF YOUR CELLS WOULD BE TALLER THAN YOU!

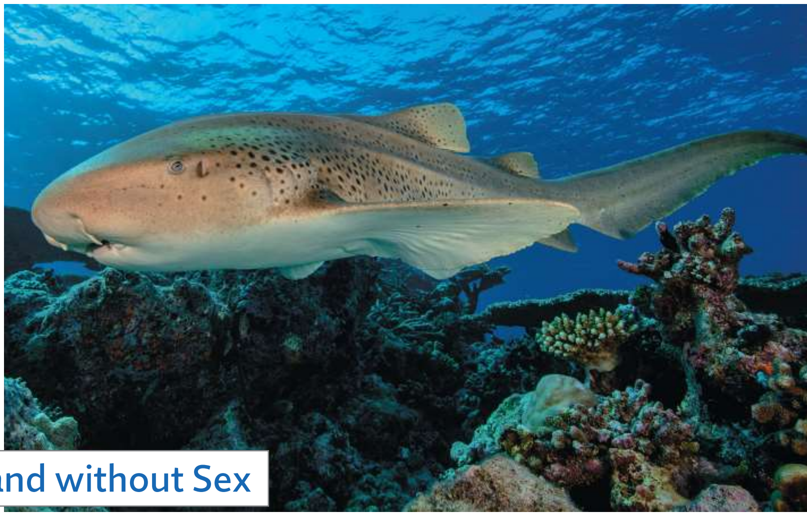
KEEPING TRACK OF CHROMOSOMES DURING CELL DIVISION IS VITAL: DUPLICATING THE WRONG NUMBER OF CHROMOSOMES IS ALMOST ALWAYS FATAL.



A TUMOR RESULTS FROM AN ERROR IN THE DIVISION OF ONE OF THE BODY'S OWN CELLS.

CHAPTER THREAD

Life with and without Sex



Zebra shark. The zebra shark can be found living around coral reefs and sandy bottoms in the Indian and Pacific Oceans.

BIOLOGY AND SOCIETY Life with and without Sex

Virgin Birth of a Shark

Biologists at the Reef HQ Aquarium in Queensland, Australia helped care for Leonie, a female zebra shark (*Stegostoma fasciatum*) captured from the wild. To promote a breeding program, a male shark was introduced to Leonie's tank, resulting in several litters of offspring. When the aquarium decided to end the breeding program, the male shark was removed, and Leonie lived in the tank with a daughter.

No one was surprised that Leonie continued to lay eggs. After all, sharks, like chickens (or, for that matter, humans), produce infertile eggs even in the absence of sex. But Leonie's keepers were shocked when, in 2015, she laid eggs with viable embryos in them. One of those eggs hatched into Cleo, a healthy daughter. This is surprising because the vast majority of animal species create offspring only through sexual reproduction, involving the union of a male's sperm with a female's egg. But, despite the fact that Leonie was last in the company of a male three years prior, she produced a normal daughter. Cleo remains on display at the aquarium today.

DNA analysis confirmed that Cleo's genes came solely from her mother. The birth had resulted from parthenogenesis, the production of offspring by a female without involvement of a male. Parthenogenesis is rare among vertebrates (animals with backbones), although it has been documented in about 70 species as diverse as lizards (including the Komodo dragon, the world's largest lizard), domesticated birds (such as chickens and turkeys), and frogs. (In case you were wondering, there are no documented cases of parthenogenesis among humans or other mammals.) It is extremely rare, however, for a single female to produce offspring via both sexual reproduction and parthenogenesis. Leonie's case proved that zebra sharks can switch between two reproductive modes—the first documented case of this ability among sharks. Biologists are investigating the evolutionary basis of this phenomenon and considering what implications it may have on efforts to repopulate endangered species such as the zebra sharks and Komodo dragons.

The ability of organisms to procreate best distinguishes living things from nonliving matter. All organisms—from bacteria to lizards to you—are the result of repeated cell divisions. Therefore, the perpetuation of life depends on cell division, the production of new cells. In this chapter, we'll look at how individual cells are copied and then see how cell reproduction underlies the process of sexual reproduction. Throughout our discussion, we'll consider examples of asexual and sexual reproduction among both plants and animals.

What Cell Reproduction Accomplishes

When you hear the word *reproduction*, you probably think of the birth of new organisms. But reproduction actually occurs much more often at the cellular level. Consider the skin on your arm. Skin cells are constantly reproducing themselves and moving outward toward the surface, replacing dead cells that have rubbed off. This renewal of your skin goes on throughout your life. And when your skin is injured, reproduction of cells helps heal the wound.

When a cell undergoes reproduction, the process is called **cell division**. The two "daughter" cells that result from cell division are genetically identical to each other and to the original "parent" cell. (Biologists traditionally use the word *daughter* in this context to refer to offspring cells even though cells lack gender.) Before the parent cell splits into two, it duplicates its **chromosomes**, the structures that contain most of the cell's DNA. Then, during cell division, each daughter cell receives one identical set of chromosomes from the original parent cell.

As summarized in Figure 8.1, cell division plays several important roles in the lives of organisms. For example, within your body, millions of cells must divide every second to replace damaged or lost cells. Another function of cell division is growth. All of the trillions of cells in your body are the result of repeated cell divisions that began in your mother's body with a single fertilized egg cell.

Another vital function of cell division is reproduction. Many single-celled organisms, such as amoebas, reproduce by dividing in half, and the offspring are genetic replicas of the parent. This is an example of **asexual reproduction**, the creation of genetically identical offspring by a single parent, without the participation of sperm and egg. Offspring produced by asexual reproduction inherit all their chromosomes from a single parent and are thus genetic duplicates. An individual that reproduces asexually gives rise to a **clone**, a group of genetically identical individuals.

Many multicellular organisms can reproduce asexually as well. For example, some sea star species can grow new individuals from fragmented pieces. If you've ever grown a houseplant from a clipping, you've observed asexual reproduction in plants. In asexual reproduction, there is one simple principle of inheritance: The lone parent and each of its offspring have identical genes. The type of cell division responsible for asexual reproduction and for the growth and maintenance of multicellular organisms is called mitosis.

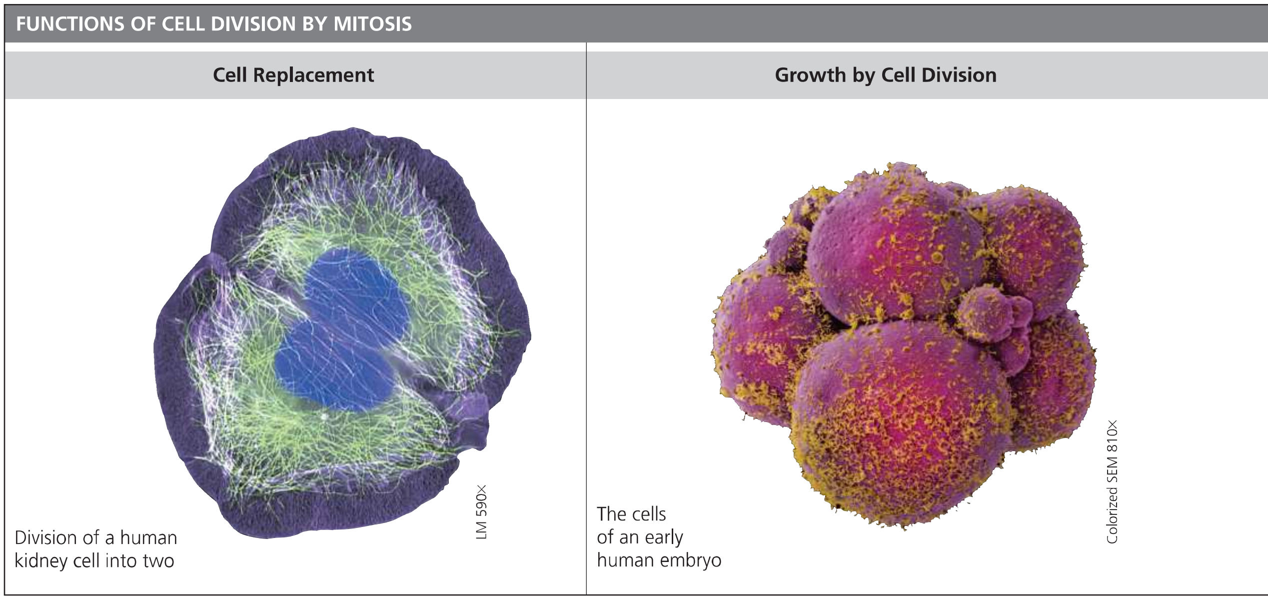
Sexual reproduction is different; it requires fertilization of an egg by a sperm. The production of **gametes**—egg and sperm—involves a special type of cell division called meiosis, which occurs only in reproductive organs. As we'll discuss later, a gamete has only half as many chromosomes as the parent cell that gave rise to it.

In summary, two kinds of cell division are involved in sexually reproducing organisms: mitosis for growth and maintenance and meiosis for reproduction. To define and distinguish these processes, the remainder of the chapter is divided into two main sections: one on mitosis and one on meiosis. ✓

✓ CHECKPOINT

Ordinary cell division produces two daughter cells that are genetically identical. Name three functions of this type of cell division. Which of these functions occur in your body?

■ Answer: Cell replacement, growth of an organism, and asexual reproduction of an organism. Only the first two occur in your body.



▶ Figure 8.1 Three functions of cell division by mitosis.

The Cell Cycle and Mitosis

Almost all the genes of a eukaryotic cell—around 21,000 in humans—are located on chromosomes in the cell nucleus. (The main exceptions are genes on small DNA molecules found in mitochondria and chloroplasts.) Because chromosomes are the lead players in cell division, we'll focus on them before turning our attention to the cell as a whole.

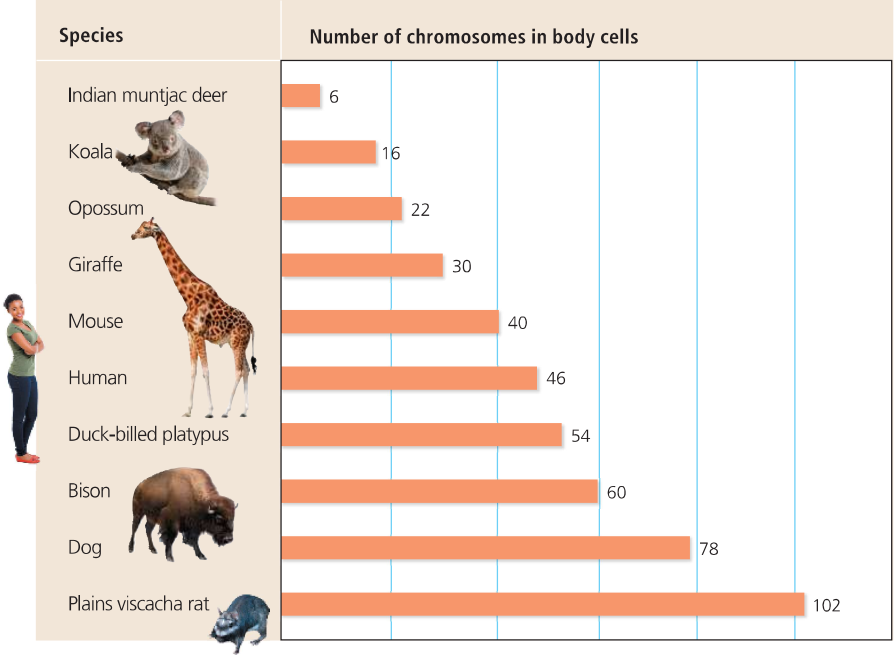
IF STRETCHED OUT, THE DNA IN ANY ONE OF YOUR CELLS WOULD BE TALLER THAN YOU!

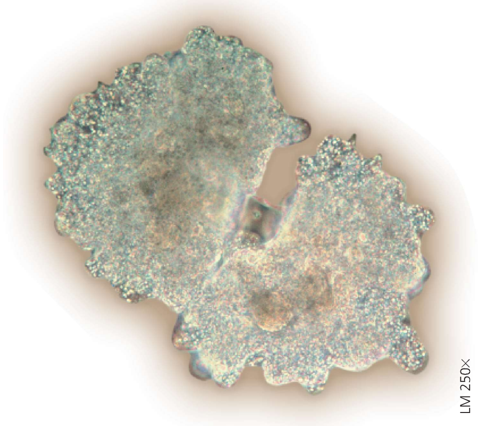
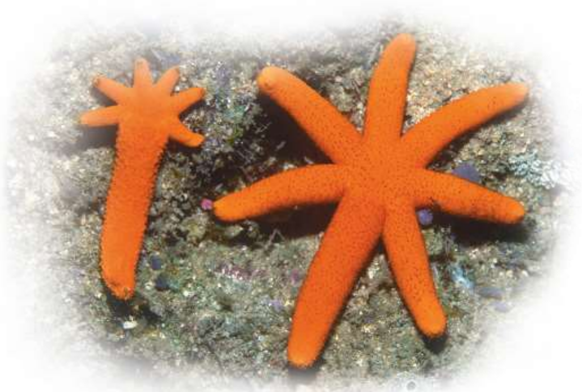
Eukaryotic Chromosomes

Each eukaryotic chromosome contains one very long DNA molecule, typically bearing thousands of genes. The number of chromosomes in a eukaryotic cell depends on the species **(Figure 8.2)**. For example, human body cells have 46 chromosomes, while the body cells of a dog have 78 and those of a koala have 16. Chromosomes are made up of a material called **chromatin**, fibers composed of roughly equal amounts of DNA and protein molecules. The protein molecules help organize the chromatin and help control the activity of its genes.

Most of the time, the chromosomes exist as thin fibers that are much longer than the nucleus they are stored in. In fact, if fully extended, the DNA in just one of your cells would be more than 6 feet long! Chromatin in this state is too thin to be seen using a light

▼ **Figure 8.2 The number of chromosomes in the cells of selected mammals.** Notice that humans have 46 chromosomes and that the number of chromosomes does not correspond to the size or complexity of an organism.



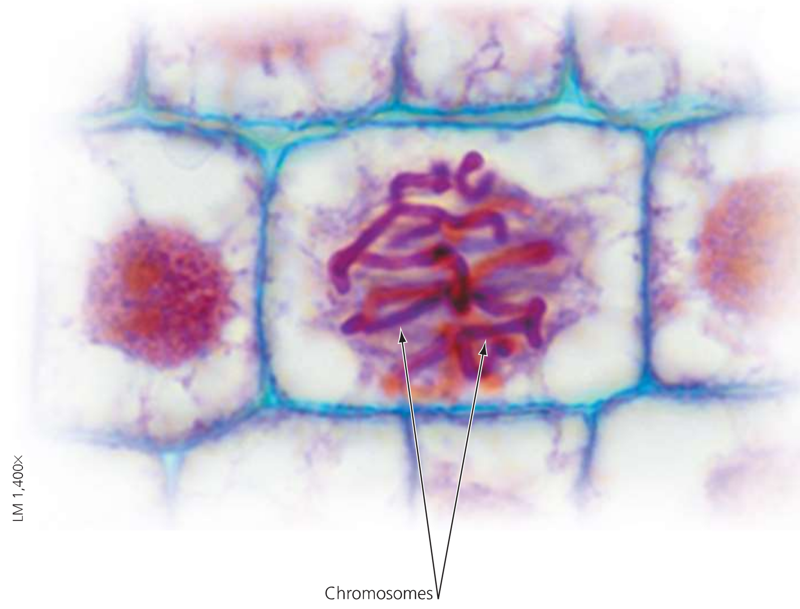
	Asexual Reproduction	
 LM 250× Reproduction of an amoeba	 Fragmentation and regeneration of a sea star. The sea star on the right lost and replaced an arm. The severed arm grew into the new sea star on the left.	 Reproduction of an African violet from a clipping (large leaf)

microscope. As a cell prepares to divide, its chromatin fibers coil up, forming compact chromosomes that become visible under a light microscope **(Figure 8.3)**.

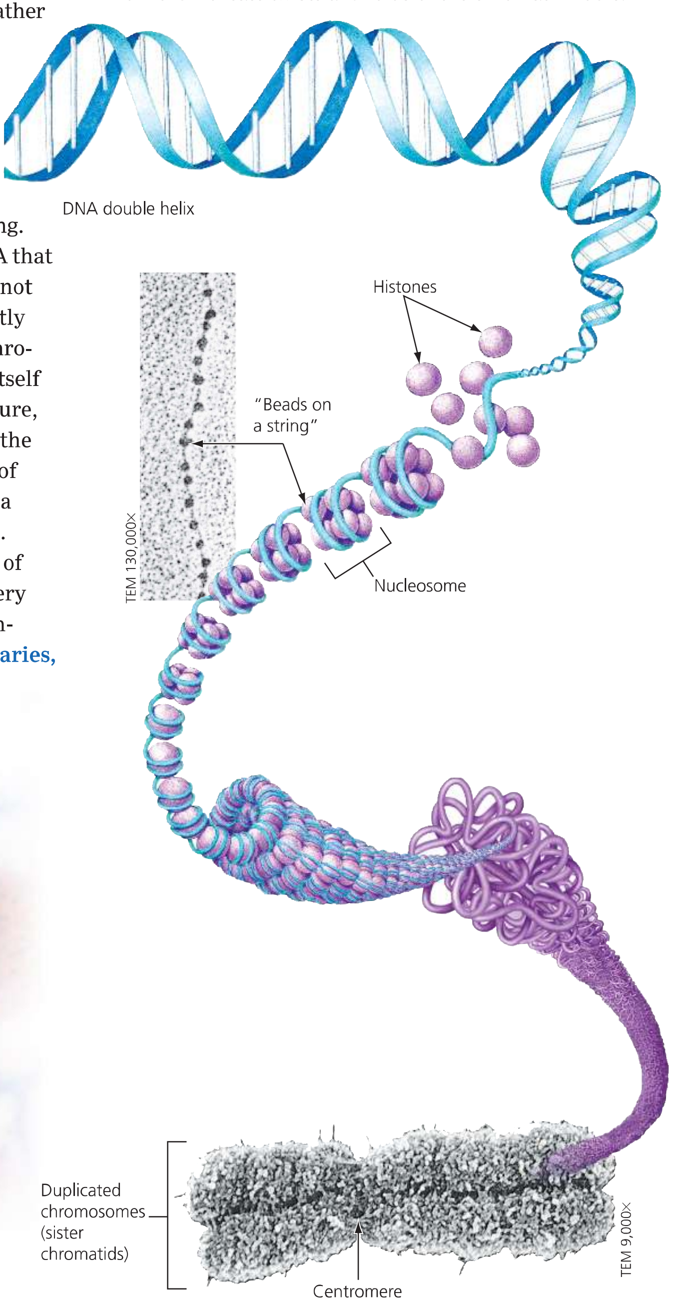
Such long molecules of DNA can fit into the tiny nucleus because within each chromosome the DNA is packed into an elaborate, multilevel system of coiling and folding. A crucial aspect of DNA packing is the association of the DNA with small proteins called **histones**. Why is it necessary for a cell's chromosomes to be compacted in this way? Imagine that your belongings are spread out around your room. If you had to move, you would gather up all your things and put them in small containers. Similarly, a cell must compact its DNA before it can move it to a new cell.

Figure 8.4 presents a simplified model of DNA packing. First, histones attach to the DNA. In electron micrographs, the combination of DNA and histones has the appearance of beads on a string. Each "bead," called a **nucleosome**, consists of DNA that is wound around several histone molecules. When not dividing, the DNA of active genes takes on this lightly packed arrangement. When preparing to divide, chromosomes condense even more: The beaded string itself wraps, loops, and folds into a tight, compact structure, as you can see in the chromosome at the bottom of the figure. Viewed as a whole, Figure 8.4 gives a sense of how successive levels of coiling and folding enable a huge amount of DNA to fit into a cell's tiny nucleus. If you think of a DNA molecule as a very long piece of yarn, a chromosome is like a bundle of yarn: one very long piece folded into a tight package for easier handling. **The structure of chromosomes therefore varies, depending on the function the chromosomes are performing: loose and unwound when the cell is undergoing its normal functions, but compact and tightly wound when the cell is dividing.**

▼ **Figure 8.3 A plant cell just before division, with chromosomes colored by stains.**

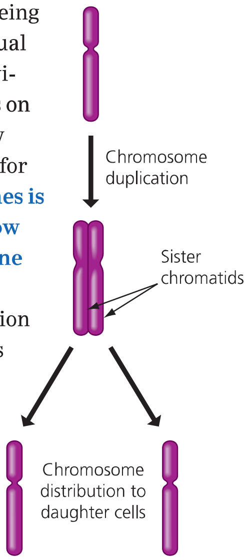


▼ **Figure 8.4 DNA packing in a eukaryotic chromosome.** Successive levels of coiling of DNA and associated proteins ultimately result in highly compacted chromosomes. The fuzzy appearance of the final chromosome at the bottom arises from the intricate twists and folds of the chromatin fibers.



Duplicating Chromosomes

Think of the chromosomes as being like a detailed instruction manual on how to run a cell. During division, the original cell must pass on a copy of the manual to the new cell while also retaining a copy for itself. **Duplicating chromosomes is therefore a vital step in the flow of genetic information from one generation to the next.**



▲ **Figure 8.5 Duplication and distribution of a single chromosome.** During cell reproduction, the cell duplicates each chromosome and distributes the two copies to the daughter cells.

Before a cell begins the division process, it must duplicate all its chromosomes. The DNA molecule of each chromosome is copied through the process of DNA replication (discussed in detail in Chapter 10), and new histone protein molecules attach as needed. The result is that—at this point—each chromosome consists of identical copies called **sister chromatids**, which contain the same genes. At the bottom of Figure 8.4, the two sister chromatids are joined together most tightly at a narrow "waist" called the **centromere**.

When the cell divides, the sister chromatids of a duplicated chromosome separate from each other **(Figure 8.5)**. When a chromatid is separated from its sister, it is considered a full-fledged chromosome, and it is identical to the original chromosome. One of the new chromosomes goes to one daughter cell, and the other goes to the other daughter cell. In this way, each daughter cell receives a complete and identical set of chromosomes. A dividing human skin cell, for example, has 46 duplicated chromosomes, and each of the two daughter cells that result from it has 46 single chromosomes.

The Cell Cycle

The rate at which a cell divides depends on its role within the organism's body. Some cells divide once a day, others divide less often, and some highly specialized cells, such as mature muscle cells, do not divide at all.

The **cell cycle** is the ordered sequence of events that extends from the time a cell is first formed from a dividing parent cell until its own division into two cells. Think of the cell cycle as the "lifetime" of a cell, from its "birth" to its own reproduction. As **Figure 8.6** shows, most of the cell cycle is spent in **interphase**. Interphase is a time when a cell goes about its usual business, performing its normal functions within the organism. For example, during interphase a cell in your stomach lining might make and release enzyme molecules that aid in digestion. While in interphase, a cell roughly doubles everything in its cytoplasm. It increases its supply of proteins, increases the number of many of its organelles (such as mitochondria and ribosomes), and grows in size. Typically, interphase lasts for at least 90% of the cell cycle.

Interphase (see Figure 8.6) can be divided into three subphases: the G_1 phase ("first gap"), the S phase ("synthesis" of DNA—also known as DNA replication), and the G_2 phase ("second gap"). Although the G phases are called "gaps," cells are actually quite active and grow throughout all three subphases of interphase. The chromosomes are duplicated during the S phase, which typically lasts about half of interphase. At the beginning of the S phase, each chromosome is single. At the end of this subphase, after DNA replication, the chromosomes are doubled, each consisting of two sister chromatids joined along their lengths. During the G_2 phase, the cell completes preparations for cell division.

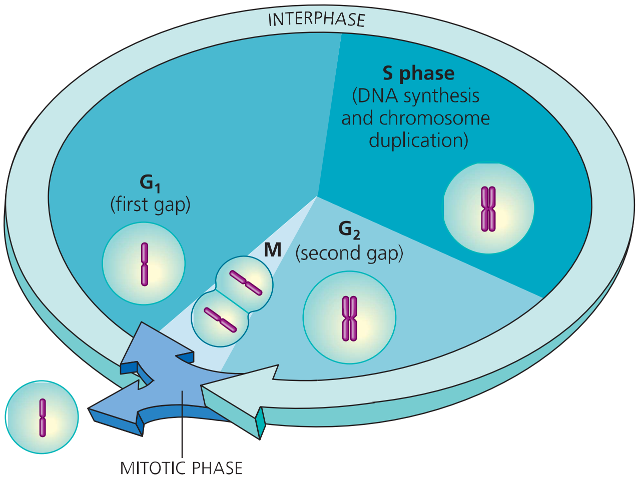
The part of the cell cycle when the cell is actually dividing is called the **mitotic (M) phase**. It includes two overlapping stages, mitosis and cytokinesis. In **mitosis**, the nucleus and its contents, most importantly the duplicated chromosomes, divide and are evenly distributed, forming two daughter nuclei. During **cytokinesis**, the cytoplasm (along with all the organelles) is divided in two. The combination of mitosis and cytokinesis produces two genetically identical daughter cells, each fully equipped with a nucleus, cytoplasm, organelles, and plasma membrane. ✓

✓ CHECKPOINT

1. A duplicated chromosome consists of two sister _____ joined together at the _____.
2. What are the two broadest divisions of the cell cycle? What two processes are involved in the actual duplication of the cell?

■ Answers: **1.** chromatids; centromere **2.** interphase and the mitotic phase; mitosis and cytokinesis

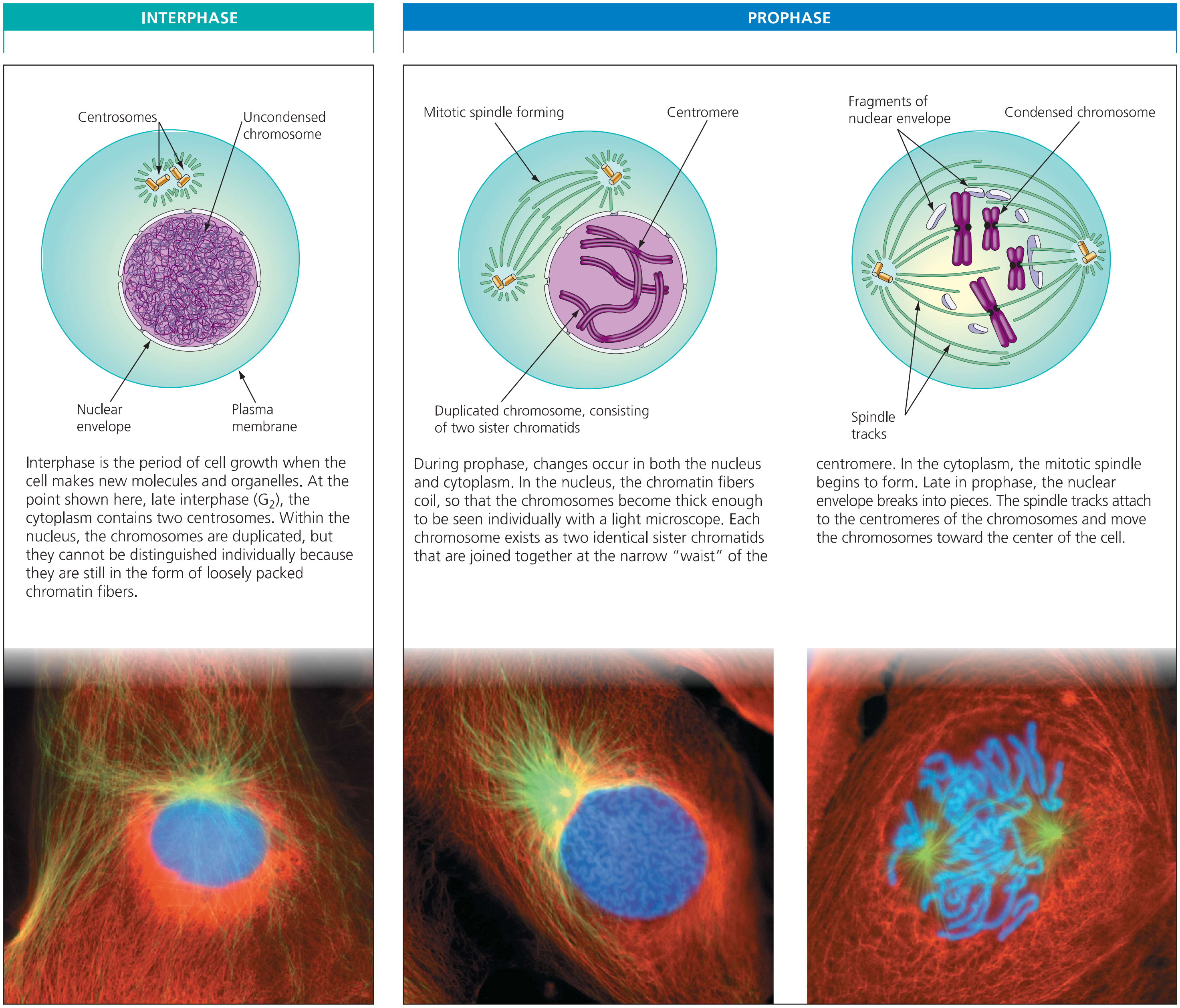
▼ **Figure 8.6 The eukaryotic cell cycle.** The cell cycle extends from the "birth" of a cell (just after the point indicated by the double-headed arrow at the bottom of the cycle), resulting from cell reproduction, to the time the cell itself divides in two. (During interphase, the chromosomes are diffuse masses of thin fibers; they do not actually appear in the rodlike form you see here.)



Mitosis and Cytokinesis

Figure 8.7 illustrates the cell cycle for an animal cell using drawings, descriptions, and fluorescent light micrographs. The micrographs running along the bottom row of the page show dividing cells from a salamander, with chromosomes depicted in blue. The drawings in the top row include details that are not visible in the micrographs. In these cells, we illustrate just four chromosomes to keep the process a bit simpler to follow; remember that one of your cells actually contains 46 chromosomes. The text within the figure describes the events occurring

▼ **Figure 8.7** **Cell reproduction: a dance of the chromosomes.** After the chromosomes duplicate during interphase, the elaborately choreographed stages of mitosis—prophase, metaphase, anaphase, and telophase—distribute the duplicate sets of chromosomes to two separate nuclei. Cytokinesis then divides the cytoplasm, yielding two genetically identical daughter cells.



Interphase is the period of cell growth when the cell makes new molecules and organelles. At the point shown here, late interphase (G_2), the cytoplasm contains two centrosomes. Within the nucleus, the chromosomes are duplicated, but they cannot be distinguished individually because they are still in the form of loosely packed chromatin fibers.

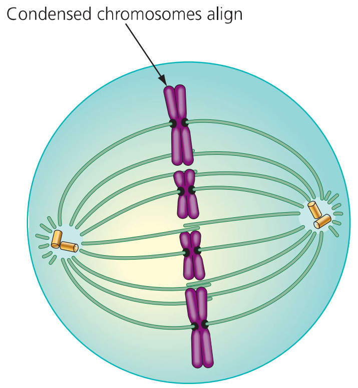
During prophase, changes occur in both the nucleus and cytoplasm. In the nucleus, the chromatin fibers coil, so that the chromosomes become thick enough to be seen individually with a light microscope. Each chromosome exists as two identical sister chromatids that are joined together at the narrow "waist" of the centromere. In the cytoplasm, the mitotic spindle begins to form. Late in prophase, the nuclear envelope breaks into pieces. The spindle tracks attach to the centromeres of the chromosomes and move the chromosomes toward the center of the cell.

at each stage. Study this figure carefully (it has a lot of information and it's important!) and notice the striking changes in the nucleus and other cellular structures.

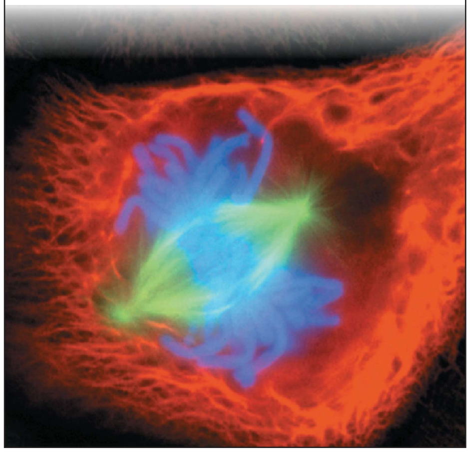
Biologists distinguish four main stages of mitosis: **prophase**, **metaphase**, **anaphase**, and **telophase**. The timing of these stages is not precise, and they overlap a bit. Think of stages in your own life—infancy, childhood, adulthood, old age—and you'll realize that the division between stages isn't always clear, and the timings of the stages vary from person to person; so it is with the stages of mitosis.

The chromosomes are the stars of the mitotic drama, and their movements depend on the **mitotic spindle**, a football-shaped structure of microtubule tracks (colored green in the figure) that guides the separation of the two sets of daughter chromosomes. The tracks of spindle microtubules grow from structures within the cytoplasm called centrosomes.

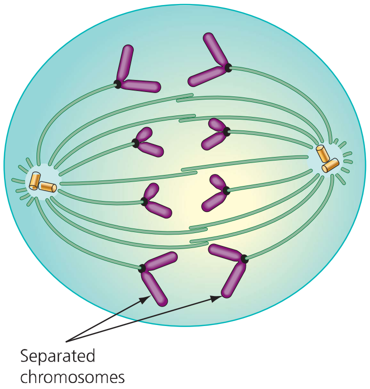
METAPHASE



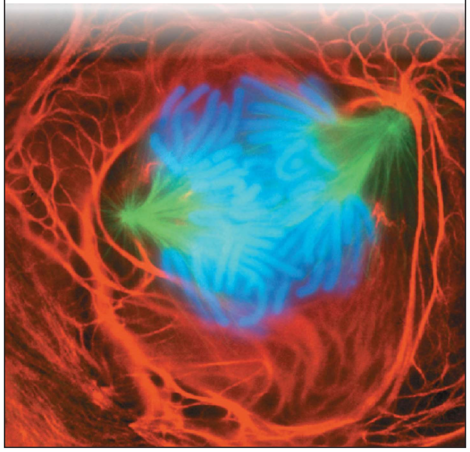
The mitotic spindle is now fully formed. The centromeres of all the chromosomes line up between the two poles of the spindle. For each chromosome, the tracks of the mitotic spindle attached to the two sister chromatids pull toward opposite poles. This tug of war keeps the chromosomes in the middle of the cell.



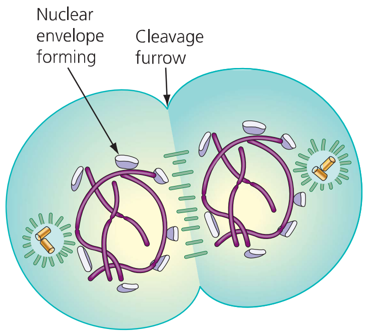
ANAPHASE



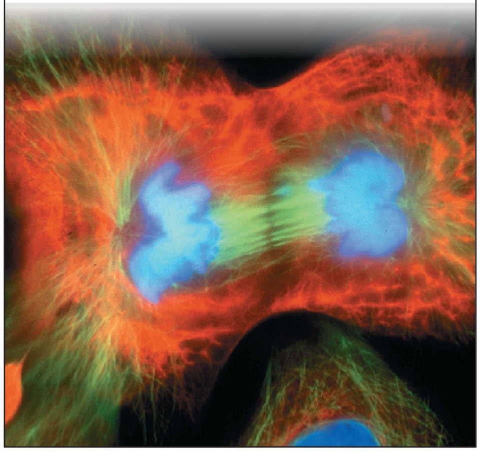
Anaphase begins suddenly when the sister chromatids of each chromosome separate. Each is now considered a full-fledged (daughter) chromosome. The chromosomes move toward opposite poles of the cell as the spindle tracks shorten. Simultaneously, the tracks not attached to chromosomes lengthen, pushing the poles farther apart and elongating the cell.



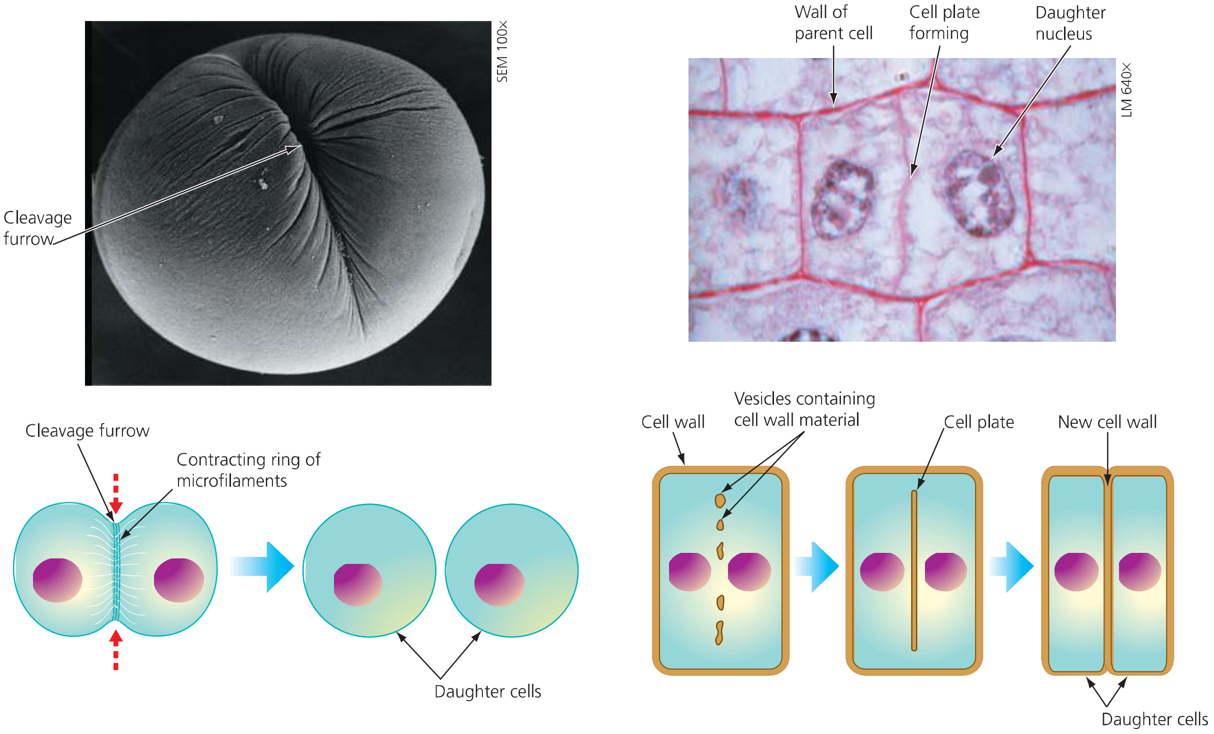
TELOPHASE



Telophase begins when the two groups of chromosomes have reached opposite ends of the cell. Telophase is the reverse of prophase: Nuclear envelopes form, the chromosomes uncoil, and the spindle disappears. Mitosis, the division of one nucleus into two genetically identical daughter nuclei, is now finished. Cytokinesis, the division of the cytoplasm, usually occurs with telophase. In animals, a cleavage furrow pinches the cell in two, producing two daughter cells.



▼ **Figure 8.8** **Cytokinesis in animal and plant cells.**



(a) Animal cell cytokinesis **(b) Plant cell cytokinesis**

Cytokinesis, the division of the cytoplasm into two cells, usually begins during telophase, overlapping the end of mitosis. In animal cells, the cytokinesis process is known as **cleavage**. The first sign of cleavage is the appearance of an indentation called a cleavage furrow. A ring of microfilaments in the cytoplasm just under the plasma membrane contracts, like the pulling of a drawstring on a hooded sweatshirt, deepening the furrow and pinching the parent cell in two **(Figure 8.8a)**.

Cytokinesis in a plant cell occurs differently. Vesicles containing cell wall material collect at the middle of the cell. The vesicles fuse, forming a membranous disk called the **cell plate**. The cell plate grows outward, accumulating more cell wall material as more vesicles join it. Eventually, the membrane of the cell plate fuses with the plasma membrane, and the cell plate's contents join the parental cell wall. The result is two daughter cells **(Figure 8.8b)**. ✓

✓ CHECKPOINT

An organism called a plasmodial slime mold is one huge cytoplasmic mass with many nuclei. Explain how a variation in the cell cycle could cause this "monster cell" to arise.

■ *Answer: Mitosis occurs repeatedly without cytokinesis.*

Cancer Cells: Dividing Out of Control

For a plant or animal to grow and maintain its tissues normally, it must control the timing of cell division—speeding up, slowing down, or turning the process off or on as needed. The sequential events of the cell cycle are directed by a **cell cycle control system** that consists of specialized proteins within the cell. These proteins integrate information from the environment and from other body cells and send "stop" and "go-ahead" signals at certain key points during the cell cycle. For example, the cell cycle normally halts within the G_1 phase of interphase unless the cell receives a go-ahead signal through certain control proteins. If that signal never arrives, the cell will switch into a permanently nondividing state. The cell cycles of your nerve and muscle cells, for example, are arrested this way. If the go-ahead signal is received and the G_1 checkpoint is passed, the cell will usually complete the rest of the cycle. **Therefore, the reproductive behavior of cells—whether they will divide or not—results from interactions of many different molecules.**

What Is Cancer?

Cancer, which currently claims the lives of one out of every five people in the United States and other industrialized nations, is a disease of the cell cycle. Cancer cells do not respond normally to the cell cycle control system; they divide excessively and may invade other tissues of the body. If unchecked, cancer cells may continue to divide until they kill the host. Cancer cells are thus referred to as "immortal" because, unlike other human cells, they will never cease dividing. In fact, thousands of laboratories around the world today use a laboratory strain of human cells that were originally obtained from a woman named Henrietta Lacks, who died of cervical cancer in 1951.

The abnormal behavior of cancer cells begins when a single cell undergoes genetic changes (mutations) in one or more genes that encode for proteins in the cell cycle control system. These changes cause the cell to grow abnormally. The immune system generally recognizes and destroys such cells. However, if the cell evades destruction, it may proliferate to form a **tumor**, an abnormally growing mass of body cells. If the abnormal cells remain at the original site, the lump is called a **benign tumor**. Benign tumors can cause problems if they grow large and disrupt certain organs, such as the brain, but often they can be completely removed by surgery and are rarely deadly.

A TUMOR RESULTS FROM AN ERROR IN THE DIVISION OF ONE OF THE BODY'S OWN CELLS.

In contrast, a **malignant tumor** is one that has the potential to spread into neighboring tissues and other parts of the body, forming new tumors **(Figure 8.9)**. A malignant tumor may or may not have actually begun to spread, but if it does, it will soon displace normal tissue and interrupt organ function. A person with a malignant tumor is said to have **cancer**. The spread of cancer cells beyond their original site is called **metastasis**, and such cells are said to metastasize. Cancers are named according to where they originate. Liver cancer, for example, always begins in liver tissue and may metastasize from there.

Cancer Treatment

Once a tumor starts growing in the body, how can it be treated? There are three main types of cancer treatment. Surgery to remove a tumor is usually the first step. For many benign tumors, surgery alone may be sufficient. If not, the next step is usually **radiation therapy**. Cancerous tumors are exposed to high-energy radiation, which harms cancer cells more than normal cells. Radiation therapy is often effective against malignant tumors that have not yet spread. However, radiation can damage normal body cells enough to produce side effects, such as nausea and hair loss. **Chemotherapy**, the use of drugs to disrupt cell division, is used to treat tumors that have spread throughout the body. Some chemotherapy drugs prevent cell division by interfering with the mitotic spindle. Other drugs prevent the mitotic spindle from forming in the first place. Chemotherapy often has significant side effects because it contacts and may damage many different body tissues.

Frontiers of Cancer Treatment

Medical researchers are constantly searching for new ways to combat cancerous cells. One particularly promising area is immunotherapy, treatments that use the body's immune system to attack tumors. Immunotherapy can be accomplished by boosting the body's natural immunity in general or by boosting specific immune components that attack cancer cells. Alternatively, immune components (such as proteins specifically designed to recognize and help destroy cancer cells) may be created in the lab and injected into a patient. This type of therapy has been effective against cancers of the breast, stomach, and some forms of leukemia and lymphoma. Many cancer researchers believe that immunotherapy represents the next major breakthrough in cancer treatment that could save many lives in the coming decades.

Cancer Prevention and Survival

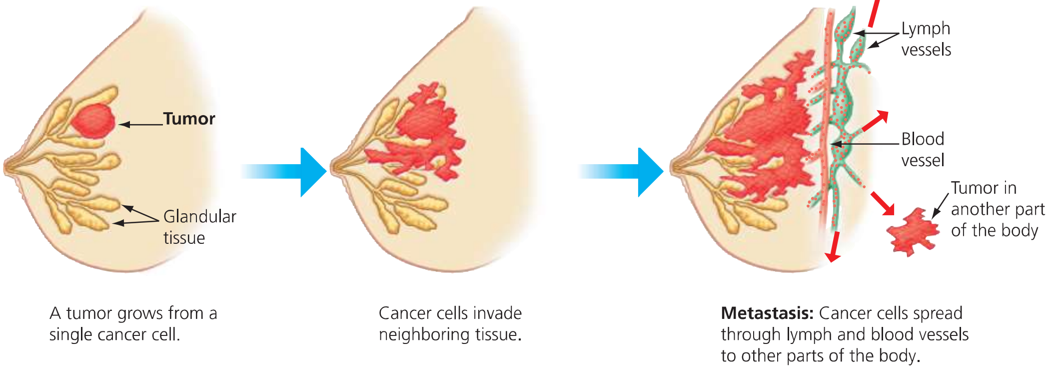
Although cancer can strike anyone, there are certain lifestyle changes you can make to reduce your chances of developing cancer or increase your chances of surviving it. Not smoking, exercising adequately (usually defined as at least 150 minutes of moderate exercise each week), avoiding overexposure to the sun, and eating a high-fiber, low-fat diet can all help reduce the likelihood of getting cancer. Seven types of cancer can be easily detected: skin and oral (by physical exam), breast (by self-exams or mammograms for higher-risk women and women 50 and older), prostate (by rectal exam), cervical (by Pap smear), testicular (by self-exam), and colon (by colonoscopy). Regular visits to the doctor can help identify tumors early, which is the best way to increase the chance of successful treatment. ✓

✓ CHECKPOINT

What differentiates a benign tumor from a malignant tumor?

■ *Answer: A benign tumor remains at its point of origin, whereas a malignant tumor can spread.*

▼ **Figure 8.9 Growth and metastasis of a malignant tumor of the breast.**



A tumor grows from a single cancer cell.

Cancer cells invade neighboring tissue.

Metastasis: Cancer cells spread through lymph and blood vessels to other parts of the body.

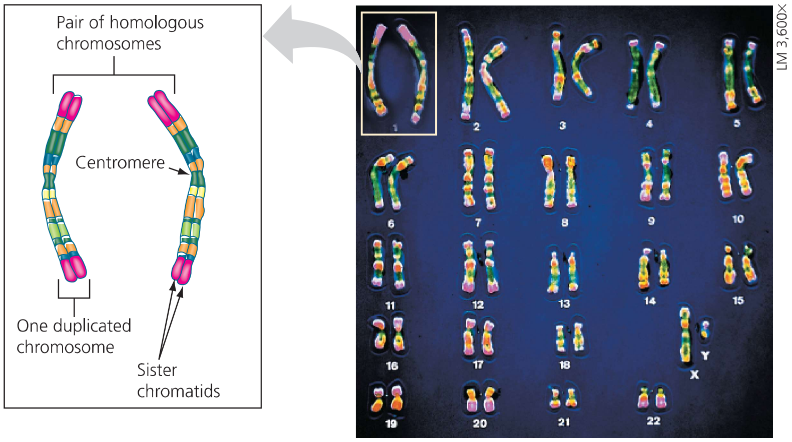
Meiosis, the Basis of Sexual Reproduction

Only maple trees produce more maple trees; only goldfish make more goldfish; and only people make more people. These simple facts of life have been recognized for thousands of years and are reflected in the age-old saying, “Like begets like.” But in a strict sense, “Like begets like” applies only to asexual reproduction, where offspring inherit all their DNA from a single parent. Asexual offspring are exact genetic replicas of that one parent and of each other, and their appearances are very similar.

The family photo in **Figure 8.10** makes the point that in a sexually reproducing species like does not exactly beget like. You probably resemble your biological parents more closely than you resemble strangers, but you do not look exactly like your parents or a sibling—unless you are an identical twin. Each offspring of sexual reproduction inherits a unique combination of genes from its two parents, and this combined set of genes programs a unique combination of traits. As a result, sexual reproduction can produce tremendous variety among offspring.

▲ **Figure 8.10 The varied products of sexual reproduction.** Every child inherits a unique combination of genes from his or her parents and displays a unique combination of traits.

▼ **Figure 8.11 Pairs of homologous chromosomes in a human male karyotype.** This karyotype shows 22 completely homologous pairs (autosomes) and a 23rd pair that consists of an X chromosome and a Y chromosome (sex chromosomes). With the exception of X and Y, the homologous chromosomes of each pair match in size, centromere position, and staining pattern.



Sexual reproduction depends on the cellular processes of meiosis and fertilization. But before exploring these processes, we need to return to chromosomes and the role they play in the life cycle of sexually reproducing organisms.

Homologous Chromosomes

If we examine cells from different individuals of a single species—sticking to one sex, for now—we find that they have the same number and types of chromosomes. Viewed with a microscope, your chromosomes would look exactly like those of Beyoncé (if you’re a woman) or Jay Z (if you’re a man).

A typical body cell, called a **somatic cell**, has 46 chromosomes in humans. A technician can break open a human cell in metaphase of mitosis, stain the chromosomes with dyes, take a picture with the aid of a microscope, and arrange the chromosomes in matching pairs by size. The resulting display is called a **karyotype** **(Figure 8.11)**. Notice in the figure that each chromosome is duplicated, with two sister chromatids joined along their length. Within the white box, for example, each “stick” is actually a pair of sister chromatids stuck together (as shown in the drawing to the left). Notice also that almost every chromosome has a twin that resembles it in length and centromere position; in the figure, the white box surrounds one set of twin chromosomes. The two chromosomes of such a matching pair, called **homologous chromosomes**, carry genes controlling the same inherited characteristics. For example, if a gene influencing freckles is located at a particular place on one chromosome—within the yellow band in the drawing in Figure 8.11, for instance—then the homologous chromosome has that same gene in the same location. However, the two homologous chromosomes may have different versions of the same gene. Let’s restate this concept because it often confuses students: A pair of homologous chromosomes has two nearly identical chromosomes, each of which consists of two identical sister chromatids after chromosome duplication.

In human females, the 46 chromosomes fall neatly into 23 homologous pairs. For a male, however, the chromosomes in one pair do not look alike. This nonmatching pair, only partly homologous, is the male’s sex chromosomes. **Sex chromosomes** determine a person’s sex (male versus female). In mammals, males have one X chromosome and one Y chromosome. Females have two X chromosomes. (Other organisms have different systems; in this chapter, we focus on humans.) The remaining chromosomes (44 in humans), found in both males and females, are called **autosomes**. For both autosomes and sex chromosomes, you inherited one chromosome of each pair from your mother and the other from your father.

Gametes and the Life Cycle of a Sexual Organism

The **life cycle** of a multicellular organism is the sequence of generation-to-generation stages from fertilization to the production of its own offspring. Having two sets of chromosomes, one inherited from each parent, is a key factor in the life cycle of humans and all other species that reproduce sexually. **Figure 8.12** shows the human life cycle, emphasizing the number of chromosomes.

Humans (as well as most other animals and many plants) are **diploid** organisms because all typical body cells (somatic cells) contain pairs of homologous chromosomes. In other words, all your chromosomes come in matching sets. This is similar to shoes in your closet: You may have 46 shoes, but they are organized as 23 pairs, with the members of each pair being nearly identical to each other. The total number of chromosomes, 46 in humans, is the diploid number (abbreviated 2*n*). The gametes, egg and sperm cells, are not diploid. Made by meiosis in an ovary or testis, each gamete has a single set of chromosomes: 22 autosomes plus a sex chromosome, either X or Y. A cell with a single chromosome set is called a **haploid** cell; it has only one member of each pair of homologous chromosomes. To visualize the haploid state, imagine your closet containing only one shoe from each pair. For humans, the haploid number, *n*, is 23.

In the human life cycle, a haploid sperm fuses with a haploid egg in a process called **fertilization**. The resulting fertilized egg, called a **zygote**, is diploid. It has two sets of chromosomes, one set from each parent. The life cycle is completed as a sexually mature adult develops from the zygote. Mitotic cell division ensures that all somatic cells of the human body receive a copy of all of the zygote's 46 chromosomes. Thus, every one of the trillions of cells in your body can trace its ancestry back through mitotic divisions to the single zygote produced when your father's sperm and your mother's egg fused about nine months before you were born (although you probably don't want to dwell on those details!).

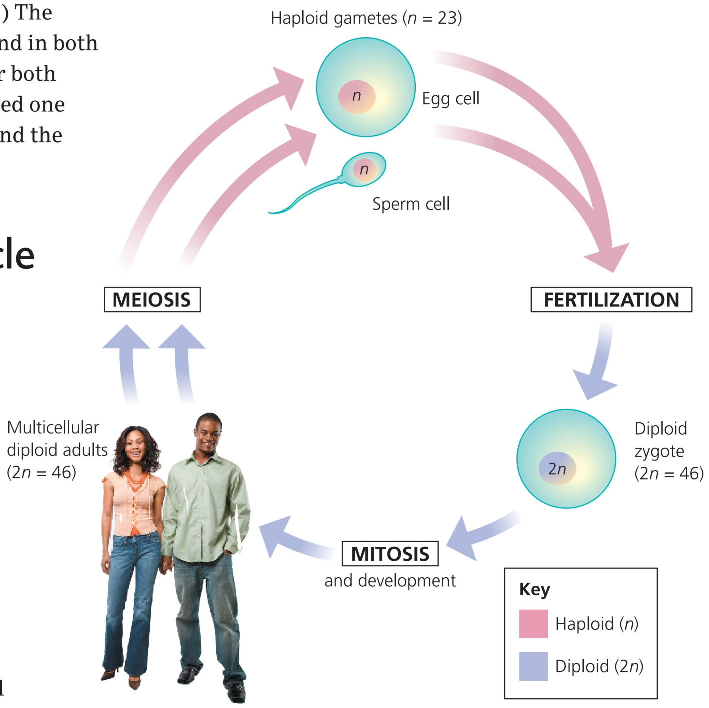
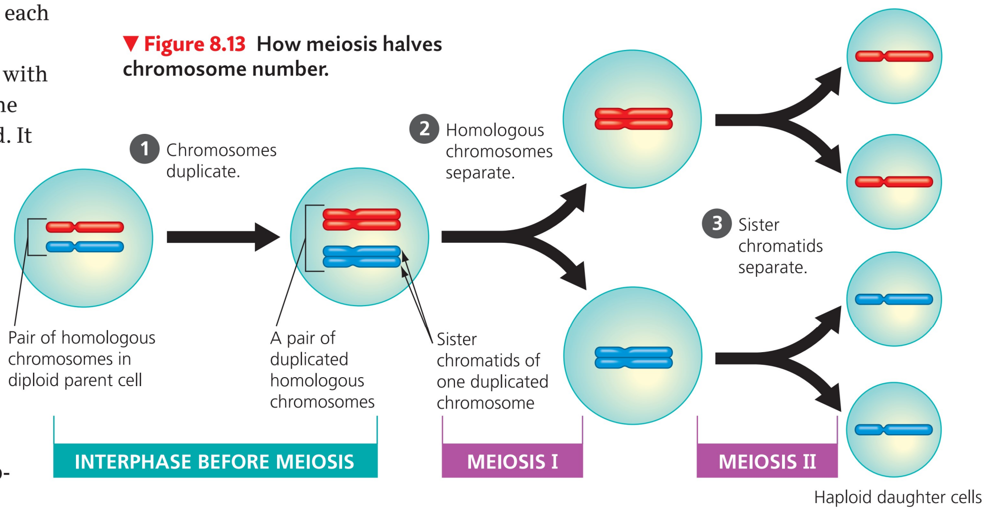


Figure Walkthrough
Mastering Biology
goo.gl/AJGKBd

◀ **Figure 8.12 The human life cycle.** In each generation, the doubling of chromosome number that results from fertilization is offset by the halving of chromosome number during meiosis.

Producing haploid gametes by meiosis keeps the chromosome number from doubling in every generation. To illustrate, **Figure 8.13** tracks one pair of homologous chromosomes. ❶ Each of the chromosomes is duplicated during interphase (before mitosis). ❷ The first division, meiosis I, segregates the two chromosomes of the homologous pair, packaging them in separate (haploid) daughter cells. But each chromosome is still doubled. ❸ Meiosis II separates the sister chromatids. Each of the four daughter cells is haploid and contains only a single chromosome from the pair of homologous chromosomes.

▼ **Figure 8.13 How meiosis halves chromosome number.**



The Process of Meiosis

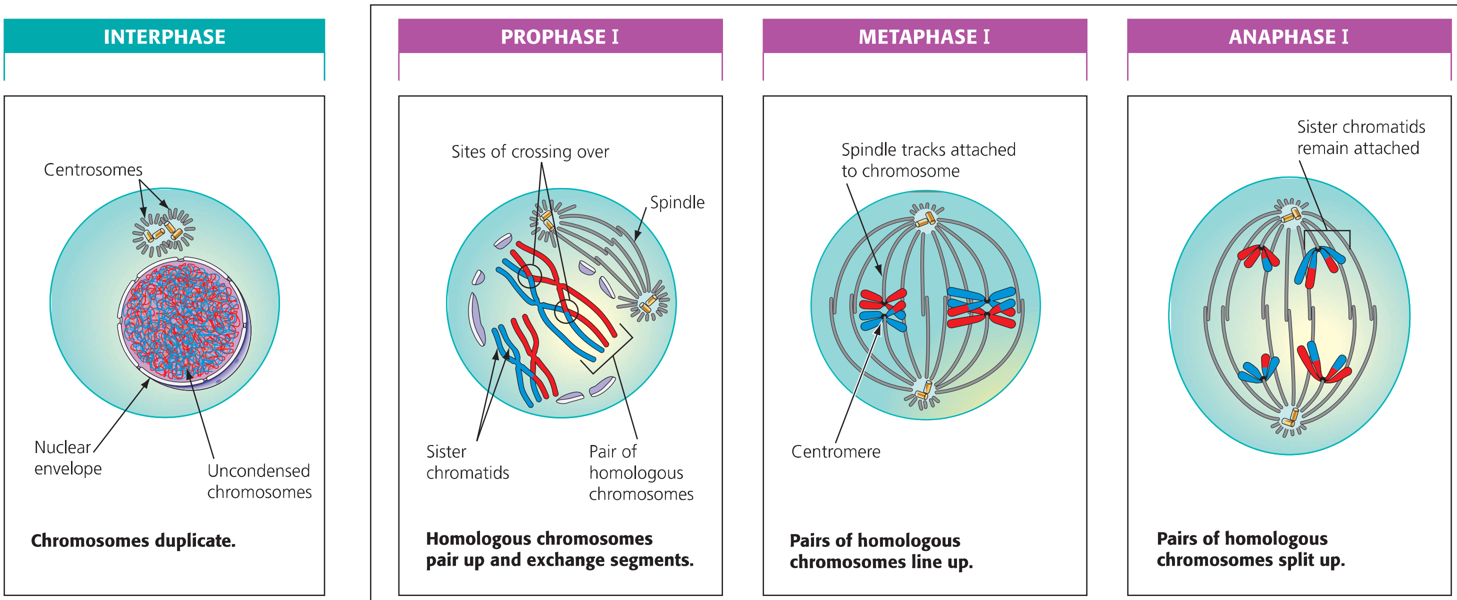
Meiosis, the process of cell division that produces haploid gametes in diploid organisms, resembles mitosis, but with two important differences. The first difference is that during meiosis the number of chromosomes is cut in half. In meiosis, a cell that has duplicated its chromosomes undergoes two consecutive divisions, called meiosis I and meiosis II. Because one duplication of the chromosomes is followed by two divisions, each of the four daughter cells resulting from meiosis has a haploid set of chromosomes—half as many chromosomes as the starting cell.

The second difference between meiosis and mitosis is an exchange of genetic material—pieces of chromosomes—between homologous chromosomes. This exchange, called crossing over, occurs during the first prophase of meiosis. We'll look more closely at crossing over later. For now, study **Figure 8.14**, including the text below it, which describes the stages of meiosis in detail for a hypothetical animal cell containing four chromosomes.

As you go through Figure 8.14, keep in mind the difference between homologous chromosomes and sister chromatids: The two chromosomes of a homologous pair are individual chromosomes that were inherited from

▼ **Figure 8.14**
The stages of meiosis.

MEIOSIS I: HOMOLOGOUS CHROMOSOMES SEPARATE



As with mitosis, meiosis is preceded by an interphase during which the chromosomes duplicate. Each chromosome then consists of two identical sister chromatids. The chromosomes consist of uncondensed chromatin fibers.

Prophase I As the chromosomes coil up, special proteins cause the homologous chromosomes to stick together in pairs. The resulting structure has four chromatids. Within each set, chromatids of the homologous chromosomes exchange corresponding segments—they "cross over." Crossing over rearranges genetic information.

As prophase I continues, the chromosomes coil up further, a spindle forms, and the homologous pairs are moved toward the center of the cell.

Metaphase I At metaphase I, the homologous pairs are aligned in the middle of the cell. The sister chromatids of each chromosome are still attached at their centromeres, where they are anchored to spindle tracks. Notice that for each chromosome pair, the spindle tracks attached to one homologous chromosome come from one pole of the cell, and the tracks attached to the other chromosome come from the opposite pole. With this arrangement, the homologous chromosomes are poised to move toward opposite poles of the cell.

Anaphase I The attachment between the homologous chromosomes of each pair breaks, and the chromosomes now migrate toward the poles of the cell. *In contrast to mitosis, the sister chromatids migrate as a pair instead of splitting up*. They are separated not from each other but from their homologous partners.

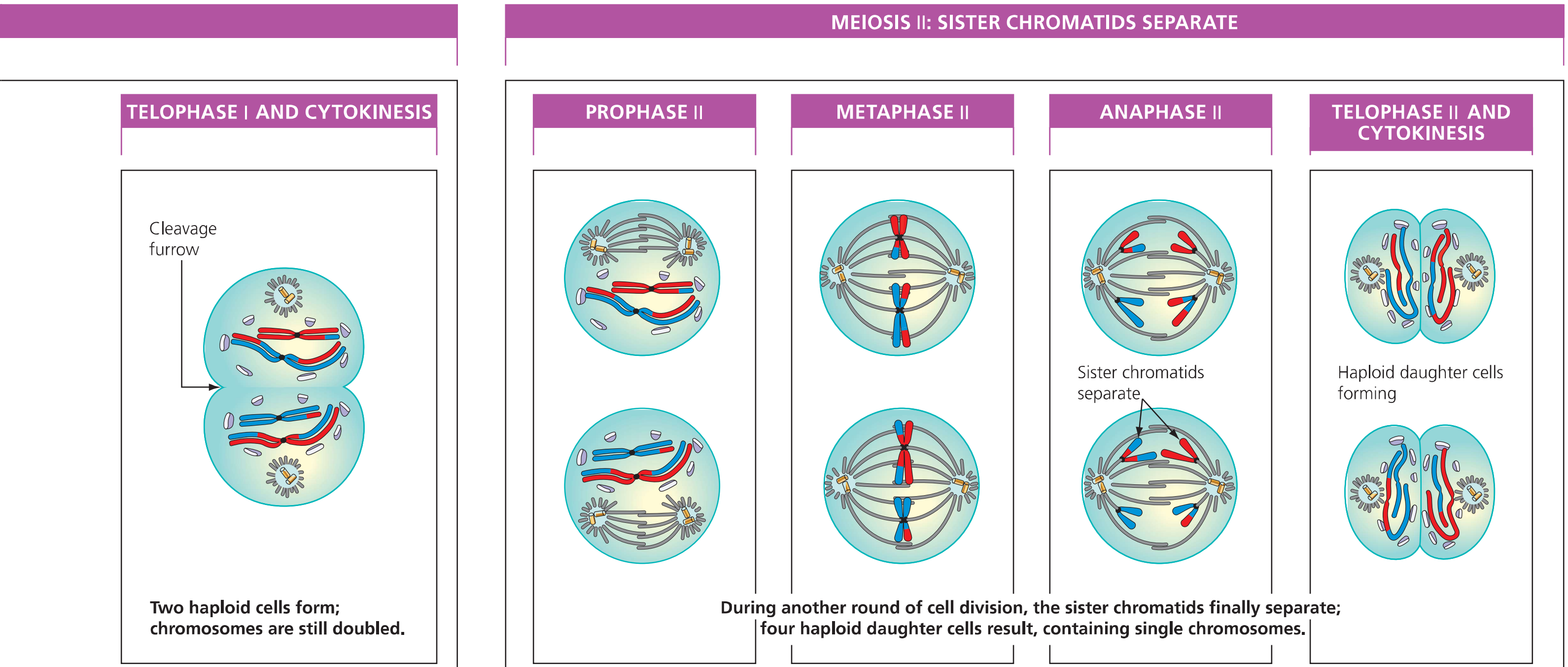
different parents, one from the mother and one from the father. The members of a pair of homologous chromosomes in Figure 8.14 (and later figures) are identical in size and shape but colored in the illustrations differently (red versus blue) to remind you that they differ in this way. In the interphase just before meiosis, each chromosome duplicates to form sister chromatids that remain together until anaphase of meiosis II. Before crossing over occurs, sister chromatids are identical and carry the same versions of all their genes. ✓

Meiosis II in a lily cell

✓ CHECKPOINT

If a single diploid somatic cell with 18 chromosomes undergoes meiosis and produces sperm, the result will be ______ sperm, each with ______ chromosomes. (Provide two numbers.)

■ *Answer: four; nine*



Two haploid cells form; chromosomes are still doubled.

During another round of cell division, the sister chromatids finally separate; four haploid daughter cells result, containing single chromosomes.

Telophase I and Cytokinesis In telophase I, the chromosomes arrive at the poles of the cell. When they finish their journey, each pole has a haploid chromosome set, although each chromosome is still in duplicate form. Usually, cytokinesis occurs along with telophase I, and two haploid daughter cells are formed.

The Process of Meiosis II Meiosis II is essentially the same as mitosis. The important difference is that meiosis II starts with a haploid cell that has **not** undergone chromosome duplication during the preceding interphase.

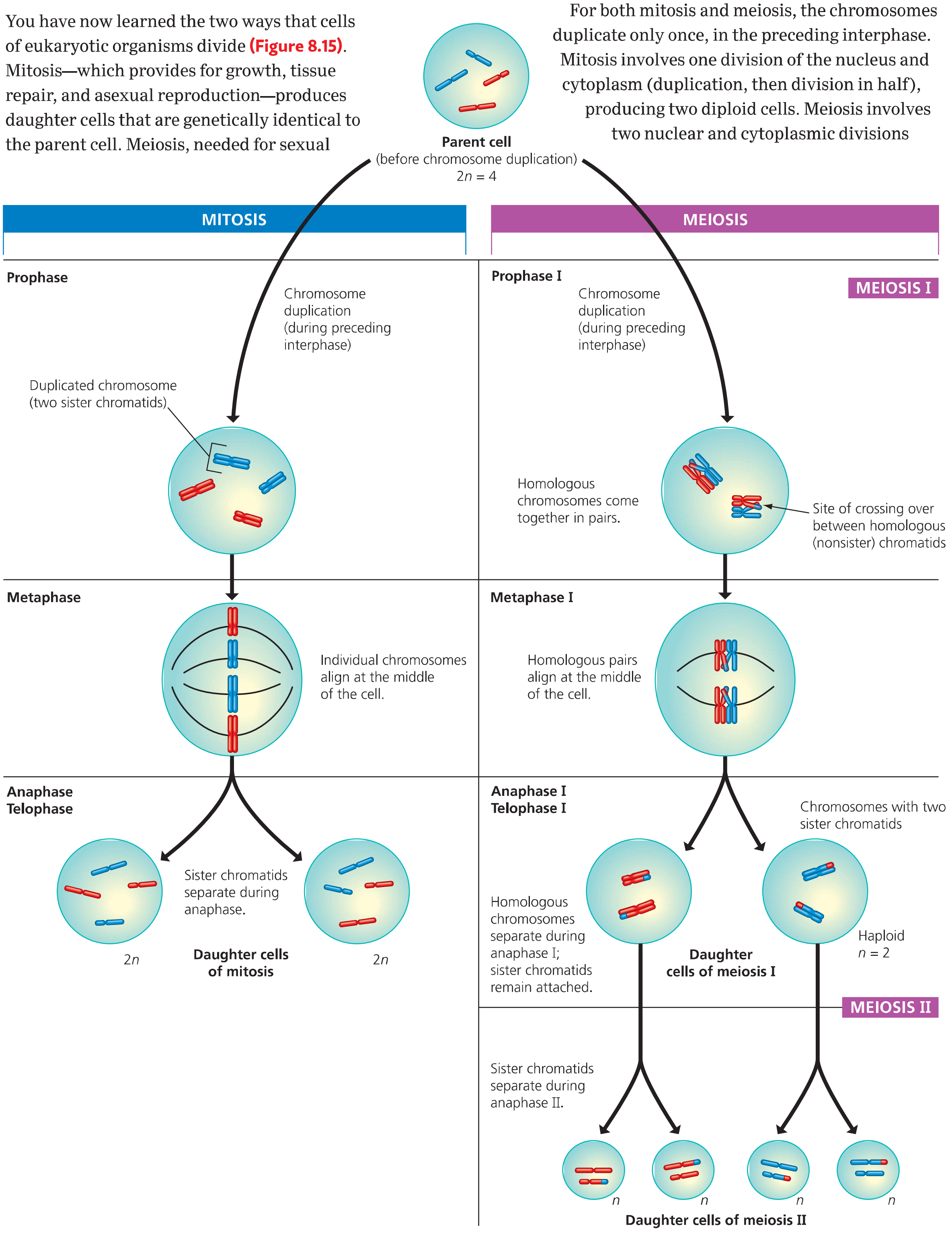
During prophase II, a spindle forms and moves the chromosomes toward the middle of the cell. During metaphase II, the chromosomes are aligned as they are in mitosis, with the tracks attached to the sister chromatids of each chromosome coming from opposite poles.

In anaphase II, the centromeres of sister chromatids separate, and the sister chromatids of each pair move toward opposite poles of the cell. In telophase II, nuclei form at the cell poles, and cytokinesis occurs at the same time. There are now four haploid daughter cells, each with single chromosomes.

Review: Comparing Mitosis and Meiosis

You have now learned the two ways that cells of eukaryotic organisms divide **(Figure 8.15)**. Mitosis—which provides for growth, tissue repair, and asexual reproduction—produces daughter cells that are genetically identical to the parent cell. Meiosis, needed for sexual reproduction, yields genetically unique haploid daughter cells—cells with only one member of each homologous chromosome pair.

For both mitosis and meiosis, the chromosomes duplicate only once, in the preceding interphase. Mitosis involves one division of the nucleus and cytoplasm (duplication, then division in half), producing two diploid cells. Meiosis involves two nuclear and cytoplasmic divisions



▶ **Figure 8.15 Comparing mitosis and meiosis.** The events unique to meiosis occur during meiosis I: In prophase I, duplicated homologous chromosomes pair along their lengths, and crossing over occurs between homologous (nonsister) chromatids. In metaphase I, pairs of homologous chromosomes (rather than individual chromosomes) are aligned at the center of the cell. During anaphase I, sister chromatids of each chromosome stay together and go to the same pole of the cell as homologous chromosomes separate. At the end of meiosis I, there are two haploid cells, but each chromosome still has two sister chromatids.

(duplication, division in half, then division in half again), yielding four haploid cells.

In comparing mitosis and meiosis, Figure 8.15 traces these two processes for a diploid parent cell with four chromosomes. As before, homologous chromosomes are those matching in size. Imagine that the red chromosomes were inherited from the mother and the blue chromosomes from the father. Notice that all the events unique to meiosis occur during meiosis I. Meiosis II is virtually identical to mitosis in that it separates sister chromatids. But unlike mitosis, meiosis II yields daughter cells with a haploid set of chromosomes. ✓

The Origins of Genetic Variation

As discussed earlier, offspring that result from sexual reproduction are genetically different from their parents and from one another. How does meiosis produce such genetic variation?

Independent Assortment of Chromosomes

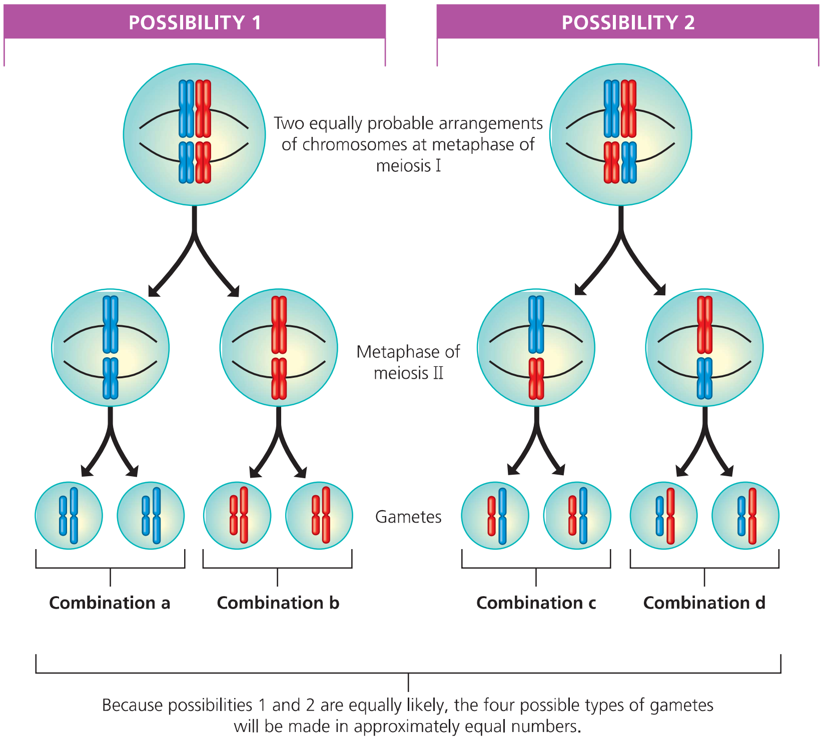
Figure 8.16 illustrates one way in which meiosis contributes to genetic variety. The figure shows how the arrangement of homologous chromosomes at metaphase of meiosis I affects the resulting gametes. Once again, our example is from a hypothetical diploid organism with four chromosomes (two pairs of homologous chromosomes), with colors used to differentiate homologous chromosomes (red for chromosomes inherited from the mother and blue for chromosomes from the father).

When aligned during metaphase I, the side-by-side orientation of each homologous pair of chromosomes is a matter of chance. Either the red or blue chromosome may be on the left or right. Thus, in this example, there are two possible ways that the chromosome pairs can align during metaphase I. In possibility 1, the chromosome pairs are oriented with both red chromosomes on the same side (blue/red and blue/red). In this case, each of the gametes produced at the end of meiosis II has only red or only blue chromosomes (combinations a and b). In possibility 2, the chromosome pairs are oriented differently (blue/red and red/blue). This arrangement produces gametes with one red and one blue chromosome (combinations c and d). Thus, with the two possible arrangements shown in this example, the organism will produce gametes with four different combinations of chromosomes. For a species with more than two pairs of chromosomes, such as humans, every chromosome pair orients independently of all the others at metaphase I. (Chromosomes X and Y behave as a homologous pair in meiosis.)

✓ CHECKPOINT

True or false: Both mitosis and meiosis are preceded by chromosome duplication.

■ Answer: true



◀ **Figure 8.16 Results of alternative arrangements of chromosomes at metaphase of meiosis I.** The arrangement of chromosomes at metaphase I determines which chromosomes will be packaged together in the haploid gametes.

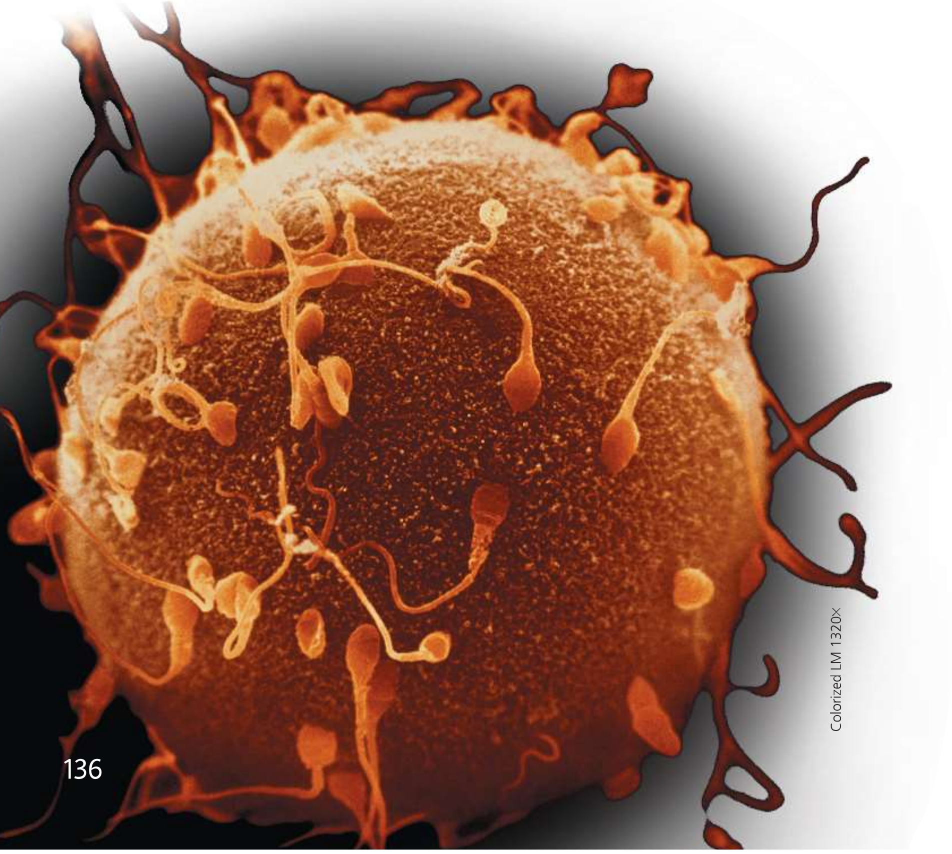
For any species, the total number of chromosome combinations that can appear in gametes is 2^n, where n represents the haploid number. For the hypothetical organism in Figure 8.16, $n = 2$, so the number of chromosome combinations is 2^2, or 4. For a human ($n = 23$), there are 2^{23}, or about 8 million, possible chromosome combinations! This means that every gamete a person produces contains one of about 8 million possible combinations of maternal and paternal chromosomes. When you consider that a human egg cell with about 8 million possibilities is fertilized at random by a human sperm cell with about 8 million possibilities **(Figure 8.17)**, you can see that a single man and a single woman can produce zygotes with 64 trillion combinations of chromosomes!

Crossing Over

So far, we have focused on genetic variety in gametes and zygotes at the whole-chromosome level. We'll now take a closer look at **crossing over**, the exchange of corresponding segments between nonsister chromatids of homologous chromosomes, which occurs during prophase I of meiosis. **Figure 8.18** shows crossing over between two homologous chromosomes and the resulting gametes. At the time that crossing over begins, very early in prophase I, homologous chromosomes are closely paired all along their lengths, with a precise gene-by-gene alignment.

The exchange of segments between nonsister chromatids—one maternal chromatid and one paternal chromatid of a homologous pair—adds to the genetic variety resulting from sexual reproduction. In Figure 8.18, if there were no crossing over, meiosis could produce only two types of gametes: the ones ending up with chromosomes that exactly match the parents' chromosomes, either all blue or all red (as in Possibility 1 in Figure 8.16). With crossing over, gametes arise with chromosomes that are partly from the mother and partly from the father. These chromosomes are called "recombinant" because they result from genetic recombination, the production

▼ Figure 8.17 The process of fertilization: a close-up view. Here you see many human sperm contacting an egg. Only one sperm can add its chromosomes to produce a zygote.



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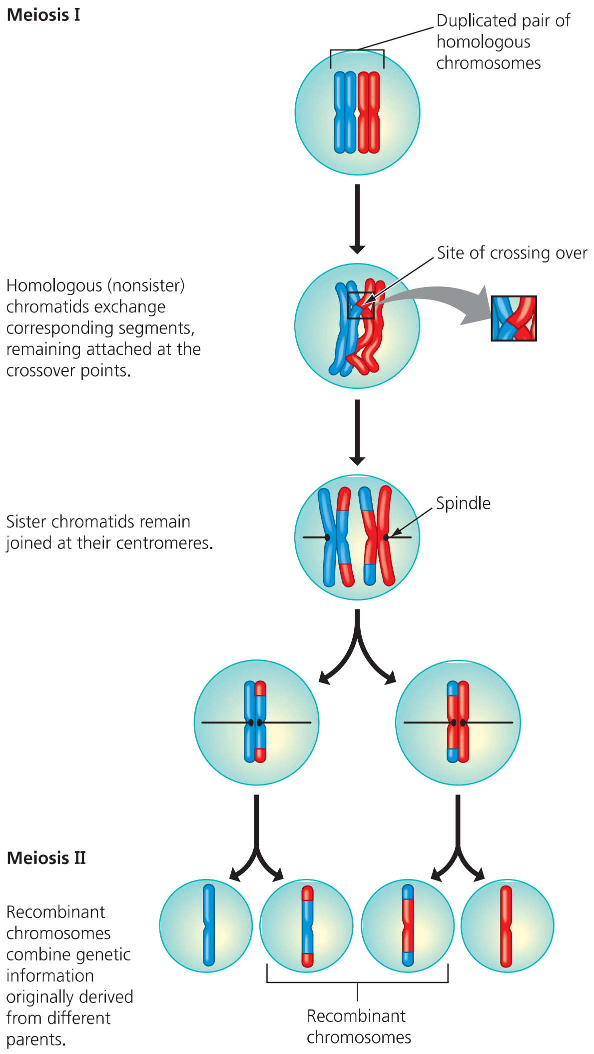
▼ Figure 8.18 The results of crossing over during meiosis for a single pair of homologous chromosomes. A real cell has multiple pairs of homologous chromosomes that produce a huge variety of recombinant chromosomes in the gametes.



of gene combinations different from those carried by the parental chromosomes.

Because most chromosomes contain thousands of genes, a single crossover event can affect many genes. When we also consider that multiple crossovers can occur in each pair of homologous chromosomes, it's not surprising that gametes and the offspring that result from them are so incredibly varied. ✓

✓ CHECKPOINT

Name two events during meiosis that contribute to genetic variety among gametes. During what stages of meiosis does each occur?

■ Answer: crossing over between homologous chromosomes during prophase I and independent orientation/assortment of the pairs of homologous chromosomes at metaphase I

THE PROCESS OF SCIENCE Life with and without Sex

Do All Animals Have Sex?

BACKGROUND

As discussed in the Biology and Society section, some species such as zebra sharks can reproduce through both sexual and asexual methods. Although some animal species can reproduce asexually, very few animals reproduce *only* asexually. In fact, biologists have traditionally considered asexual reproduction an evolutionary dead end (for reasons we'll discuss in the Evolution Connection section at the end of the chapter).

To investigate a case in which asexual reproduction seemed to be the norm, researchers from Harvard University studied a group of animals called bdelloid rotifers **(Figure 8.19a)**. This class of nearly microscopic freshwater invertebrates includes about 460 species. Despite hundreds of years of observations, no one has ever found bdelloid rotifer males or evidence of sexual reproduction. Has this entire class of animals reproduced solely by asexual means for tens of millions of years?

METHOD

In most species, the two versions of a gene in a pair of homologous chromosomes are very similar due to the constant trading of genes during sexual reproduction. If a species has survived without sex for millions of years, the researchers reasoned, then changes in the DNA sequences of homologous genes should accumulate independently, and the two versions of the genes should have significantly diverged from each other over time. The researchers therefore compared the sequences of a series of genes in bdelloid rotifers and in other closely related rotifers who were known to reproduce sexually.

RESULTS

Their results were striking **(Figure 8.19b)**. Among non-bdelloid rotifers that reproduce sexually, homologous versions of the genes were 99.5% identical, differing by only 0.5% on average. In contrast, the versions of the same gene in bdelloid rotifers were only 46 to 96% identical, differing by between 4 and 54%.

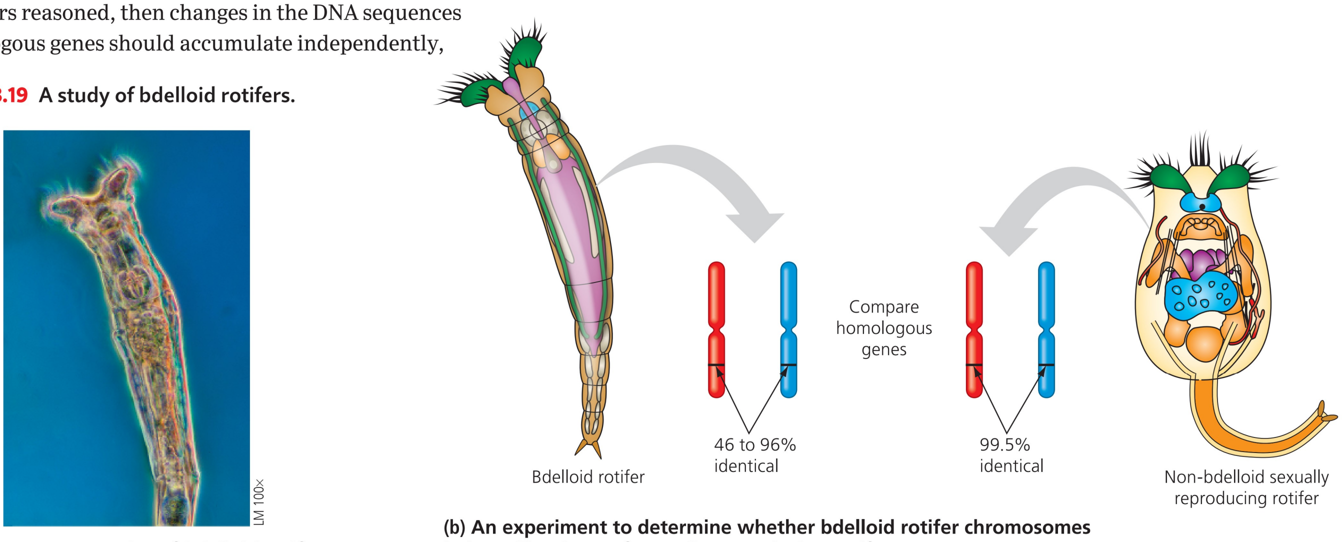
These data provided strong evidence that bdelloid rotifers have evolved for millions of years without sex. Recent research has suggested that these fascinating creatures may indeed rarely undergo some type of previously undiscovered sexual reproduction, but precisely what it is and how it works remain unknown. The study of bdelloid rotifers illustrates a general principle: Exploration of unusual cases can provide general insights into nature. In this case, studies of a tiny, obscure creature are shedding light on one of the biggest questions in all of animal biology: Why have sex?

Thinking Like a Scientist

A botanist noticed that a tree growing in a monastery in Brazil produced seedless oranges. Every navel orange tree alive today is derived from this single mutant. What common principle do navel oranges and bdelloid rotifers illustrate?

For the answer, see Appendix D.

▼ Figure 8.19 **A study of bdelloid rotifers.**



(a) One of over 460 species of bdelloid rotifers

(b) An experiment to determine whether bdelloid rotifer chromosomes behave like those of sexually reproducing rotifers

When Meiosis Goes Wrong

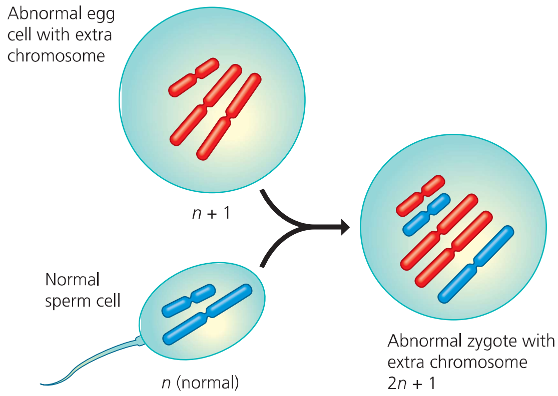
So far, our discussion of meiosis has focused on the process as it normally and correctly occurs. But what happens when there is an error in the process? Such a mistake can result in genetic abnormalities that range from mild to severe to fatal.

How Accidents During Meiosis Can Alter Chromosome Number

Within the human body, meiosis occurs repeatedly as the testes or ovaries produce gametes. Almost always, chromosomes are distributed to daughter cells without any errors. But occasionally there is a mishap, called a **nondisjunction**, in which the members of a chromosome pair fail to separate at anaphase. Nondisjunction can occur during meiosis I or II **(Figure 8.20)**. In either case, gametes with abnormal numbers of chromosomes are the result.

Figure 8.21 shows what can happen when an abnormal gamete produced by nondisjunction unites with a normal gamete during fertilization. When a normal sperm fuses with an egg cell with an extra chromosome, the result is a zygote with a total of $2n + 1$ chromosomes. Because mitosis duplicates the chromosomes as they are, the abnormality will be passed to all embryonic cells. If the organism survives, it will have an abnormal karyotype and probably a medical disorder caused by the abnormal number of genes. Nondisjunction is estimated to be involved in 10–30% of human conceptions and is the main reason for pregnancy loss. Next, we'll examine one particular case of survival nondisjunction. ✓

▼ Figure 8.21 Fertilization after nondisjunction in the mother.

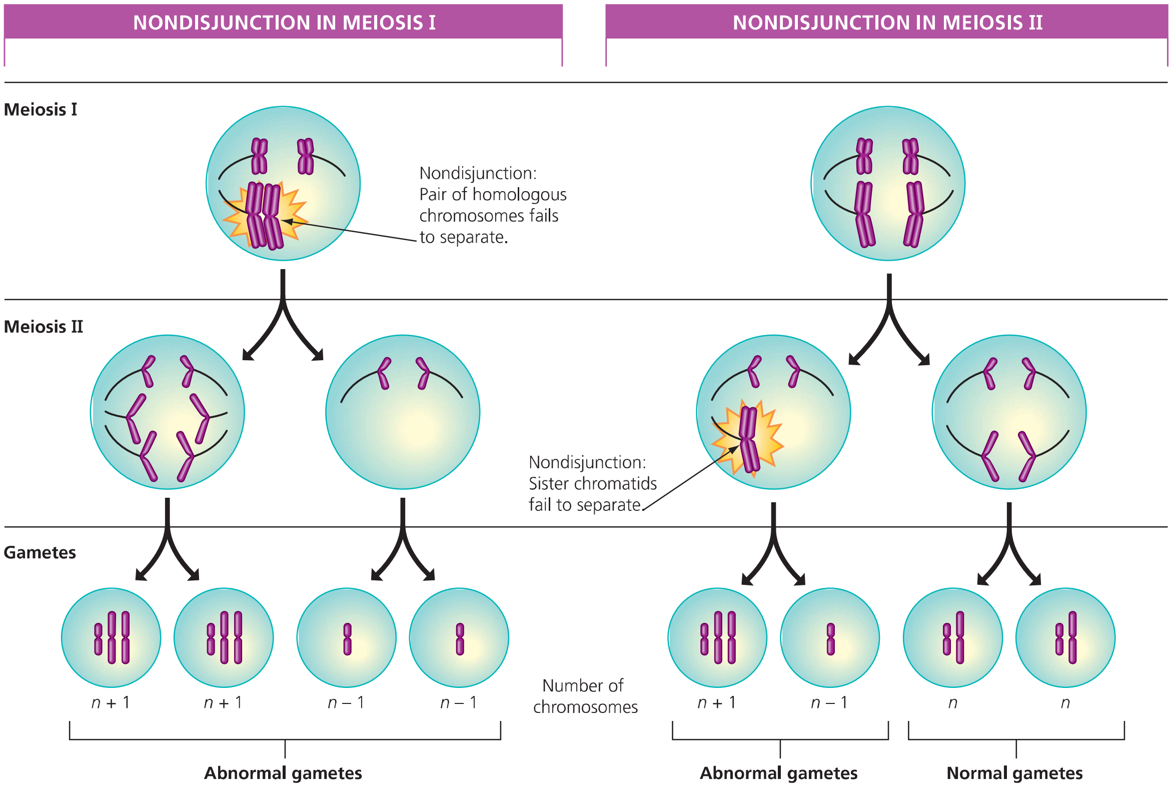


✓ CHECKPOINT

Explain how nondisjunction in meiosis could result in a diploid gamete.

■ Answer: A diploid gamete would result if there were nondisjunction of all the chromosomes during meiosis I or II.

▶ Figure 8.20 Two types of nondisjunction. In both examples in the figure, the cell at the top is diploid ($2n$), with two pairs of homologous chromosomes.



Down Syndrome: An Extra Chromosome 21

Figure 8.11 showed a normal human complement of 23 pairs of chromosomes. Compare it with the karyotype in **Figure 8.22**. Besides having two X chromosomes (because it's from a female), the karyotype in Figure 8.21 has three number 21 chromosomes. This person is triploid for chromosome 21 (instead of having the usual diploid condition) and therefore has 47 chromosomes. This condition is called **trisomy 21**.

▼ **Figure 8.22 Trisomy 21 and Down syndrome.** This child displays the characteristic facial features of Down syndrome. The karyotype (bottom) shows trisomy 21; notice the three copies of chromosome 21.

In most cases, a human embryo with an atypical number of chromosomes is spontaneously aborted (miscarried) long before birth, often before the woman is even aware that she is pregnant. In fact, some doctors speculate that miscarriages due to genetic defects occur in nearly one-quarter of all pregnancies, although this number is difficult to verify. However, some aberrations in chromosome number seem to upset the genetic balance less drastically, and people with such abnormalities can survive. These people usually have a characteristic set of symptoms, called a syndrome. A person with trisomy 21 has a condition called **Down syndrome** (named after John Langdon Down, an English physician who first described this condition in 1866).

Trisomy 21 affects about 1 out of every 850 children and is the most common chromosome number abnormality and most common serious birth defect in the United States. Down syndrome includes characteristic facial features—frequently a fold of skin at the inner corner of the eye, a round face, and a flattened nose—as well as short stature, heart defects, and susceptibility to leukemia and Alzheimer's disease. People with Down syndrome usually have a life span shorter than normal. They also exhibit varying degrees of developmental delays. However, with proper care, many people with Down syndrome live to middle age or beyond, and many are socially adept, live independently, and hold jobs. Although no one is sure why, the risk of Down syndrome increases with the age of the mother, climbing to about 1% risk for mothers at age 40. Therefore, the fetuses of pregnant women age 35 and older are candidates for chromosomal prenatal screenings (see Chapter 9). ✓

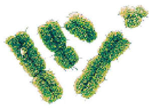
✓ CHECKPOINT

What does it mean to refer to a disease as a "syndrome," as with AIDS?

■ *Answer: A syndrome displays a set of multiple symptoms rather than just a single symptom.*

Abnormal Numbers of Sex Chromosomes

Trisomy 21 is an autosomal nondisjunction. Nondisjunction in meiosis can also lead to abnormal numbers of sex chromosomes, X and Y. Unusual numbers of sex chromosomes seem to upset the genetic balance less than unusual numbers of autosomes. This may be because the Y chromosome is very small and carries relatively few genes. Furthermore, mammalian cells normally operate with only one functioning X chromosome because other copies of the chromosome become inactivated in each cell (see Chapter 11).



DUPLICATING THE WRONG NUMBER OF CHROMOSOMES IS ALMOST ALWAYS FATAL.

Table 8.1 **Abnormalities of Sex Chromosome Number in Humans**

Sex Chromosomes	Syndrome	Symptoms
XXY	Klinefelter syndrome (male)	Sterile; underdeveloped testes; secondary female characteristics
XYY	None (normal male)	Slightly taller than average
XXX	None (normal female)	Slightly taller than average; slight risk of learning disabilities
XO	Turner syndrome (female)	Sterile; immature sex organs

Table 8.1 lists the most common human sex chromosome abnormalities. An extra X chromosome in a male, making him XXY, produces a condition called Klinefelter syndrome. If untreated, men with this disorder have abnormally small testes, are sterile, and often have breast enlargement and other feminine body contours. These symptoms can be reduced through administration of the sex hormone testosterone. Klinefelter syndrome is also found in men with more than three sex chromosomes, such as XXYY, XXXY, or XXXXY. These abnormal numbers of sex chromosomes result from multiple nondisjunctions; such men are more likely to have developmental disabilities than XY or XXY men.

Human males with a single extra Y chromosome (XYY) do not have any well-defined syndrome, although they tend to be taller than average. Females with an extra X chromosome (XXX) cannot be distinguished from XX females except by karyotype. Such women tend to be slightly taller than average and have a higher risk of learning disabilities.

Females who are lacking an X chromosome are designated XO; the O indicates the absence of a second sex chromosome. These women have Turner syndrome. They have a characteristic appearance, including short stature and often a web of skin extending between the neck and shoulders. Women with Turner syndrome are of normal intelligence but are sterile. If left untreated, they have poor development of breasts and other secondary sex characteristics. Administration of estrogen can alleviate those symptoms. The XO condition is the sole known case where having only 45 chromosomes is not fatal in humans.

Notice the crucial role of the Y chromosome in determining a person's sex. In general, having at least one Y chromosome produces biological maleness, regardless of the number of X chromosomes. The absence of a Y chromosome results in biological femaleness. ✓

✓ CHECKPOINT

Why is a person more likely to survive with an abnormal number of sex chromosomes than an abnormal number of autosomes?

■ Answer: because the Y chromosome is very small and extra X chromosomes are inactivated

EVOLUTION CONNECTION Life with and without Sex

The Advantages of Sex

Throughout this chapter, we've examined cell division within the context of reproduction. Like the zebra shark discussed in the Biology and Society section, many species (including a few dozen animal species, but many more within the plant kingdom) can reproduce both sexually and asexually **(Figure 8.23)**. An important advantage of asexual reproduction is that there is no need for a partner. Asexual reproduction may thus confer an evolutionary advantage when organisms are sparsely distributed (on an isolated island, for example) and unlikely to meet a mate. Furthermore, if an organism is superbly suited to a stable environment, asexual reproduction has the advantage of passing on its entire genetic legacy intact. Asexual reproduction also eliminates the need to expend energy forming gametes and copulating with a partner.

In contrast to plants, the vast majority of animals reproduce by sexual means. There are exceptions, such as the few species that can reproduce by parthenogenesis and the bdelloid rotifers discussed in the Process of Science section. But most animals reproduce only through sex. In fact, asexual reproduction seems to be an evolutionary "dead end" in the animal kingdom. Therefore, sex must enhance evolutionary fitness. But how? The answer remains elusive. Most hypotheses focus on the unique combinations of genes formed during meiosis and fertilization. By producing offspring of varied genetic makeup, sexual reproduction may enhance survival by speeding adaptation to a changing environment. Another idea is that shuffling genes during sexual reproduction might reduce the incidence of harmful genes more rapidly and allow for disadvantageous mutations to be more quickly eliminated from the gene pool. But for now, one of biology's most basic questions—Why have sex?—remains a hotly debated topic that is the focus of much ongoing research.

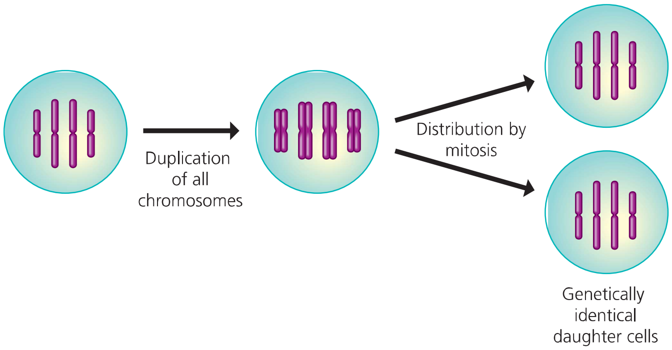
▼ **Figure 8.23 Sexual and asexual reproduction.** Many plants, such as this strawberry, have the ability to reproduce both sexually (through flowers that produce fruit) and asexually (through runners).

Chapter Review

SUMMARY OF KEY CONCEPTS

What Cell Reproduction Accomplishes

Cell reproduction, also called cell division, produces genetically identical cells:



Some organisms use mitosis (ordinary cell division) to reproduce. This is called asexual reproduction, and it results in offspring that are genetically identical to the lone parent and to each other. Mitosis also enables multicellular organisms to grow and develop and to replace damaged or lost cells. Organisms that reproduce sexually, by the union of a sperm with an egg cell, carry out meiosis, a type of cell division that yields gametes with only half as many chromosomes as body (somatic) cells.

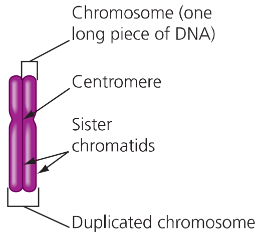
The Cell Cycle and Mitosis

Eukaryotic Chromosomes

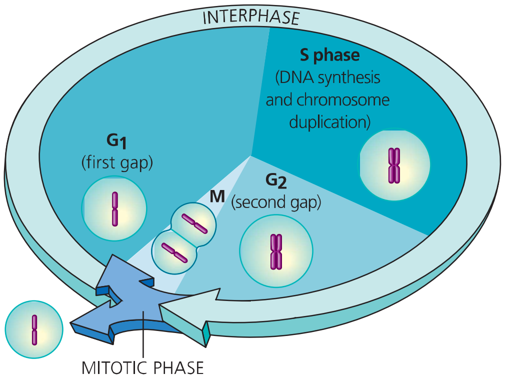
The genes of a eukaryotic genome are grouped into multiple chromosomes in the nucleus. Each chromosome contains one very long DNA molecule, with many genes, that is wrapped around histone proteins. Individual chromosomes are coiled up and therefore visible with a light microscope only when the cell is in the process of dividing; otherwise, they are in the form of thin, loosely packed chromatin fibers.

Duplicating Chromosomes

Because chromosomes contain the information needed to control cellular processes, they must be copied and distributed to daughter cells. Before a cell starts dividing, the chromosomes duplicate, producing sister chromatids (containing identical DNA) joined together at the centromere.



The Cell Cycle



Mitosis and Cytokinesis

Mitosis is divided into four phases: prophase, metaphase, anaphase, and telophase. At the start of mitosis, the chromosomes coil up and the nuclear envelope breaks down (prophase). Next, a mitotic spindle made of microtubule tracks moves the chromosomes to the middle of the cell (metaphase). The sister chromatids then separate and are moved to opposite poles of the cell (anaphase), where two new nuclei form (telophase). Cytokinesis overlaps the end of mitosis. In animals, cytokinesis occurs by cleavage, which pinches the cell in two. In plants, a membranous cell plate divides the cell in two. Mitosis and cytokinesis produce genetically identical cells.

Cancer Cells: Dividing Out of Control

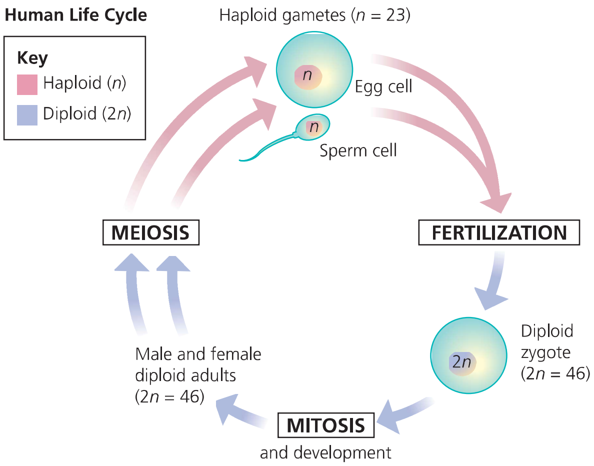
When the cell cycle control system malfunctions, a cell may divide excessively and form a tumor. Cancer cells may grow to form malignant tumors, invade other tissues (metastasize), and even kill the host. Surgery can remove tumors, and radiation and chemotherapy are effective as treatments because they interfere with cell division. You can increase the likelihood of surviving some forms of cancer through lifestyle changes and regular screenings.

Meiosis, the Basis of Sexual Reproduction

Homologous Chromosomes

The somatic cells (body cells) of each species contain a specific number of chromosomes; human cells have 46, made up of 23 pairs of homologous chromosomes. The chromosomes of a homologous pair carry genes for the same characteristics at the same places. Mammalian males have X and Y sex chromosomes (only partly homologous), and females have two X chromosomes.

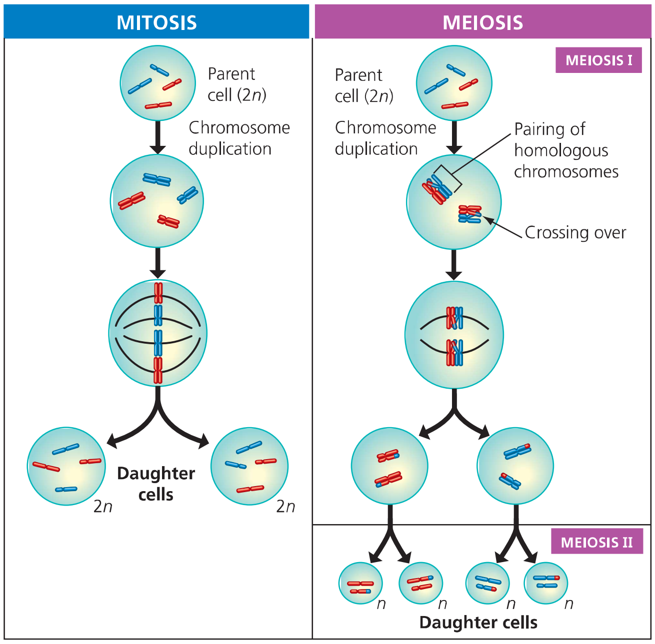
Gametes and the Life Cycle of a Sexual Organism



The Process of Meiosis

Meiosis, like mitosis, is preceded by chromosome duplication. But in meiosis, the cell divides twice to form four daughter cells. The first division, meiosis I, starts with the pairing of homologous chromosomes. In crossing over, homologous chromosomes exchange corresponding segments. Meiosis I separates the members of the homologous pairs and produces two daughter cells, each with one set of (duplicated) chromosomes. Meiosis II is essentially the same as mitosis; in each of the cells, the sister chromatids of each chromosome separate.

Review: Comparing Mitosis and Meiosis



The Origins of Genetic Variation

Because the chromosomes of a homologous pair come from different parents, they carry different versions of many of their genes. The large number of possible arrangements of chromosome pairs at metaphase of meiosis I leads to many different combinations of chromosomes in eggs and sperm. Random fertilization of eggs by sperm greatly increases the variation. Crossing over during prophase of meiosis I increases variation still further.

When Meiosis Goes Wrong

An abnormal number of chromosomes can cause problems. Down syndrome is caused by an extra copy of chromosome 21, a result of nondisjunction, the failure of homologous chromosomes to separate during meiosis I or of sister chromatids to separate during meiosis II. Nondisjunction can also produce gametes with extra or missing sex chromosomes, which lead to varying degrees of malfunction but do not usually affect survival.

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SELF-QUIZ

1. Which of the following is not a function of mitosis in humans?
   a. repair of wounds
   b. growth
   c. production of gametes from diploid cells
   d. replacement of lost or damaged cells
2. In what sense are the two daughter cells produced by mitosis identical?
3. Why is it hard to observe individual chromosomes in interphase?
4. A biochemist measures the amount of DNA in cells growing in the laboratory. The quantity of DNA in a cell would be found to double
   a. between prophase and anaphase of mitosis.
   b. between the G_1 and G_2 phases of the cell cycle.
   c. during the M phase of the cell cycle.
   d. between prophase I and prophase II of meiosis.
5. What phases of mitosis are opposites in terms of changes in the nucleus?
6. Complete the following table to compare mitosis and meiosis.

	Mitosis	Meiosis
a. Number of chromosomal duplications		
b. Number of cell divisions		
c. Number of daughter cells produced		
d. Number of chromosomes in daughter cells		
e. How chromosomes line up during metaphase		
f. Genetic relationship of daughter cells to parent cells		
g. Functions performed in the human body		

7. If an intestinal cell in a dog contains 78 chromosomes, a dog sperm cell would contain ________ chromosomes.
8. A micrograph of a dividing cell from a mouse shows 19 chromosomes, each consisting of two sister chromatids. During which stage of meiosis could this micrograph have been taken? (Explain your answer.)

9. Tumors that remain at their site of origin are called ________, and tumors that can migrate to other body tissues are called ________.

10. A diploid body (somatic) cell from a fruit fly contains eight chromosomes. This means that ________ different combinations of chromosomes are possible in its gametes.

11. Although nondisjunction is a random event, there are many more people with an extra chromosome 21, which causes Down syndrome, than people with an extra chromosome 3 or chromosome 16. Explain.

For answers to the Self Quiz, see Appendix D.

IDENTIFYING MAJOR THEMES

For each statement, identify which major theme is evident (the relationship of structure to function, information flow, pathways that transform energy and matter, interactions within biological systems, or evolution) and explain how the statement relates to the theme. If necessary, review the themes (see Chapter 1) and review the examples highlighted in blue in this chapter.

12. Passing along genetic instructions from one generation to the next requires a precise duplication of the chromosomes.

13. The combined actions of many different proteins determine whether a cell will divide or not.

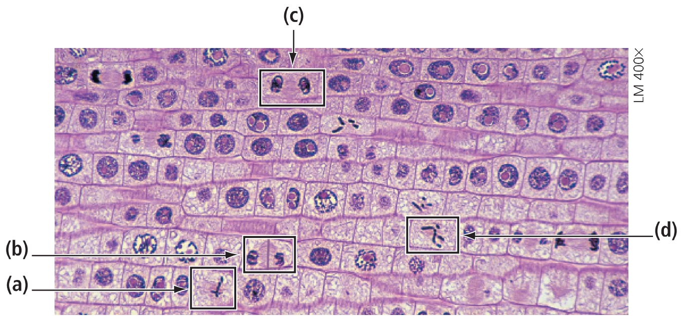
14. By examining the compactness of a chromosome region (loose versus tightly wound), you can gain insight into whether the genes in that region are actively being used.

For answers to Identifying Major Themes, see Appendix D.

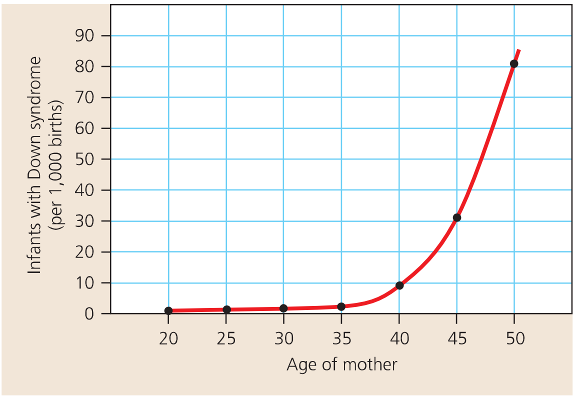
THE PROCESS OF SCIENCE

15. A mule is the offspring of a horse and a donkey. A donkey sperm contains 31 chromosomes and a horse egg has 32, so the zygote has 63. The zygote develops normally. However, a mule is sterile; meiosis cannot occur normally in its testes or ovaries. Explain why mitosis is normal in cells containing both horse and donkey chromosomes, but the mixed set interferes with meiosis.

16. You prepare a slide with a thin slice of an onion root tip. You see the following view in a light microscope. Identify the stage of mitosis for each of the outlined cells, a–d.



17. **Interpreting Data** The graph shows the incidence of Down syndrome in the offspring of normal parents as the age of the mother increases. For women under the age of 30, how many infants with Down syndrome are born per 1,000 births? At age 40? At age 50? How many times more likely is a 50-year-old woman to give birth to a baby with Down syndrome than a 30-year-old woman?



BIOLOGY AND SOCIETY

18. If an endangered species can reproduce by parthenogenesis, what implications might this have on efforts to repopulate that species? How might a parthenogenesis program harm such a species?

19. Every year, about a million Americans are diagnosed with cancer. This means that about 75 million Americans now living will eventually have cancer, and one in five will die of the disease. There are many kinds of cancers and many causes, such as smoking, overexposure to ultraviolet rays, a high-fat and low-fiber diet, and some workplace chemicals. Hundreds of millions of dollars are spent each year on searching for treatments, yet far less money is spent on prevention. Should we devote more resources to treating cancer or to preventing it? Explain.

20. The practice of buying and selling gametes, particularly eggs from fertile women, is becoming common in the United States and some other industrialized nations. Do you object to this type of transaction? Would you sell your gametes? At any price? Whether you would do so or not, should this practice be restricted?

21. The anticancer drug Taxol freezes the mitotic spindle after it forms, which may stop a tumor from growing. It is made from a chemical in the bark of the Pacific yew, a tree found mainly in the northwestern United States. It has fewer side effects than many other anticancer drugs and seems effective against some hard-to-treat cancers of the ovary and breast. Another drug, vinblastine, prevents the mitotic spindle from forming. It was first obtained from the periwinkle plant, native to the tropical rain forests of Madagascar. Given these examples, preserving biodiversity may be the key to discovering lifesaving anticancer drugs. Such drugs are often discovered in developing areas, but because they are expensive, they primarily benefit people in developed regions. Do you see a conflict in this? Explain.