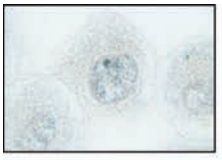
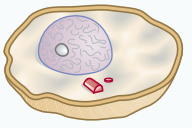
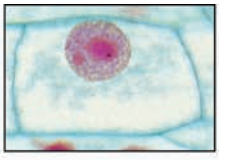
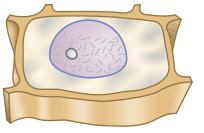
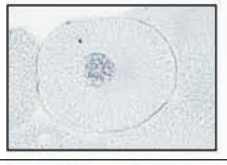
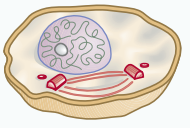
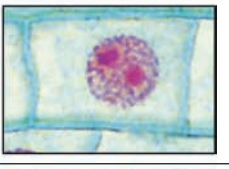
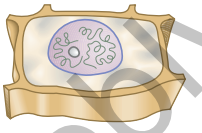
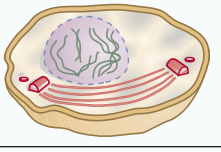
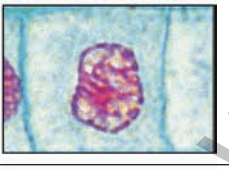
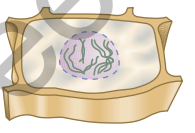
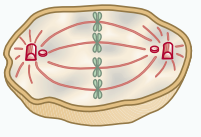
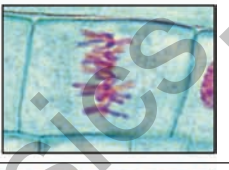
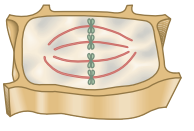
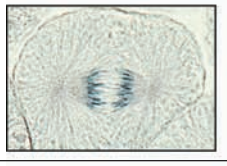
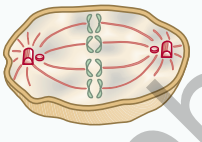
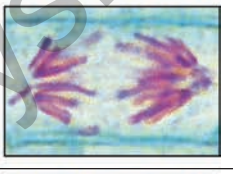
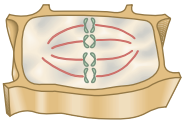
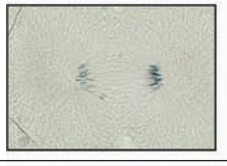
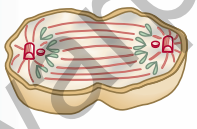
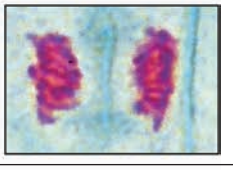
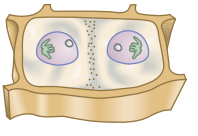
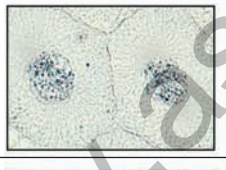
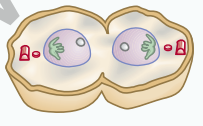
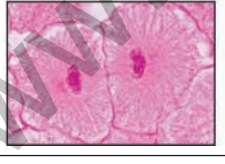
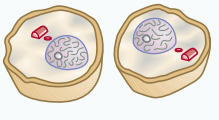
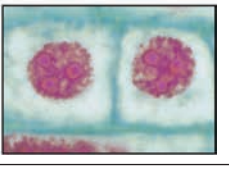
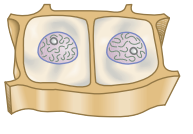
TABLE 9.1 Summary of the Cell Cycle

The stages of the cell cycle are shown in photographs and drawings for both animal and plant cells. The photographed animal cells are from whitefish blastulas. The photographed plant cells are from onion root tips.

Stage	Animal Cells		Plant Cells		Summary
Interphase					As the cell prepares for mitosis, the chromosomes replicate during the S phase of interphase.
Early Prophase					The replicated chromatids begin to coil into recognizable chromosomes; the nuclear membrane fragments; spindle fibers form; nucleolus and nuclear membrane disintegrate.
Late Prophase					
Metaphase					Chromosomes attach to spindle fibers at their centromeres and then move to the equator.
Anaphase					Chromatids, now called daughter chromosomes, separate toward the poles.
Telophase					The nuclear membranes and nucleoli re-form; spindle fibers fragment; the chromosomes unwind and change from chromosomes to chromatin.
Late Telophase					
Daughter Cells					Cytokinesis occurs and two daughter cells are formed from the dividing cells.

code for proteins that discourage cell division. A healthy cell receives signals from both groups of proteins about how appropriate it is to divide. The balance of information provided by these two groups of proteins allows for controlled cell division.

One tumor-suppressor gene is *p53*. Near the end of G_1, the protein produced by the *p53* gene identifies if the cell's DNA is damaged. If the DNA is healthy, *p53* allows the cell to divide (figure 9.12a). If the *p53* protein detects damaged DNA, it triggers other proteins to become active and repair the DNA. If the damage is too extensive for repair, the *p53* protein triggers an entirely different response from the cell. The *p53* protein causes the cell to self-destruct. **Apoptosis** is the process whereby a cell

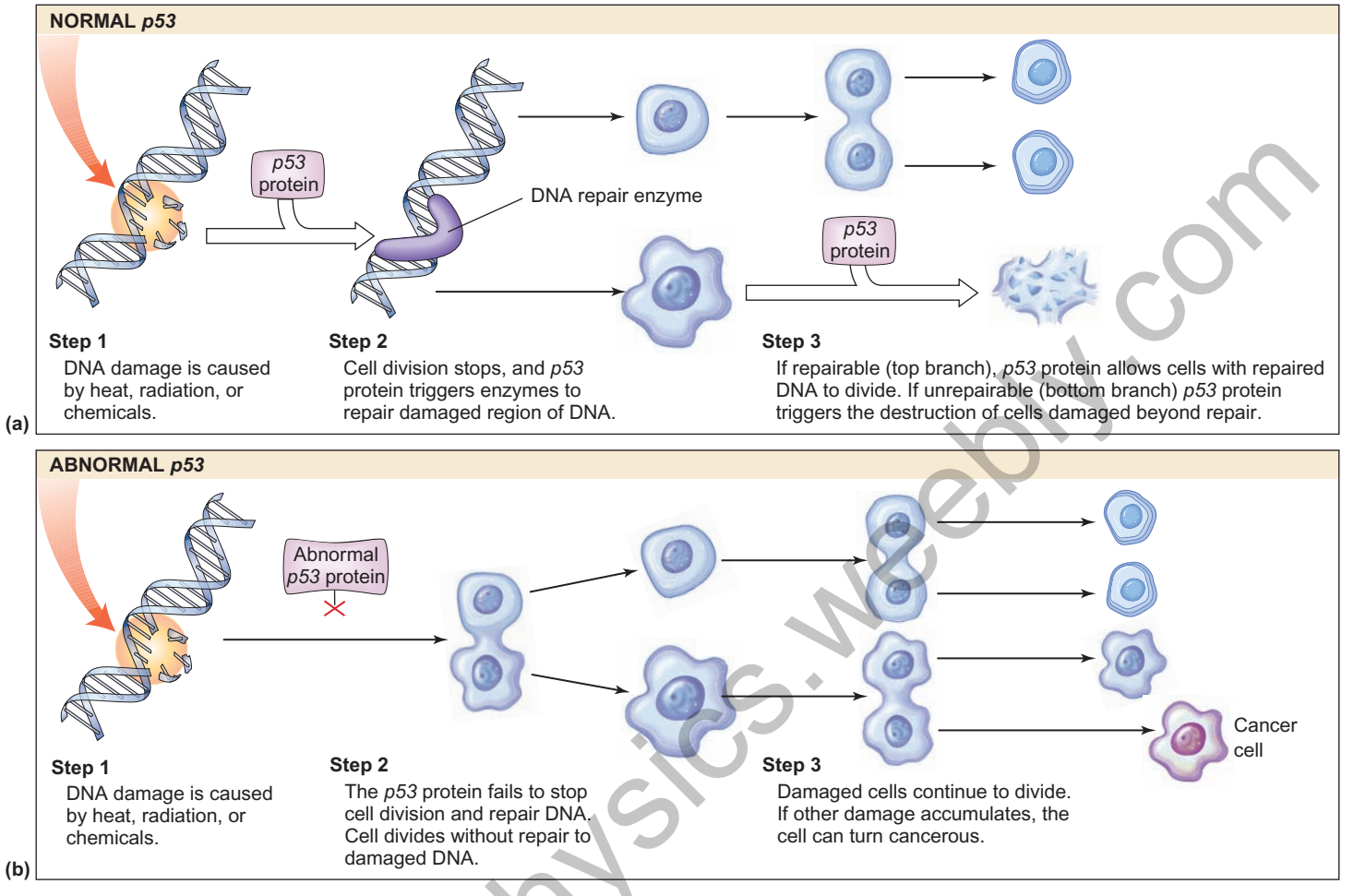


FIGURE 9.12 The Function of *p53* Protein
(a) Normal *p53* protein stops cell division until damaged DNA is repaired. If the DNA is unrepairable, the *p53* protein causes cell death. *(b)* Mutated *p53* protein allows cells with damaged DNA to divide.

digests itself from the inside out. You might think of it as cellular suicide. In this scenario, apoptosis prevents mutated cells from continuing to grow. Other healthy cells will undergo cell division to replace the lost cell.

Consider the implications of a mutation within the *p53* gene. If the *p53* protein does not work correctly, then cells with damaged DNA may move through cell division. As these cells move through many divisions, their inability to detect damaged DNA disposes them to accumulate more mutations than do other cells. These mutations may occur in their proto-oncogenes and other tumor-suppressor genes. As multiple mutations occur in the genes responsible for regulating cell division, the cell is less likely to control cell division appropriately. When a cell is unable to control cell division, cancer can develop.

9.4 CONCEPT REVIEW

12. What are checkpoints?
13. What role does *p53* have in controlling cell division?

9.5 Cancer

Cancer is a disease caused by the failure to control cell division. This results in cells that divide too often and eventually interfere with normal body function. Scientists view cancer as a disease caused by mutations in the genes that regulate cell division. The mutations can be inherited or caused by agents in the environment. For example, the tar from cigarette smoke has been directly linked to mutations in the *p53* gene. The tar in cigarette smoke is categorized as both a *mutagen* and a *carcinogen*. **Mutagens** are agents that mutate, or chemically damage, DNA. **Carcinogens** are mutagens that cause cancer.

Mutagenic and Carcinogenic Agents

Many agents have been associated with higher rates of cancer. The one thing they all have in common is their ability to alter the sequence of nucleotides in the DNA molecule. When damage occurs to DNA, the replication and transcriptional machinery may no longer be able to read the DNA's genetic information (figure 9.13).

FIGURE 9.13 Carcinogens
Carcinogenic agents come in many forms.

This is a partial list of mutagens that are found in our environment.

Radiation
X rays and gamma rays
Ultraviolet light
  UV-A, from tanning lamps
  UV-B, the cause of sunburn

Chemicals
Arsenic
Benzene
Dioxin
Polyvinyl chloride (PVC)
Chemicals found in smoked meats and fish
Asbestos
Alcohol
Cigarette tar
Food containing nitrates (e.g., bacon)

Some viruses insert a copy of their genetic material into a cell's DNA. When this insertion occurs in a gene involved with regulating the cell cycle, it creates an insertion mutation, which may disrupt the cell's ability to control mitosis. Many of the viruses that are associated with higher rates of cancer are associated with a particular type of cancer (figure 9.14):

Viruses	*Cancer*
Hepatitis B virus (HBV)	Liver cancer
Herpes simplex virus (HSV) type II	Uterine cancer
Epstein-Barr virus	Burkitt's lymphoma
Human T-cell lymphotropic virus (HTLV-1)	Lymphomas and leukemias
Papillomavirus	Several cancers

Because cancer is caused by *changes* in DNA, scientists have found that a person's genetic makeup may be linked to developing certain cancers. A predisposition to develop cancer

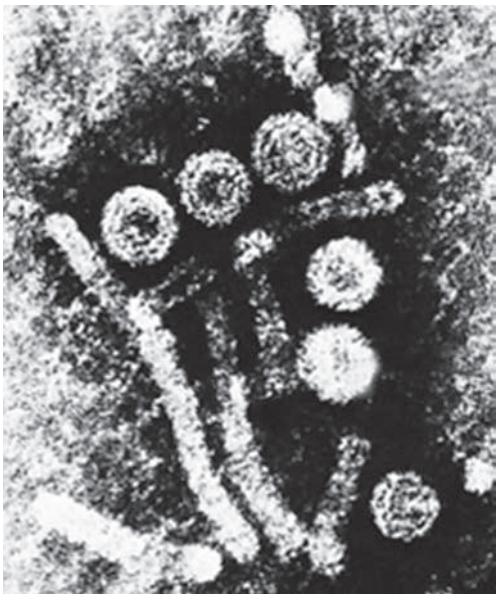


FIGURE 9.14 Cancer Caused by Viruses
Cancer is both environmental and genetic. The hepatitis B virus is among the many agents that can increase the likelihood of developing cancer.

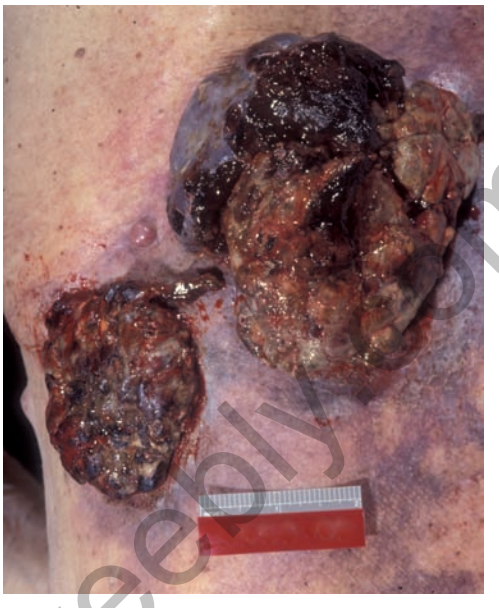


FIGURE 9.15 Skin Cancer
Malignant melanoma is a type of skin cancer. It forms as a result of a mutation in pigmented skin cells. These cells divide repeatedly, giving rise to an abnormal mass of pigmented skin cells. The two large dark areas in the photograph, are the cancer on a person's back; the surrounding cells have the genetic information to develop into normal, healthy skin. This kind of cancer is particularly dangerous, because the cells break off and spread to other parts of the body (metastasize).

can be inherited from one's parents. The following cancers have been shown to be inherited:

Leukemias	Lung cancer
Certain skin cancers	Endometrial cancer
Colorectal cancer	Stomach cancer
Retinoblastomas	Prostate cancer
Breast cancer	

When uncontrolled mitotic division occurs, a group of cells forms a *tumor* (How Science Works 9.1). A **tumor** is a mass of cells not normally found in a certain portion of the body. A **benign tumor** is a cell mass that does not fragment and spread beyond its original area of growth. A benign tumor can become harmful, however, by growing large enough to interfere with normal body functions. Some tumors are *malignant*. **Malignant tumors** are harmful because they may spread or invade other parts of the body (figure 9.15). Cells of these tumors **metastasize,** or move from the original site and begin to grow new tumors in other regions of the body (figure 9.16).

HOW SCIENCE WORKS 9.1

The Concepts of Homeostasis and Mitosis Applied

The total number of cells stays about the same during the adult life of an organism. It is kept at a constant number because the number of cells generated by mitosis equals the number that die. This homeostatic condition is achieved when the rate of mitosis equals the rate of cell death:

$$R_{(reproduction)} = D_{(death)}$$

Cancer may result if homeostasis is not maintained because cells are reproducing faster than they die:

$$R > D$$

For example, pancreatic cancer can result from the malfunctioning of apoptosis-signaling pathways. *Signaling pathways* are biochemical reactions that trigger events in the cell. In this situation, a form of cancer, pancreatic cells are not signaled to die by apoptosis and they continue to divide unchecked.

On the other hand, if lost cells are not replaced by mitosis, the organism will no longer be able to maintain a stable, constant condition and die:

$$R < D$$

Biomedical researchers have applied this knowledge to control cells that have abnormally constant rates of mitosis. For example, certain cancer therapies affect signaling pathways by increasing apoptosis. The drug Taxol causes a significant increase in apoptosis in cancer cells.

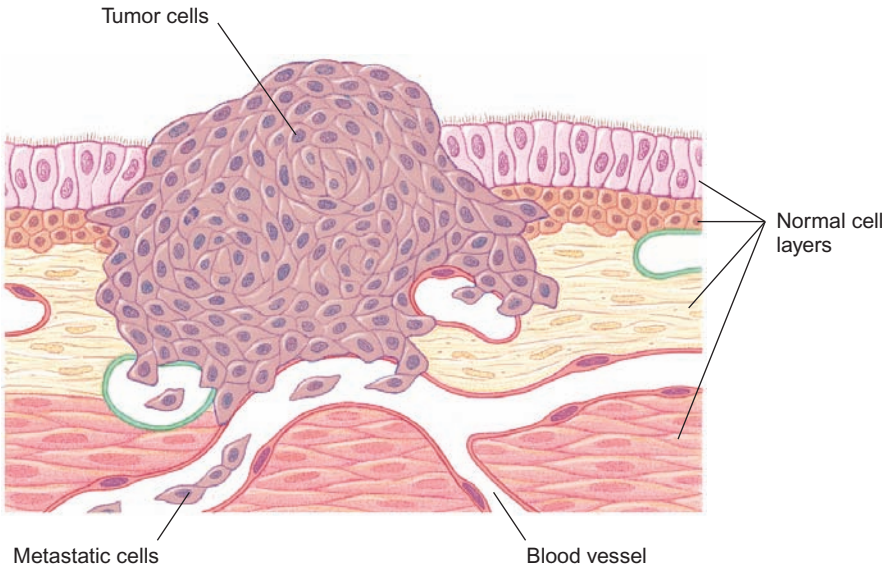


FIGURE 9.16 Metastasizing Cells
A tumor consists of cells that have lost their ability to control cell division. As these cells divide rapidly, they form a tumor and invade surrounding tissues. Cells metastasize when they reach blood vessels and are carried to other parts of the body. Once in their new locations, the cells continue to divide and form new tumors.

Epigenetics and Cancer

Although many cancers are caused by mutations, it is thought that epigenetic effects cause more cancers than mutations. Epigenetics causes changes in the expression of genetic material but does not alter (mutate) the DNA. Cells are constantly manipulating their DNA and histone proteins to regulate gene expression including those controlling cell division. For a variety of reasons, cells may perform these functions improperly. Epigenetic changes important to carcinogenesis are the result of certain chemical reactions that affect the nitrogenous base cytosine and histone proteins. Such chemical changes can lead to malfunctions of oncogenes or tumor-suppressor genes. This allows cells whose division rate had previously been regulated, to begin nonstop division; a critical step in cancer development. These modifications to both DNA and histones are able to be passed on through mitosis and in some cases meiosis.

Treatment Strategies

The Surgical Removal of Cancer

Once cancer has been detected, it is often possible to eliminate the tumor. If the cancer is confined to a few specific locations, it may be possible to remove it surgically. Many cancers of the skin or breast are dealt with in this manner. The early detection of such cancers is important because early detection increases the likelihood that the cancer can be removed before it has metastasized (figure 9.17a). However, in some cases, surgery is impractical. Leukemia is a kind of cancer caused by the uncontrolled growth of white blood cells being formed in the bone marrow. In this situation, the cancerous cells spread throughout the body and cannot be removed surgically. Surgery is also not useful when the tumor is located where it can't be removed without destroying necessary healthy tissue. For example, removing certain brain cancers can severely damage the brain. In such cases, other treatments may be used, such as chemotherapy and radiation therapy.

Chemotherapy and Radiation Therapy

Scientists believe that chemotherapy and radiation therapy for cancer take advantage of the cell's ability to monitor cell division at the cell cycle checkpoints. By damaging DNA or preventing its replication, chemotherapy and radiation cause the targeted cancer cells to stop dividing and die. Other chemotherapeutic agents disrupt parts of the cell, such as the spindle, that are critical for cell division. Most common cancers cannot be controlled with chemotherapy alone. Chemotherapy is often used in combination with radiation therapy.

Radiation therapy uses powerful X rays or gamma rays to damage the DNA of the cancer cells (figure 9.17b). At times, radiation

(a)

(b)

FIGURE 9.17 Surgical and Radiation Treatments of Cancer
(a) Surgery is one option for treating cancer. Sometimes, if the cancer is too advanced or has already spread, other therapies *(b)* such as radiation are necessary.

can be used when surgery is impractical. This therapy can be applied from outside the body or by implanting radioactive "seeds" into the tumor. In both cases, a primary concern is to protect healthy tissue from the radiation's harmful effects. When radiation is applied from outside the body, a beam of radiation is focused on the cancerous cells and shields protect as much healthy tissue as possible.

Unfortunately, chemotherapy and radiation therapy can also have negative effects on normal cells. Chemotherapy may expose all the body's cells to the toxic ingredients and then weaken the body's normal defense mechanisms, because it decreases the body's ability to reproduce new white blood cells by mitosis. As a precaution against infection, cancer patients undergoing chemotherapy must be given antibiotics. The antibiotics help them defend against dangerous bacteria that might invade their bodies. Other side effects of chemotherapy include intestinal disorders and hair loss, which are caused by damage to the healthy cells in the intestinal tract and the skin that normally divide by mitosis.

Whole-Body Radiation

Whole-body radiation is used to treat some leukemia patients, who have cancer of the blood-forming cells located in their bone marrow; however, not all of these cells are cancerous. A radiation therapy method prescribed for some patients involves the removal of some of their bone marrow and isolation of the noncancerous cells. The normal cells can then be grown in a laboratory. After these healthy cells have been cultured and increased in number, the patient's whole body is exposed to high doses of radiation sufficient to kill all the cancerous cells remaining in the bone marrow. Because this treatment can cause significant damage to the immune system, it is potentially deadly. As a precaution the patient is isolated from all harmful substances and infectious microbes. They are fed sterile food, drink sterile water, and breathe sterile air while being closely monitored and treated with antibiotics. The cultured noncancerous cells are injected back into the patient. As if the cells had a memory, they migrate back to their origins in the bone marrow, establish residence, and begin regulated cell division all over again.

Because radiation damages healthy cells, it is used very cautiously. In cases of extreme exposure to radiation, people develop *radiation sickness*. The symptoms of this disease include hair loss, bloody vomiting and diarrhea, and a reduced white blood cell count. Vomiting, nausea, and diarrhea occur because the radiation kills many of the cells lining the gut and interferes with the replacement of the intestine's lining, which is constantly being lost as food travels through. Hair loss occurs because radiation prevents cell division at the hair root; these cells must divide for the hair to grow. Radiation reduces white blood cells because it prevents their continuous replacement from cells in the bone marrow and lymph nodes. When radiation strikes these rapidly dividing cells and kills them, the lining of the intestine wears away and bleeds, hair falls out, and there are very few new white blood cells to defend the body against infection.

Nanoparticle Therapy

The use of nanoparticle cancer therapy is being explored in many research labs. Nanoparticles cover a range between 1 and 100 nanometers in diameter and can be synthesized so that they attach only to specific cancer cells taken from a patient. They can be combined with cancer-specific, anticancer proteins. When injected into an organism, these combination particles travel throughout the body without causing harm or being rejected until they attach to their targeted cancer cells. When they combine with cell surface molecules, the anticancer drug is delivered and the cancer cell destroyed. While still in the research phase, nanoparticle cancer therapy has been shown to stop the growth of prostate, breast, and lung tumors in rodents.

9.5 CONCEPT REVIEW

14. Why is radiation used to control cancer?
15. List three factors associated with the development of cancer.
16. What role does epigenetics play in cancer development?

9.6 Determination and Differentiation

The process of mitosis enables a single cell to develop into an entire body, with trillions of cells. A **zygote** is the original single cell that results from the union of an egg and sperm. The zygote divides by mitosis to form genetically identical daughter cells. Mitotic cell division is repeated over and over until an entire body is formed.

Although the cells in the mature body are the same genetically, they do not all have the same function. There are nerve cells, muscle cells, bone cells, skin cells, and many other types. The difference among cell types is not in the genes they *possess*, but in the genes they *express* (i.e., through epigenetics).

Determination is the cellular process of deciding which genes a cell will express when mature. Determination marks the point where a cell commits to becoming a certain kind of cell and starts down the path of becoming that cell type. When a cell reaches the end of that path, it is said to be *differentiated*. A **differentiated** cell has become a particular cell type.

Skin cells provide a good example of determination and differentiation. Some skin cells produce hair; others do not. All the body's cells have the gene to produce hair, but not all cells do. When a cell starts to undergo the process of becoming a hair-producing cell, it is undergoing determination. Once the cell has become a hair-producing cell, it is differentiated. This differentiated cell is called a hair follicle cell (figure 9.18).

9.6 CONCEPT REVIEW

17. What is the difference between determination and differentiation?

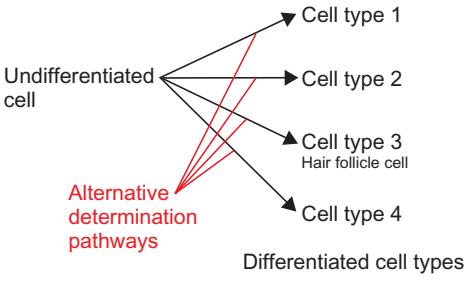


FIGURE 9.18 Determination and Differentiation
A cell starts as undetermined and undifferentiated. Specific genes are expressed to provide a cell its unique identity. Here, an undetermined cell goes through the process of determination to express the genes needed to be a hair follicle. When the process is complete and the hair follicle genes are expressed, the cell is differentiated.

9.7 Cell Division and Sexual Reproduction

Meiosis is a form of cell division involved in sexual reproduction. Meiosis has a different function than mitosis, the cell division that we have just been discussing. Mitosis is responsible for growth and repair of tissues. Meiosis is responsible for the production of eggs and sperm. The cells of sexually reproducing organisms have two sets of chromosomes and thus have two sets of genetic information. One set was received from the mother's egg, the other from the father's sperm. It is necessary for organisms that reproduce sexually to form sex cells having only one set of chromosomes.

If sex cells contained two sets of chromosomes, the zygote resulting from their union would have four sets of chromosomes with twice the total genetic information of the parents. With each new generation, the number of chromosomes would continue to increase. Thus, eggs and sperm must be formed by a method that reduces the amount of genetic information by half.

Scientists have terms to distinguish when a cell has either one or two copies of genetic information. **Haploid** cells carry only one complete set of their genetic information. **Diploid** cells carry two complete sets of their genetic information. Meiosis is the cell division process that generates haploid reproductive cells from diploid cells. In many sexually reproducing organisms, such as humans, meiosis takes place in the cells of organs that are devoted to reproduction—the **gonads.** The gonads in females are known as **ovaries;** in males, **testes.** Ovarian and testicular cells that divide by meiosis produce reproductive cells called *gametes*. **Gamete** is a general term for reproductive cells like eggs and sperm. These gametes are also referred to as *germ cells*. Algae and plants also possess organs for sexual reproduction. Some of these are very simple. In algae such as *Spirogyra*, individual cells become specialized for gamete production. In plants, the structures are very complex. In flowering plants, the **pistil** produces eggs, or ova, and the **anther** produces pollen, which contains sperm (figure 9.19).

In sexually reproducing organisms, the life cycle involves both mitosis and meiosis. In figure 9.20, the haploid number of chromosomes is noted as *n*. The zygote and all the resulting cells that give

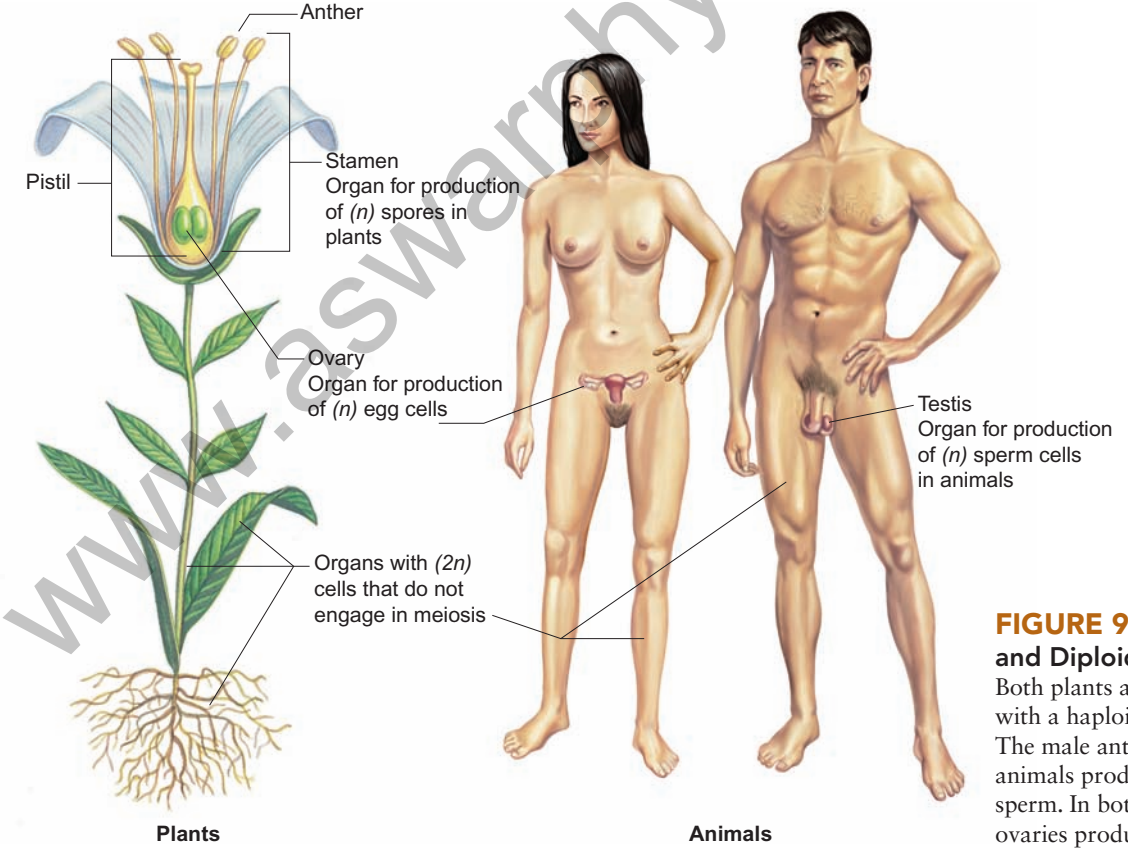


FIGURE 9.19 Haploid and Diploid Cells
Both plants and animals produce cells with a haploid number of chromosomes. The male anther in plants and the testes in animals produce haploid male cells, sperm. In both plants and animals, the ovaries produce haploid female cells, eggs.

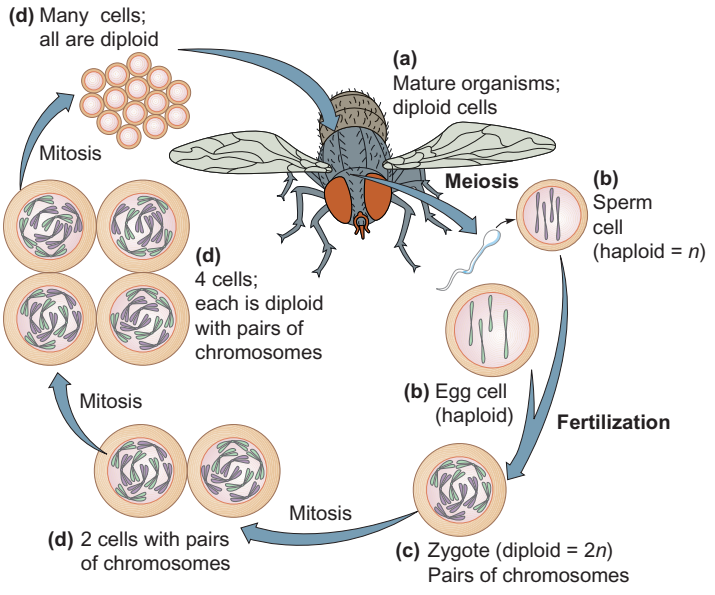


FIGURE 9.20 The Life Cycle of a Fruit Fly
(a) The diploid cells of this adult fruit fly have 8 chromosomes in their nuclei. *(b)* In preparation for sexual reproduction, the number of chromosomes must be reduced by half, so that the gametes will be haploid and have 4 chromosomes, *(c)* When the egg and sperm unite during fertilization, the original diploid number of 8 chromosomes will be restored. *(d)* The offspring will grow and produce new cells by mitosis.

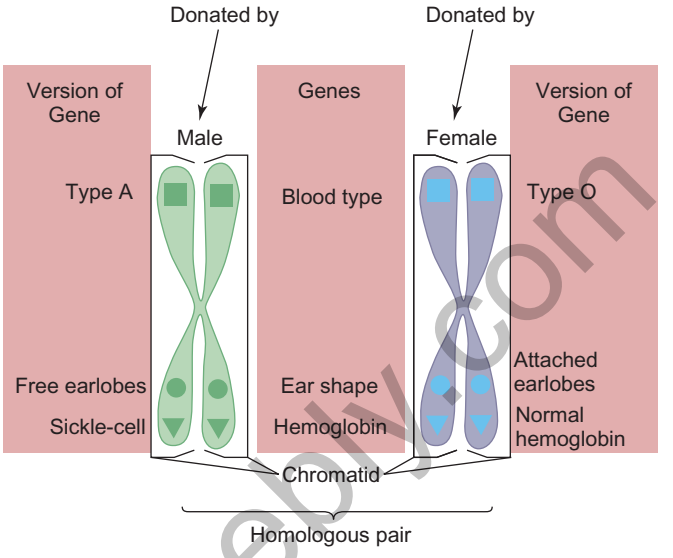


FIGURE 9.21 A Pair of Homologous Chromosomes
A pair of chromosomes are said to be homologous if they have genes for the same traits. Notice that the genes may not be identical, but the genes code for the same type of information. Homologous chromosomes are of the same length, have the same types of genes in the same sequence, and have their centromeres in the same location—one chromosome came from the male parent and the other from the female parent.

rise to the adult fruit fly are diploid. The diploid number of chromosomes is noted as $2n$—mathematically, $n + n = 2n$. The gametes are produced by meiosis in female and male adult fruit flies. Notice that the male and female gamete each contain 4 chromosomes. Collectively, these 4 chromosomes represent one complete set of all the genetic information that is necessary for a fruit fly.

Fertilization is the joining of the genetic material from two haploid cells. During fertilization, each gamete contributes one set of genetic information (one set of chromosomes) toward forming a new organism. Recall that the zygote is the diploid cell that results from the egg and sperm combining their genetic information. The zygote contains two sets of genetic information on 8 chromosomes (4 from the egg and 4 from the sperm—two sets of chromosomes). The zygote divides by *mitosis* and the cells grow to become an adult fruit fly, which will then produce either eggs or sperm by meiosis in its gonads. The characteristics of the fruit fly will depend on the combination of genetic information it inherits from both parents on its 8 chromosomes.

Diploid cells have two sets of chromosomes—one set from each parent. Because chromosomes contain DNA, each chromosome has many genes along its length. Each chromosome in a diploid cell can be paired to another chromosome on the basis of the genes on those chromosomes. **Homologous chromosomes** have the same order of genes along their DNA (figure 9.21). Because of the similarity of genetic information in homologous chromosomes are the same size and their centromeres are found in the same locations. Each parent contributes one member of each of the pairs of the homologous chromosomes. **Non-homologous chromosomes** have different genes on their DNA. The fruit fly has four pairs of homologous chromosomes—or 8 total chromosomes. Different species of organisms vary in the number of chromosomes they contain (table 9.2).

TABLE 9.2 Chromosome Numbers

Organism	Diploid Number	Haploid Number
Jumper ant	2	1
Tapeworm	4	2
Mosquito	6	3
Housefly	12	6
Onion	16	8
Rice	24	12
Tomato	24	12
Cat	38	19
Gecko	46	23
Human	**46**	**23**
Rat	46	23
Chimpanzee	48	24
Potato	48	24
Horse	64	32
Dog	78	39
Stalked adder's tongue fern	1,260	630

Before we move on and describe meiosis in detail, consider the different purposes of mitosis and meiosis: Mitosis results in cells that have the same number of chromosomes as the parent cell, whereas meiosis results in cells that have half the chromosomes as the parent cell. An important question to ask is, "how are the processes of mitosis and meiosis different, so that gametes receive only half of the parent cell's chromosomes?"

9.7 CONCEPT REVIEW

18. How do haploid cells differ from diploid cells?
19. Why is meiosis necessary in organisms that reproduce sexually?
20. Define the terms *zygote*, *fertilization*, and, *homologous chromosomes*.
21. Diagram fertilization as it would occur between a sperm and an egg with the haploid number of 3.

9.8 Meiosis—Gamete Production

Consider a cell that has only 4 chromosomes (figure 9.22). The two from the father are shown in blue and the two from the mother are in green. Notice in figure 9.22 that there are two pairs of homologous chromosomes. Each pair consists of a green chromosome and a blue chromosome. One pair is long. The other pair is short.

Meiosis involves two cell divisions and produces four cells. **Meiosis I** consists of the processes that occur during the first division, and **meiosis II** consists of the processes that occur during the second division. Before meiosis occurs, the cell is in interphase of the cell cycle. As with mitosis, the interphase that precedes meiosis includes DNA replication. Before DNA replication, chromosomes have only one chromatid. After DNA replication, chromosomes consist of two chromatids.

Meiosis I

Meiosis I is a **reduction division,** in which the chromosome number in the two cells produced is reduced from diploid to haploid. The sequence of events in meiosis I is divided into four phases: prophase I, metaphase I, anaphase I, and telophase I.

Prophase I

Key events:

- Chromosomes condense.
- Spindle and spindle fibers form.
- Nuclear membrane disassembles.
- Synapsis and crossing-over occur.

A number of important events occur during Prophase I. Several of these events also occur during prophase of mitosis: the nuclear membrane disassembles; the spindle fibers form; and the chromosomes condense. However, in meiosis, once the chromosomes are fully condensed, **synapsis** causes homologous chromosomes to move toward one another, so that the chromosomes lie next to each other. While the chromosomes are synapsed, *crossing-over* occurs. **Crossing-over** is the exchange of equivalent sections of DNA on homologous chromosomes. Crossing-over is shown in figure 9.23 as bits of blue on the green chromosome and bits of green on the blue chromosome. The crossing-over process is carefully regulated to make sure that the DNA sections that are exchanged contain equivalent information. This means that usually no information is lost or gained by either chromosome; genetic information is simply exchanged. Because the two members of each homologous pair of chromosomes came from different parents (one from the mother and one from father), there are minor differences in the DNA present on the two chromosomes. Crossing-over happens many times along the length of the homologous chromosomes.

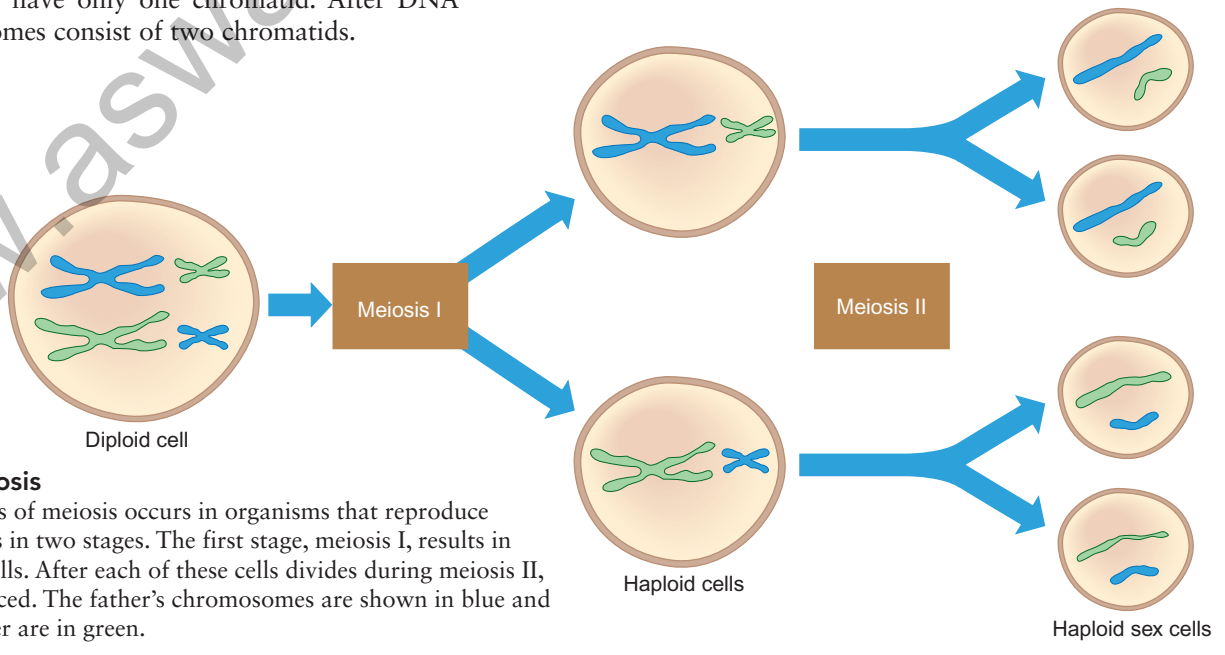


FIGURE 9.22 Meiosis
The cell division process of meiosis occurs in organisms that reproduce sexually. Meiosis occurs in two stages. The first stage, meiosis I, results in the formation of two cells. After each of these cells divides during meiosis II, four gametes are produced. The father's chromosomes are shown in blue and the two from the mother are in green.

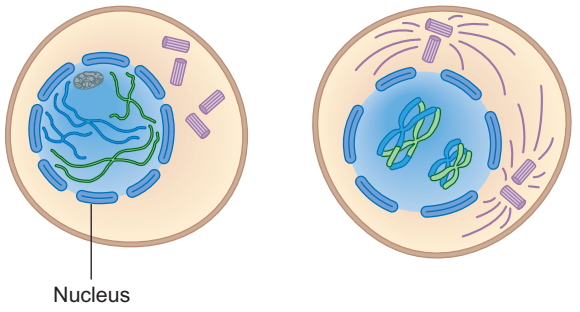


FIGURE 9.23 Prophase I
During prophase I, several visible changes occur as the cell prepares for division. The nuclear membrane is being broken down and the spindle begins to form. As the nuclear membrane disintegrates, the chromosomes can be moved throughout the cell. As the cell advances through prophase, the chromosomes also become more condensed and are paired as homologous pairs.

Crossing-over is very important, because it allows a more thorough mixing of genes from one generation to the next. Without crossing-over, each of the chromosomes an organism inherits in the mother's egg would be passed on exactly as it was to the organism's offspring.

Metaphase I

Key event:

- Chromosomes align on equatorial plane as synapsed pairs.

In metaphase I, the centromere of each chromosome attaches to the spindle. The synapsed pair of homologous chromosomes moves into position on the cell's equatorial plane as a single unit. The orientation of the members of each pair of chromosomes is random with regard to the cell's poles. Figure 9.24 shows only one possible arrangement. An equally likely arrangement of chromosomes during this stage would be to flip the positions of two identically sized chromosomes. In the figure, this flipped arrangement would place all of the green chromosomes on one side of the cell. The number of possible arrangements increases with the number of chromosomes present in the cell. The arrangement is determined by chance.

Compare metaphase I of meiosis with metaphase of mitosis (figure 9.24 and figure 9.7). Note the different ways the chromosomes are arranged. In mitosis, each chromosome is arranged at the equator independently of the others and the chromatids will separate. In meiosis I the chromosomes are arranged at the equator in homologous pairs and the homologous chromosomes (each consisting of two chromatids) separate.

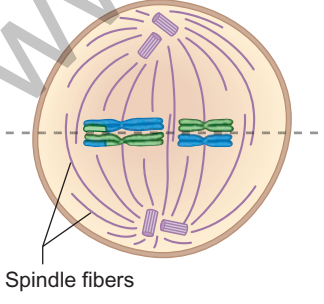


FIGURE 9.24 Metaphase I
Notice that the homologous chromosome pairs are arranged on the equatorial plane in the synapsed condition. The dotted line represents the equatorial plane. This cell shows one way the chromosomes could be lined up; however, a second arrangement is possible.

Anaphase I

Key events:

- Homologous chromosomes separate from each other.
- Chromosomes move toward cell's poles.
- Reduction occurs (diploid-2*n* to haploid-*n*).

Anaphase I is the stage during which homologous chromosomes separate (figure 9.25). During this stage, the chromosome number is *reduced from diploid to haploid*. The two members of each pair of homologous chromosomes move away from each other toward opposite poles. The direction each takes is determined by how each pair was originally oriented on the spindle.

This arrangement of chromosomes in anaphase I, causes the key difference between mitosis and meiosis. In anaphase of mitosis, chromatids separate from each other. In anaphase I of meiosis, homologous chromosomes separate from each other. Each chromosome is independently attached to a spindle fiber at its centromere. Unlike the anaphase stage of mitosis, in anaphase I of meiosis the centromeres that hold the chromatids together do not divide. The chromosomes are still in their replicated form, consisting of 2 chromatids in anaphase I.

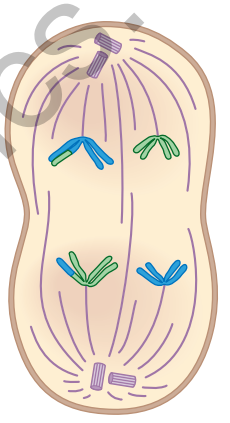


FIGURE 9.25 Anaphase I
During this phase, one member of each homologous pair is segregated from the other member of the pair. Notice that the chromatids of the chromosomes do not separate.

Because the homologous chromosomes and the genes they carry are being separated from one another, this process is called **segregation.** The way in which a single pair of homologous chromosomes segregates does not influence how other pairs of homologous chromosomes segregate. That is, each pair segregates independently of other pairs. This is known as **independent assortment** of chromosomes. Both segregation and independent assortment are key components in understanding how to solve genetics problems.

Telophase I

Key events:

- Spindle fibers disassemble.
- Chromosomes uncoil.
- Nuclear membrane re-forms.
- Nucleoli reappear.

Telophase I consists of changes that return the cell to an interphase-like condition (figure 9.26). The chromosomes uncoil and become long, thin threads; the nuclear membrane reforms around them; and nucleoli reappear. Following this activity, cytokinesis divides the cytoplasm into two separate cells.

Because of meiosis I, the total number of chromosomes is divided equally, so that each daughter cell has one member of each homologous chromosome pair. This means that each cell receives one-half the genetic information of the parent cell, but it has 1 chromosome of each kind and thus has one full set of chromosomes. Each chromosome is still composed of 2 chromatids joined at the centromere. The chromosome number for the cells is reduced from diploid ($2n$) to haploid (n). In the cell we have been using as our example, the number of chromosomes is reduced from 4 to 2. The four pairs of chromosomes have been distributed to the two daughter cells.

Depending on the type of cell, there may be a time following telophase I when the cell engages in normal metabolic activity corresponding to an interphase stage. Figure 9.27 summarizes the events in meiosis I.

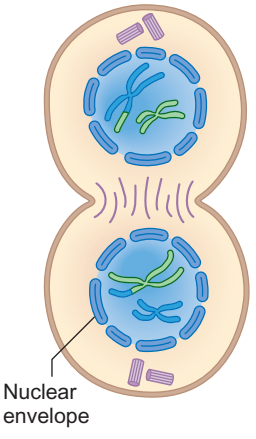


FIGURE 9.26 Telophase I
Cytokinesis occurs during telophase I. During cytokinesis, two cells are formed. Each cell is haploid, containing one set of chromosomes.

Meiosis II

Meiosis II includes four phases: prophase II, metaphase II, anaphase II, and telophase II. The two daughter cells formed during meiosis I both continue through meiosis II, so that four cells result from the two divisions. During the time between telophase I and the beginning of meiosis II, no DNA replication occurs. The genetic information in cells starting meiosis II is the same as that in cells ending meiosis I. *The events in the division sequence of meiosis II are the same as those that occur in mitosis.*

Prophase II

Key events:

- Chromosomes condense.
- Spindle and spindle fibers form.
- Nuclear membrane disassembles.
- Nucleoli disassemble.

Prophase II is similar to prophase in mitosis; the nuclear membrane is disassembled and the spindle apparatus begins to form. However, it differs from prophase I in that the cells are haploid, not diploid (figure 9.28).

Metaphase II

Key event:

- Chromosomes align at the equator in unpaired manner.

Metaphase II is typical of any metaphase stage, because the chromosomes attach by their centromeres to the spindle at

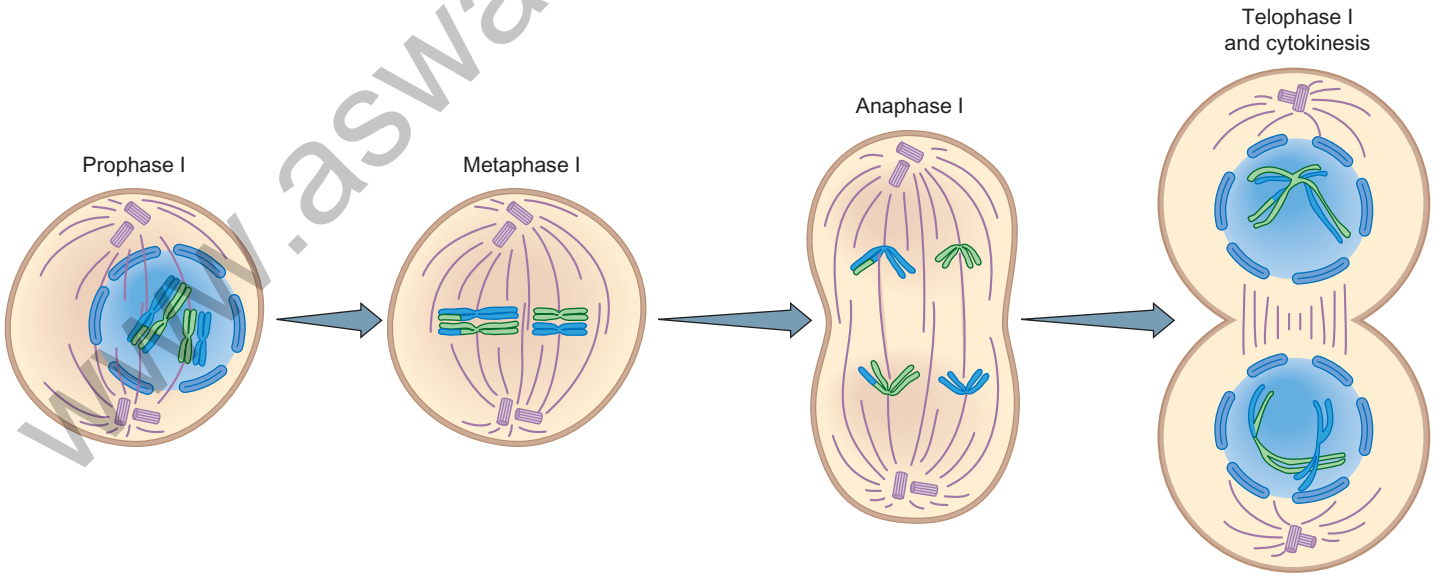


FIGURE 9.27 Meiosis I
The stages in meiosis I result in reduction division. This reduces the number of chromosomes in the parental cell from the diploid number to the haploid number in each of the two daughter cells.

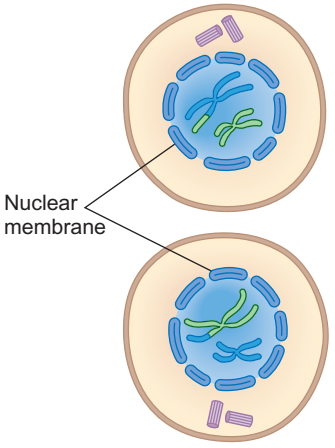


FIGURE 9.28 Prophase II
The two daughter cells are preparing for the second division of meiosis.

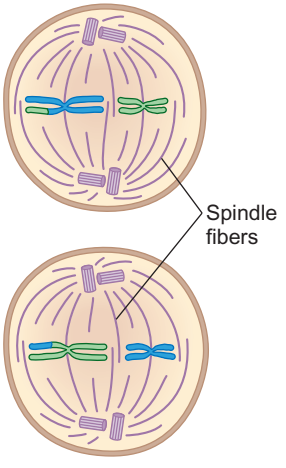


FIGURE 9.29 Metaphase II
During metaphase II, each chromosome lines up on the equatorial plane. Each chromosome is composed of 2 chromatids (a replicated chromosome) joined at a centromere.

the equatorial plane of the cell. Because pairs of homologous chromosomes are no longer together in the same cell, each chromosome moves as a separate unit (figure 9.29).

Anaphase II

Key event:

- Chromatids separate and begin to move to cell's poles.

Anaphase II of meiosis differs from anaphase I of meiosis in that, during anaphase II, the centromere of each chromosome divides, and the chromatids, now called *daughter chromosomes,* move to opposite poles. This is similar to mitosis (figure 9.30). There are no paired homologous chromosomes in this stage; therefore, segregation and independent assortment cannot occur as in meiosis I.

Telophase II

Key events:

- Nuclear membrane re-forms.
- Chromosomes uncoil.
- Nucleoli reappear.
- Spindle fibers disassemble.

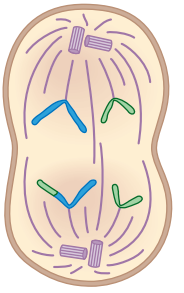


FIGURE 9.30 Anaphase II
Anaphase II is very similar to anaphase of mitosis. The centromere of each chromosome divides and 1 chromatid separates from the other. As soon as this happens, they are no longer referred to as chromatids; each strand of nucleoprotein is now called a daughter chromosome.

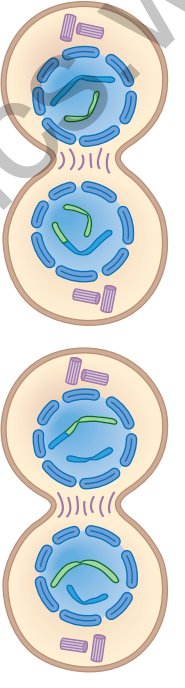


FIGURE 9.31 Telophase II
During the telophase II stage, the nuclear membranes form, chromosomes uncoil. Cytokinesis occurs.

During telophase II, the cell returns to a nondividing condition. New nuclear membranes form, nucleoli reappear, chromosomes uncoil, the spindles disappear and cytokinesis occurs (figure 9.31).

Telophase II is followed by the maturation of the four cells into gametes—either sperm or eggs. In many organisms, including humans, egg cells are produced in such a manner that three of the four cells resulting from meiosis in a female disintegrate. However, because the one that survives is randomly chosen, the likelihood of obtaining any particular combination of genes is not affected. The events of meiosis II are shown in figure 9.32.

The stages of meiosis I and meiosis II are summarized in table 9.3. The differences between mitosis and meiosis have been identified throughout this chapter. A comparison of these two processes appears in table 9.4.

TABLE 9.3 Stages of Meiosis

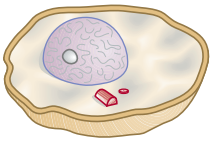
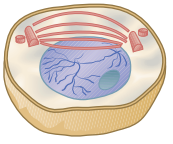
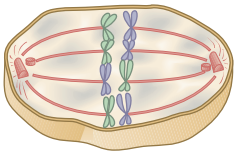
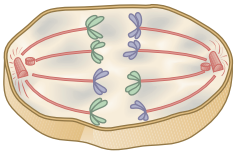
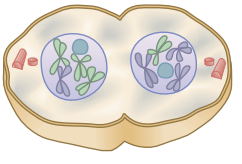
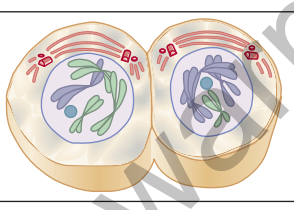
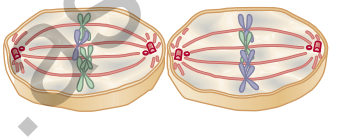
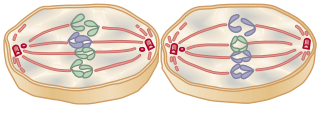
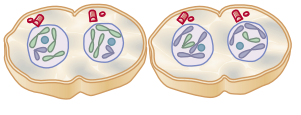
Interphase		Diploid	As the diploid ($2n$) cell moves from G_0 into meiosis, the chromosomes replicate during the S phase of interphase.
Prophase I		Diploid	The replicated chromatin begins to coil into recognizable chromosomes and the homologous chromosomes synapse; chromatids may cross-over; the nuclear membrane and nucleoli fragment; centrioles move to form the cell's poles; spindle fibers are formed.
Metaphase I		Diploid	Synapsed homologous chromosomes attach to the spindle fibers at their centromeres. Pairs of homologous chromosomes align at the equator.
Anaphase I		Transition	The two members of homologous pairs of chromosomes separate from each other as they move toward the poles of the cell.
Telophase I		Haploid	The two newly forming daughter cells are now haploid (n) because each contains only one of each pair of homologous chromosomes; the nuclear membranes and nucleoli re-form; spindle fibers fragment; the chromosomes unwind and change from chromosomes (composed of 2 chromatids) to chromatin.
Prophase II		Haploid	Each of the two haploid (n) daughter cells from meiosis I undergoes chromatin coiling to form chromosomes, each of which is composed of 2 chromatids; the nuclear membrane fragments; centrioles move to form the cell's poles; spindle fibers form.
Metaphase II		Haploid	Chromosomes attach to the spindle fibers at the centromeres and move to the equator of the cell.
Anaphase II		Haploid	Centromeres separate, allowing the 2 chromatids of a chromosome to separate toward the poles.
Telophase II		Haploid	Four haploid (n) cells are formed from the division of the two meiosis I cells; the nuclear membranes and nucleoli re-form; spindle fibers fragment; the chromosomes unwind and change from chromosomes to chromatin; these cells become the sex cells (egg or sperm).

FIGURE 9.32 Meiosis II
During meiosis II, the centromere of each chromosome splits and each chromosome divides into separate chromatids. Four haploid cells are produced, each with 1 chromatid of each kind. These four haploid cells are gametes.

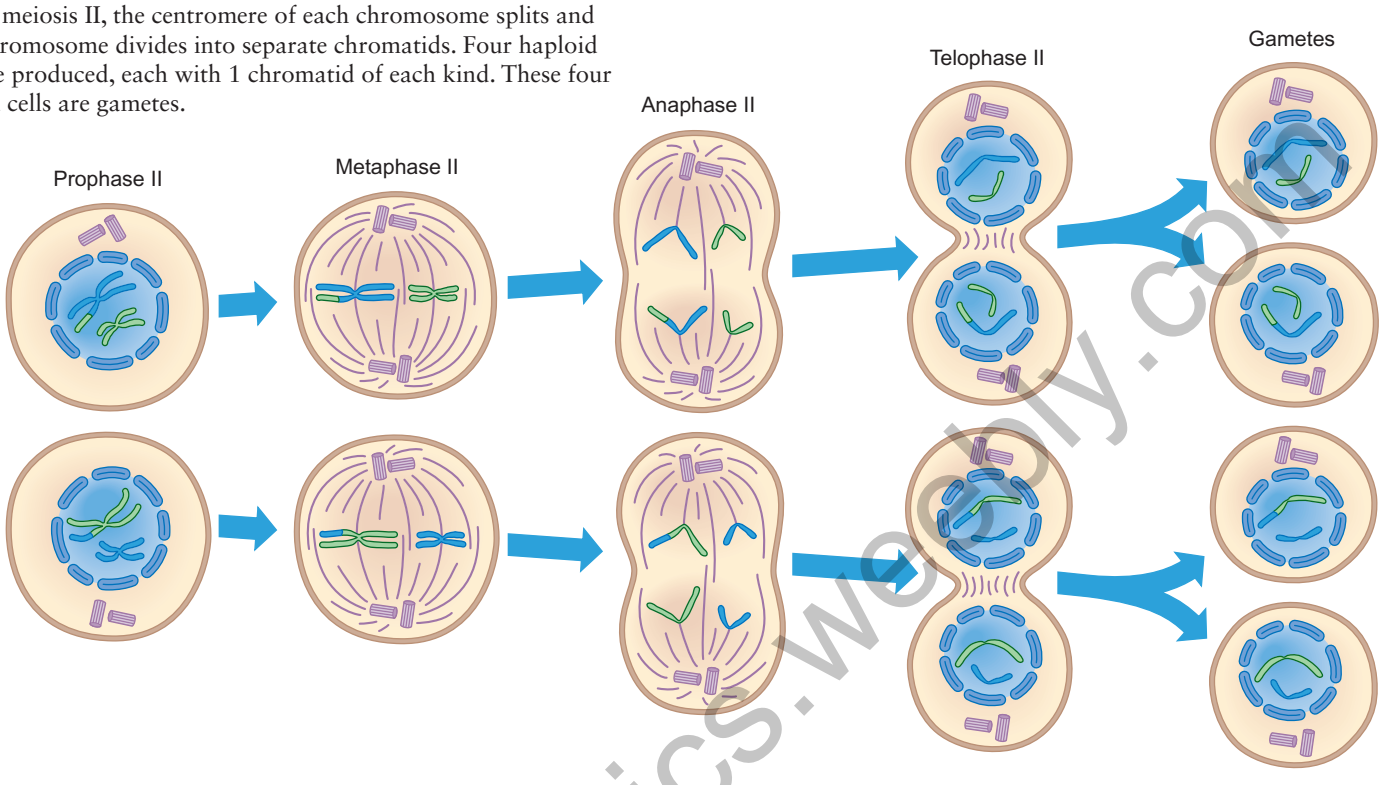


TABLE 9.4 Comparison of Mitosis and Meiosis

Mitosis	Meiosis
1. One division completes the process.	1. Two divisions are required to complete the process.
2. Chromosomes do not synapse.	2. Homologous chromosomes synapse in prophase I.
3. Homologous chromosomes do not cross-over.	3. Homologous chromosomes cross-over in prophase I.
4. Centromeres divide in anaphase.	4. Centromeres divide in anaphase II but not in anaphase I.
5. Daughter cells have the same number of chromosomes as the parent cell ($2n \rightarrow 2n$ or $n \rightarrow n$).	5. Daughter cells have half the number of chromosomes as the parent cell ($2n \rightarrow n$).
6. Daughter cells have the same genetic information as the parent cell.	6. Daughter cells are genetically different from the parent cell.
7. Mitosis generates body cells.	7. Meiosis generates sex cells.
8. Mitosis results in growth, the replacement of worn-out cells, and the repair of damage.	8. Meiosis is necessary for sexual reproduction.

9.8 CONCEPT REVIEW

22. Diagram the metaphase I stage of a cell with the diploid number of 8.
23. What is unique about prophase I?
24. In which phase of meiosis do daughter chromosomes form?
25. Why is it impossible for synapsis to occur during meiosis II?
26. Can a haploid cell undergo meiosis? Why or why not?
27. List three differences between mitosis and meiosis.

9.9 Genetic Diversity—The Biological Advantage of Sexual Reproduction

Cell division allows organisms to reproduce either asexually or sexually. There are advantages and disadvantages to both. Asexual reproduction always produces organisms that are genetically identical to the parent. A single organism, separated from others of its kind, can still reproduce if it can reproduce asexually. Organisms that can reproduce only

sexually are at a disadvantage, because they require two different organisms to reproduce. Also, sexually reproducing populations tend to grow at a much slower rate than do asexually reproducing populations. However, asexually reproducing populations could be wiped out by a single disease or a change in living conditions, because the members of the population are genetically similar.

Sexual reproduction offers an advantage over asexual reproduction. Populations that have a large genetic diversity are more likely to survive. When living conditions change or a disease occurs, some members of the population are more likely to survive if the population consists of many, genetically different individuals.

One reason for learning meiosis is to see how the events of meiosis and fertilization create genetic variation within a population. Haploid cells from two different individuals combine to form new, unique combinations of genetic information. Each new organism, with its unique combination of genetic information, may be important to the survival of the species.

Genetic diversity in a population is due to differences in the types of genes present in individual organisms. Although all the members of the population have the genes for the same basic traits, the exact information coded in the genes may vary from individual to individual. An **allele** is a specific version of a gene. Examples of alleles are: blood type A versus blood type O, dark versus light skin, normal versus sickle-cell hemoglobin, and attached versus free earlobes.

Five factors create genetic diversity in offspring by creating either new alleles or new combinations of alleles: mutation, crossing-over, segregation, independent assortment, and fertilization.

Mutation

Several types of mutations were discussed in chapter 8: point mutations and chromosomal aberrations. In point mutations, a change in a DNA nucleotide results in the production of a different protein. In chromosomal aberrations, genes are rearranged. Both types of mutations can create new proteins. Both types of mutations increase genetic diversity by creating new alleles.

Recall that epigenetic modifications to both DNA and histones are also able to be passed on through mitosis and, in some cases, meiosis. These result in different forms of gene expression displayed through determination.

Crossing-Over

The second source of variation is crossing-over. **Crossing-over** is the exchange of equivalent portions of DNA between homologous chromosomes, which occurs during prophase I while homologous chromosomes are synapsed. Remember that a chromosome is a double strand of DNA. To break chromosomes and exchange pieces of them, bonds between sugars and phosphates are broken. This is done at comparable locations on both chromatids, and the two pieces switch places. After switching places, the two pieces of DNA are bonded together by re-forming the bonds between the sugar and the phosphate molecules.

Crossing-over allows new combinations of genetic information to occur. While mutations introduce new genetic information to the population, crossing-over introduces new combinations of previously existing information. An organism receives one set of genetic information from each of its parents. Each gamete contains chromosomes that have crossed-over and therefore contains some of the father's and some of the mother's genes. As a result, traits from the mother *and* from the father can be inherited on a single piece of DNA.

Examine figure 9.33 carefully to note precisely what occurs during crossing-over. This figure shows a pair of homologous chromosomes close to each other. Each gene occupies a specific place on the chromosome, its **locus.** Homologous chromosomes contain an identical order of genes, and chromosomes may contain thousands of genes.

Notice in figure 9.34 that, without crossing-over, only two kinds of genetically different gametes result. Two of the four gametes have one type of chromosome, whereas the other two have the other type of chromosome. With crossing-over, four genetically different gametes are formed. With just one cross-over, the number of genetically different gametes is doubled.

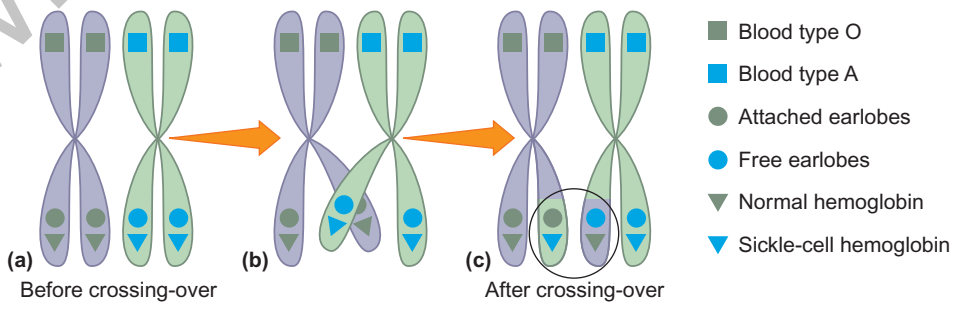


FIGURE 9.33 Synapsis and Crossing-Over
(a) While pairs of homologous chromosomes are in synapsis, *(b)* one part of 1 chromatid can break off and be exchanged for an equivalent part of its homologous chromatid. *(c)* As a result, new combinations of genetic information are created.

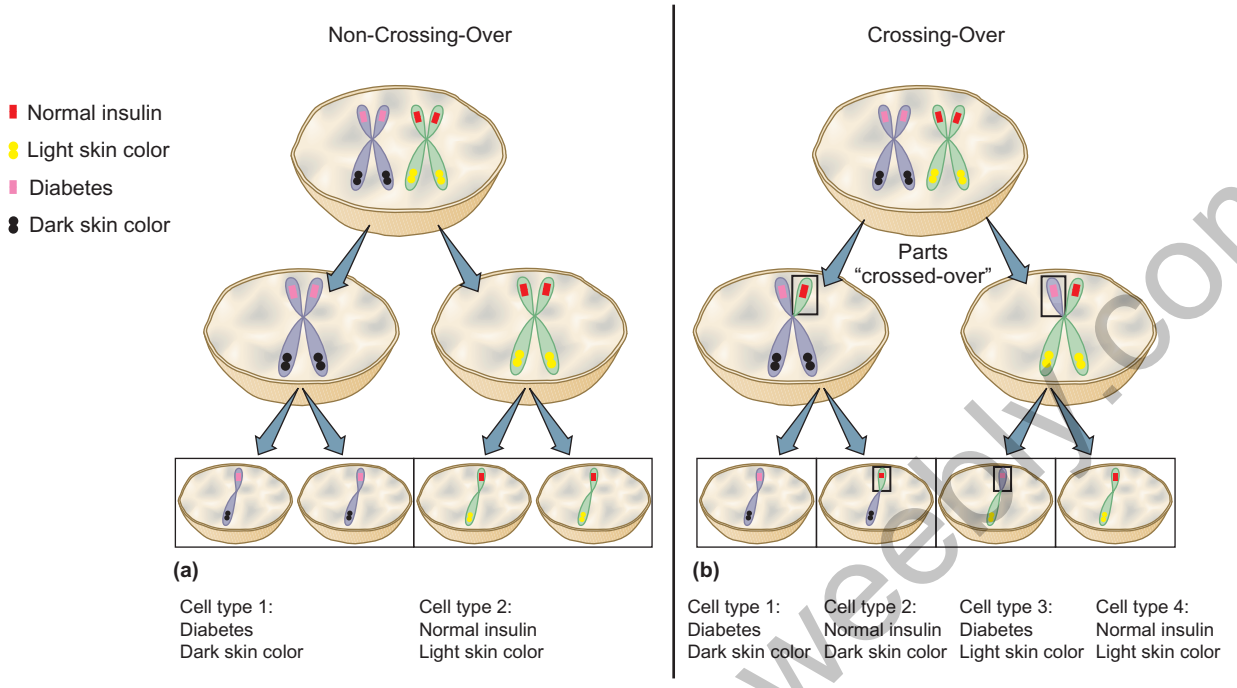


FIGURE 9.34 Variations Resulting from Crossing-Over
Cells with identical genetic information are boxed together. *(a)* These cells resulted from meiosis without crossing-over. Only two unique cell types of cells were produced. Cell type 1—Diabetes, dark skin color. Cell type 2—Normal insulin, light skin color. *(b)* These cells had one cross-over. From one cross-over, the number of genetically unique gametes doubled from two to four. Type 1—Diabetes, dark skin color. Type 2—Normal insulin, dark skin color. Type 3—Diabetes, light skin color. Type 4—Normal insulin, light skin.

In fact, crossing-over can occur at a number of points on a chromosome; that is, there can be more than one cross-over per chromosome pair. Because crossing-over can occur at almost any point along the length of the chromosome, great variation is possible (figure 9.35).

The closer two genes are to each other on a chromosome (i.e., the more closely they are *linked*), the more likely they will stay together, because the chance of crossing-over occurring between them is lower than if they were far apart. Thus, there is a high probability that they will be inherited together. The farther apart two genes are, the more likely it is that they will be separated during crossing-over. This fact enables biologists to map the order of gene loci on chromosomes.

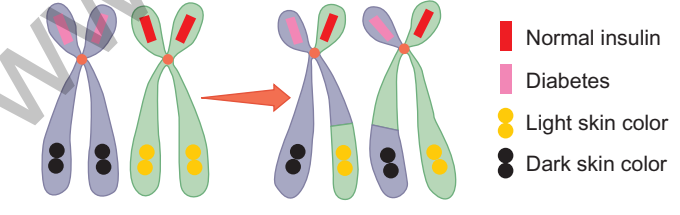


FIGURE 9.35 Multiple Cross-Overs
Crossing-over can occur several times between the chromatids of one pair of homologous chromosomes.

Segregation

Recall that segregation is the process during which the alleles on homologous chromosomes separate during meiosis I. Review figure 9.34; the normal insulin allele and the diabetes allele are both present in the diploid cell. However, following meiosis the normal insulin allele and the diabetes allele are segregated into separate haploid cells away from the other allele. Half of this individual's gametes would carry genetic information for normal functional insulin. The other half of the individual's gametes would carry genetic information for nonfunctional insulin (diabetes). Consider if this individual's mate had the same genetic makeup. If the mate also had one normal gene for insulin production and one abnormal gene for diabetes, that person also would produce two kinds of gametes. Because of segregation, this couple could produce children that were genetically different from themselves. If both parents contributed a gamete that carried diabetes, their child would be diabetic. Other combinations of gametes would result in children without diabetes. Segregation increases genetic diversity by allowing parents to produce children that are genetically different from their parents and from their siblings.

Independent Assortment

So far in discussing genetic diversity, we have dealt with only one pair of chromosomes. Now let's consider how genetic variation increases when we add a second pair of chromosomes.

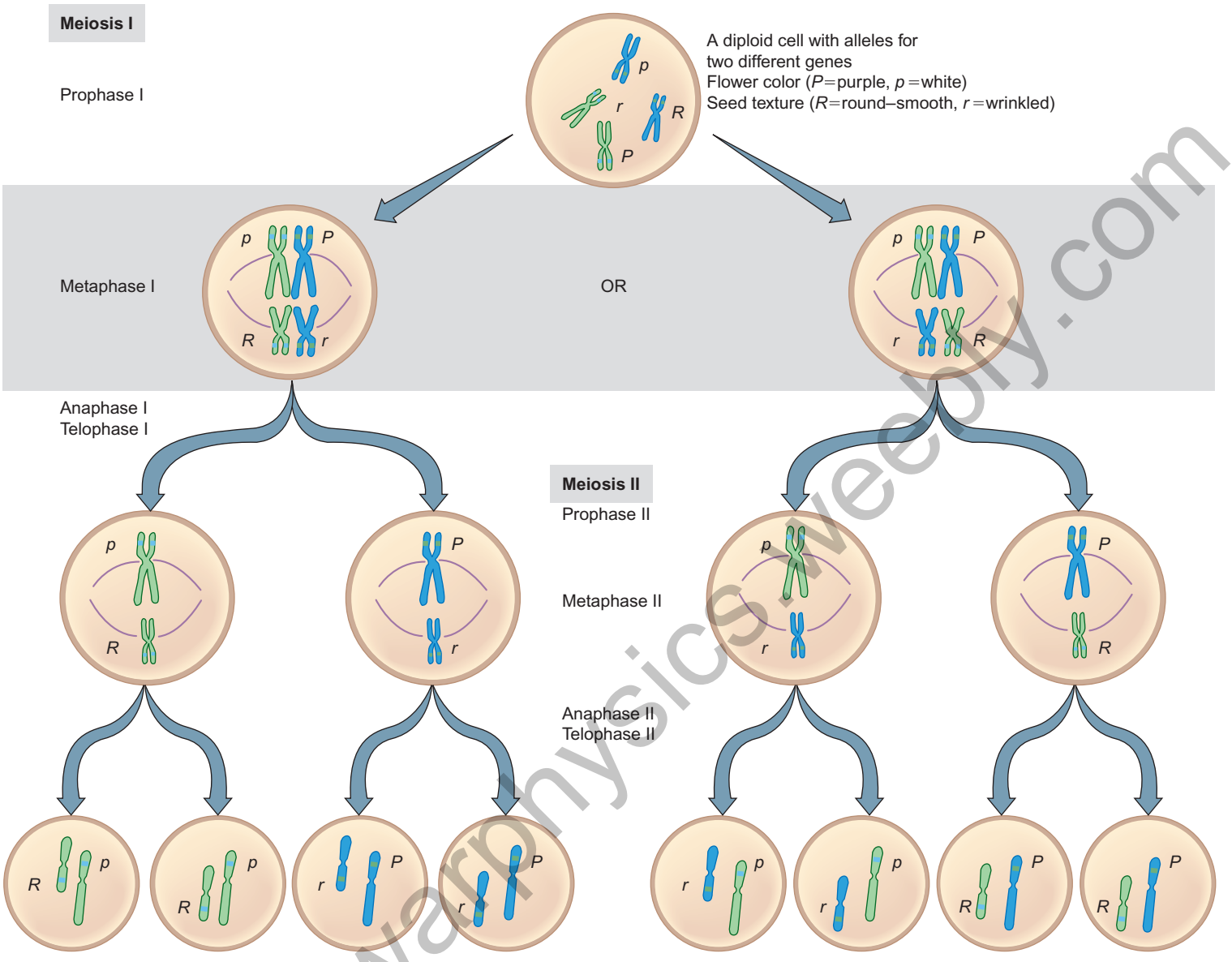


FIGURE 9.36 The Independent Assortment of Homologous Chromosome Pairs
The orientation of one pair of chromosomes on the equatorial plane does not affect the orientation of another pair of chromosomes. Note that different possible arrangements of chromosomes can be compared on the left and right side of this figure. Comparing the sets of cells that result from each initial arrangement will show the new genetic combinations that result from independent assortment.

Independent assortment is the segregation of homologous chromosomes independent of how other homologous pairs segregate.

Figure 9.36 shows chromosomes with traits for the garden pea plant. The chromosomes carrying alleles for flower color (P = purple; p = white) always separate from each other. The second pair of chromosomes with the information for seed texture also separates. Because the pole to which an individual chromosome moves is determined randomly, half the time the chromosomes divide so that the trait for purple flowers and the trait for round-smooth seeds move in one direction, whereas the trait for white flowers and the trait for wrinkled seeds move in the opposite direction. An equally likely alternative is that, the trait for purple flowers and the trait for wrinkled seeds go together toward one pole of the cell, whereas the trait for white flowers and the trait for round-smooth seeds go to the other pole. With two pairs of homologous chromosomes there are four possible kinds of cells produced by independent assortment during meiosis.

With three pairs of homologous chromosomes, there are eight possible kinds of cells produced as a result of independent assortment. The number of possible chromosomal combinations of gametes is calculated by using the expression 2^n, where n equals the number of pairs of chromosomes. With three pairs of chromosomes, n equals 3, so $2^n = 2^3 = 2 \times 2 \times 2 = 8$. With 23 pairs of chromosomes, as in human cells,

$2^n = 2^{23} = 8{,}388{,}608$. More than 8 million genetically different kinds of sperm cells or egg cells are possible from a single human parent. This number doesn't consider the additional possible sources of variation, such as mutation and crossing-over. Thus, when genetic variation due to mutation and crossing-over is added, the number of different gametes become incredibly large.

Fertilization

Because of the large number of genetically different gametes resulting from independent assortment, segregation, mutation, and crossing-over, an incredibly large number of types of offspring can result. Because humans can produce millions of genetically different gametes, the number of kinds of offspring possible is infinite for all practical purposes, and each offspring is unique, with the exception of identical twins.

9.9 CONCEPT REVIEW

28. How much variation as a result of independent assortment can occur in cells with the following diploid numbers: 2, 4, 6, 8, and 22?
29. What are the major sources of variation in the process of meiosis?

9.10 Nondisjunction and Chromosomal Abnormalities

In the normal process of meiosis, the number of chromosomes in diploid cells is reduced to haploid. This involves segregating homologous chromosomes into separate cells during the first meiotic division. Occasionally, a pair of homologous chromosomes does not segregate properly and both chromosomes of a pair end up in the same gamete. **Nondisjunction** occurs when homologous chromosomes do not separate during meiosis. In figure 9.37, two cells are missing a chromosome and the genes that were carried on it. This condition usually results in the death of the cells. The other cells have an extra copy of a chromosome. This extra genetic information may also lead to the death of the cell. Some of these abnormal cells, however, do live and develop into sperm or eggs.

If one of these abnormal sperm or eggs unites with a normal gamete, the offspring will have an abnormal number of chromosomes. In **monosomy,** instead of the normal two chromosomes, a cell has just one of the pair of homologous chromosomes. In **trisomy,** a chromosome is present in three copies. All the cells that develop by mitosis from such zygotes will also have an abnormal number of chromosomes.

It is possible to examine cells and count chromosomes. Among the easiest cells to view are white blood cells. They are

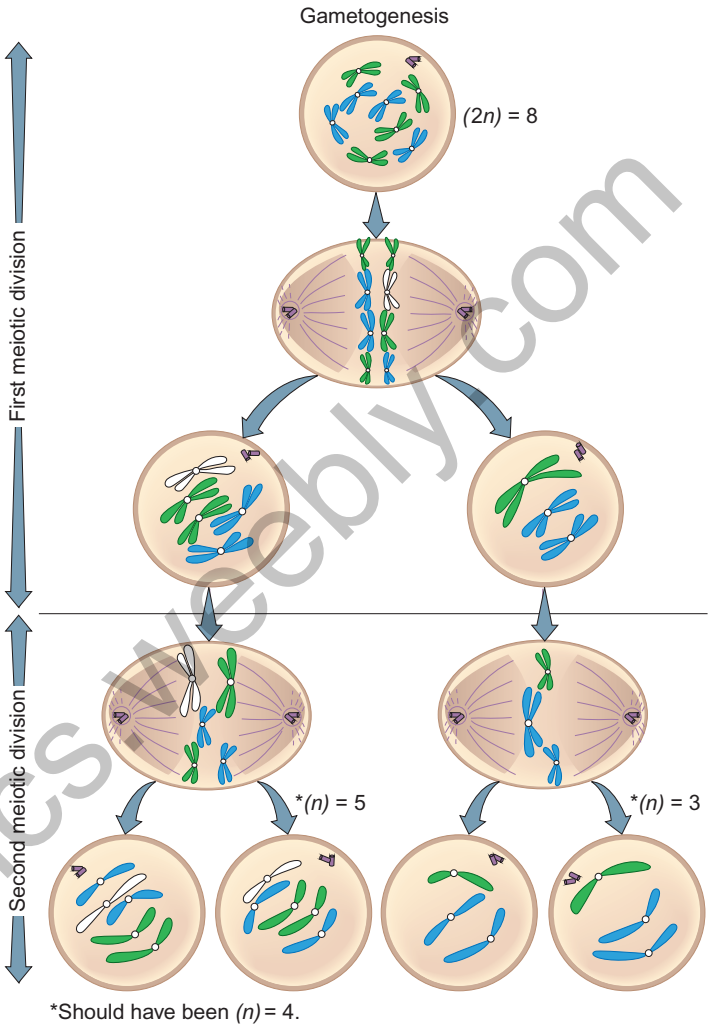


FIGURE 9.37 Nondisjunction During Gametogenesis
When a pair of homologous chromosomes fails to separate properly during meiosis I, gametogenesis results in gametes that have an abnormal number of chromosomes. Notice that two of the cells have an additional chromosome, whereas the other two are deficient by the same chromosome.

dropped onto a microscope slide, so that the cells are broken open and the chromosomes are separated. Photographs are taken of chromosomes from cells in the metaphase stage of mitosis. The chromosomes in the pictures can then be cut and arranged for comparison with known samples (figure 9.38). This picture of an individual's chromosomal makeup is referred to as a *karyotype*.

One example of the effects of nondisjunction is the condition known as **Down syndrome.** If a gamete with 2 number 21 chromosomes has been fertilized by a gamete containing the typical one copy of chromosome number 21, the resulting zygote has 47 chromosomes—one more than the expected count of 46 chromosomes (figure 9.38d). The child who developed from this fertilization has 47 chromosomes in every cell of his or her body as a result of mitosis and thus can have the symptoms characteristic of Down syndrome. These include

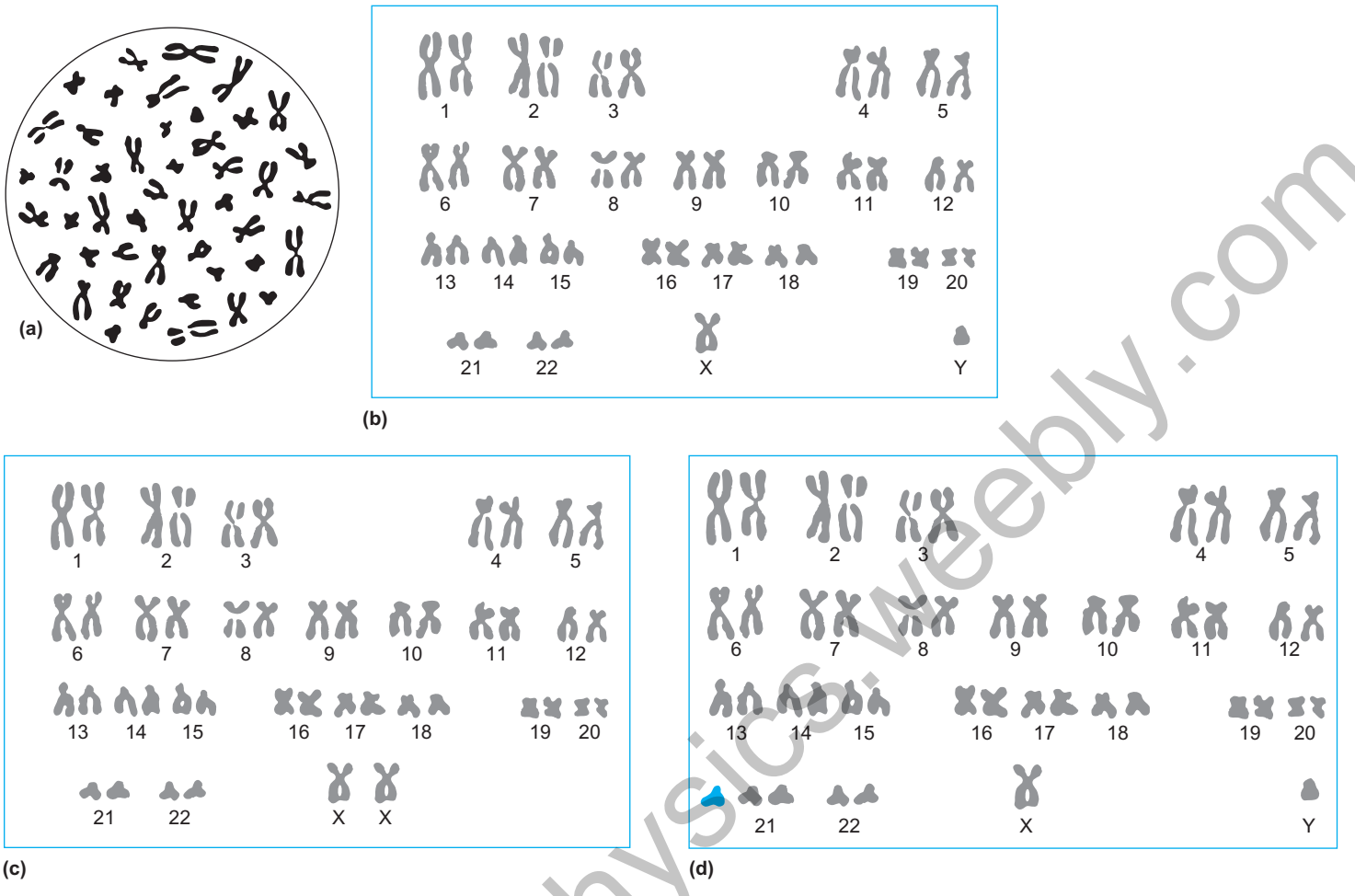


FIGURE 9.38 Human Male and Female Chromosomes
The randomly arranged chromosomes shown in the circle simulate metaphase cells spattered onto a microscope slide *(a)*. Those in parts *(b)* and *(c)* have been arranged into homologous pairs. Part *(b)* shows a male karyotype, with an X and a Y chromosome, and *(c)* shows a female karyotype, with two X chromosomes. *(d)* Notice that each pair of chromosomes is numbered and that the person from whom these chromosomes were taken has an extra chromosome number 21. The person with this trisomic condition might display a variety of physical characteristics, including slightly thickened eyelids, flattened facial features, a large tongue, and short stature and fingers. Most individuals also display some mental retardation. This condition is known as Down syndrome.

thickened eyelids, a large tongue, flattened facial features, short stature and fingers, some mental impairment, and faulty speech (figure 9.39).

In the past, it was thought that the mother's age at childbirth played an important role in the occurrence of trisomies, such as Down syndrome. In women, gametogenesis begins early in life, but cells destined to become eggs are put on hold during meiosis I. Beginning at puberty and ending at menopause, one of these cells completes meiosis I monthly. This means that cells released for fertilization later in life are older than those released earlier in life. Therefore, it was believed that the chances for abnormalities, such as nondisjunction, increase as the mother ages. However, the evidence no longer supports this age-egg link. Currently, the increase in the frequency of trisomies with age has been correlated with a decrease in the activity of a woman's immune system. As she ages, her immune system is less likely to recognize the difference between an abnormal and a normal embryo. This means that miscarriage is less common and she is more likely to carry an abnormal fetus to full term.

Figure 9.40 illustrates the frequency of the occurrence of Down syndrome births at various ages in women. Notice that the frequency increases very rapidly after age 37. Physicians normally encourage older women who are pregnant to have the cells of their fetus checked to see if they have the normal chromosome number. Nondisjunction can occur in either the production of eggs or sperm, so either parent can be the cause of an abnormal chromosome number.

9.10 CONCEPT REVIEW

30. Define the term *nondisjunction*.
31. What is the difference between monosomy and trisomy?

FIGURE 9.39 Down Syndrome
Every cell in the body of a person with Down Syndrome has 1 extra chromosome. With special care, planning, and training, people with this syndrome can lead happy, productive lives.

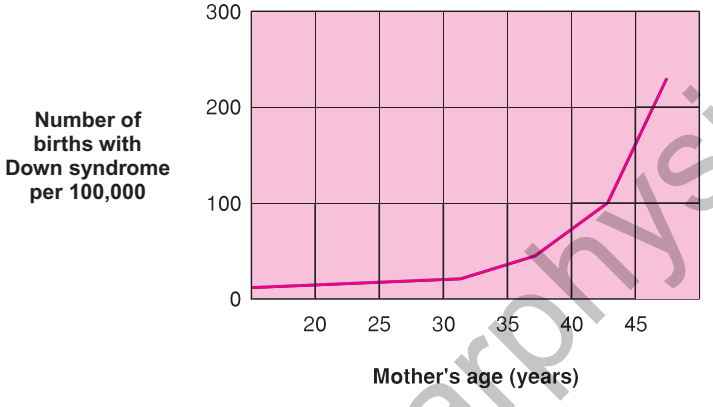


FIGURE 9.40 Down Syndrome as a Function of a Mother's Age
Notice that, as the age of the woman increases, the frequency of births of children with Down Syndrome increases only slightly until the age of approximately 37. From that point on, the rate increases drastically. This increase is thought to occur because older women experience fewer miscarriages of abnormal embryos.

Summary

Cell division is necessary for growth, repair, and reproduction. Mitosis and meiosis are two important forms of cell division. Cells go through a cell cycle, a nondividing period when normal cell activities take place followed by DNA replication, and cell division (mitosis and cytokinesis). Interphase is the period of growth and preparation for division. Mitosis is divided into four stages: prophase, metaphase, anaphase, and telophase. During mitosis, two daughter nuclei are formed from one parent nucleus. These nuclei have identical sets of chromosomes and genes that are exact copies of those of the parent. The regulation of mitosis is important if organisms are to remain healthy. Regular divisions are necessary to replace lost cells and to allow for growth. However, uncontrolled cell division may result in cancer and disruption of the total organism's well-being.

Meiosis is a specialized process of cell division, resulting in the production of four cells, each of which has the haploid number of chromosomes. The total process involves two sequential divisions, during which one diploid cell reduces to four haploid cells. Mutations and various processes of meiosis, such as crossing-over, segregation, and independent assortment, ensure that all sex cells are unique. The various mechanisms that generate genetic diversity in sexually reproducing organisms assure that when two gametes unite, the individual offspring is genetically unique.

Key Terms

Use interactive flash cards on the ***Concepts in Biology,*** *14/e website to help you learn the meaning of these terms.*

allele 194
anaphase 177
anther 186
apoptosis 181
asexual reproduction 174
asters 177
benign tumor 183
binary fission 174
carcinogens 181
cell cycle 175
cell division 174
cell plate 179
centrioles 177
centromere 176
chromatid 176
chromatin 176
cleavage furrow 179
crossing-over 188
cytokinesis 176
determination 185
differentiated 185
diploid 186
Down syndrome 197
fertilization 187
gamete 186
gonads 186
haploid 186
homologous chromosomes 187
independent assortment 189
interphase 175
kinetochore 178
locus 194
malignant tumors 183
meiosis 174
meiosis I 188
meiosis II 188
metaphase 177
metastasize 183
mitosis 174
monosomy 197
mutagens 181
nondisjunction 197
non-homologous chromosomes 187
ovaries 186
pistil 186
prophase 177
proto-oncogenes 179
reduction division 188
segregation 189
sexual reproduction 174
sister chromatids 176
spindle 177
spindle fibers 177
synapsis 188
telophase 178
testes 186
trisomy 197
tumor 183
tumor-suppressor genes 179
zygote 185

Basic Review

1. What is the key difference between mitosis and meiosis?
   a. Mitosis involves two rounds of cell division, whereas meiosis involves one round of cell division.
   b. DNA is not split between cells in meiosis, but this does occur during mitosis.
   c. Mitosis produces cells genetically identical to the parent, whereas meiosis produces cells with half the genetic information as the parent.
   d. None of the above is correct.
2. Which of the following is true of interphase?
   a. The chromosomes line up on the equatorial plane.
   b. DNA replication occurs in this phase.
   c. The DNA in the cell halves.
   d. All of the above are true.
3. Chromosomes are most likely to appear to be lining up near the middle of the cell during which phase of mitosis?
   a. interphase
   b. prophase
   c. metaphase
   d. telophase
4. Which of the following types of information do cells use to determine if they will divide?
   a. genetic health
   b. their current location
   c. the need for more cells
   d. All of the above are correct.
5. *p53* mutations lead to cancer because
   a. DNA damage is not repaired.
   b. mutated cells are allowed to grow.
   c. multiple mutations in the cell's regulatory proteins occur.
   d. All of the above are correct.
6. Haploid cells
   a. carry two copies of the genetic information.
   b. carry one copy of the genetic information.
   c. carry partial copies of the genetic information.
   d. are mutant.
7. Reduction division occurs
   a. in meiosis II.
   b. in meiosis I.
   c. in mitosis.
   d. after fertilization.
8. Genetic diversity in the gametes of an individual is generated through:
   a. mitosis.
   b. independent assortment.
   c. crossing-over.
   d. both b and c.
9. Trisomy means
   a. that three copies of a chromosome are present.
   b. Down syndrome.
   c. that only three cells are present.
   d. none of the above.
10. A nondisjunction event occurs when
    a. homologous chromosomes did not separate correctly.
    b. non-homologous chromosomes did not separate correctly.
    c. daughter cells did not undergo cytokinesis correctly.
    d. None of the above is correct.
11. Chemical changes of chromatin (DNA and histones) that do not alter the nucleotide sequence are called _____ changes.
12. Mutagens can be carcinogens. (T/F)
13. _____ is the cellular process of deciding which genes a cell will express when mature.
14. The gonads in females are known as _____.
15. These features characterize which kind of cell division? (a) Homologous chromosomes do not cross-over. (b) Centromeres divide in anaphase.

Answers
1. c 2. b 3. c 4. d 5. d 6. b 7. b 8. d 9. a 10. a 11. epigenetic 12. T 13. Determination 14. ovaries 15. mitosis.

Thinking Critically

Cancer, *p53*, Antibodies and Nanoparticles
A molecular oncologist and her colleagues at Georgetown University have developed a nanoparticle that is coated with a tumor-targeting antibody. The nanoparticle is able to locate primary and hidden metastatic tumor cells and deliver a fully functioning copy of the *p53* tumor-suppressor gene. The presence of the *p53* gene improves the efficacy of conventional cancer therapies such as chemo- and radiation therapy and reduces their side effects. Review the material on cell membranes, antibodies, cancer, and the role of *p53* and explain the details of this treatment to a friend. (You might explore the Internet for further information.)

CHAPTER 10

Patterns of Inheritance

CHAPTER OUTLINE

Geneticists Hard at Work

Mendel would be pleased to know what his discovery is revealing.

Since Gregor Mendel's work was accepted as "law" in the early 1900s, geneticists have made many important discoveries. This field has really exploded with new, life-changing or just plain interesting information since the era of molecular genetics came about during the 1950s and 1960s. Some of these discoveries revealed the existence of actual genes responsible for specific characteristics or conditions. Others help to explain the factors that control whether a gene is expressed or how its expression is modified.

Here just a few recent revelations from scientists working in the field of genetics:

- ✓ Certain soil bacteria have been discovered that have genes that allow them to feed exclusively on antibiotics. This is of concern because these bacteria live in close association with human and livestock pathogens.
- ✓ Charles Darwin proposed that human facial expressions are universal. Recent and continuing research is lending support to this hypothesis. Researchers found that, in fact, facial expressions are genetically determined.
- ✓ While the genetic abnormality causing Huntington's disease causes neurons in the brain to be destroyed, it also plays a role in destroying cancer cells. People with Huntington's are less likely than others to suffer from cancer. It appears that the *huntingtin* gene has more than one effect.
- ✓ The inheritance of "dominant black" coat color in domestic dogs involves a gene that is distinct from, but interacts with, the genes responsible for conventional coat pigmentation. Variations in this gene are responsible for the color differences in yellow, black, and brindle-colored dog breeds. This same gene is responsible for the production of a protein (β-defensin) that in other species is able to aid in the destruction of microbes. The presence of black coat color in wolves is the result of occasional interbreeding of dogs with black coat color and grey wolves.
- ✓ The gene *DISC1* (Disrupted-in-Schizophrenia 1) has been strongly implicated in cases of schizophrenia, major depression, bipolar disorder, and autism.

- **Who was Mendel? What role did he play in the field of genetics?**
- **In order to make the discoveries noted in the article, what basic ideas do you need to understand?**
- **How might these discoveries influence your understanding of life?**

Background Check

Concepts you should already know to get the most out of this chapter:

- The connection between genes, DNA, and chromosomes (chapter 8)
- The patterns of chromosome movement during meiosis (chapter 9)
- The concepts of segregation and independent assortment (chapter 9)

10.1 Meiosis, Genes, and Alleles

Genetics is the branch of science that studies how the characteristics of living organisms are inherited. Classical genetics uses an understanding of meiosis to make predictions about the kinds of genes that will be inherited by the *offspring* of a sexually reproducing pair of organisms. **Offspring** are the descendants of a set of parents.

Various Ways to Study Genes

The previous chapters of this text used the term *gene*. In chapter 8, a gene was described as a piece of DNA with the necessary information to code for a protein and regulate its expression. In chapter 9, on cell division, genes were described as locations on chromosomes. Both of these views are correct, because the DNA with the necessary information to make a protein is packaged into a chromosome. When a cell divides, the DNA is passed on to the daughter cells in chromosomes.

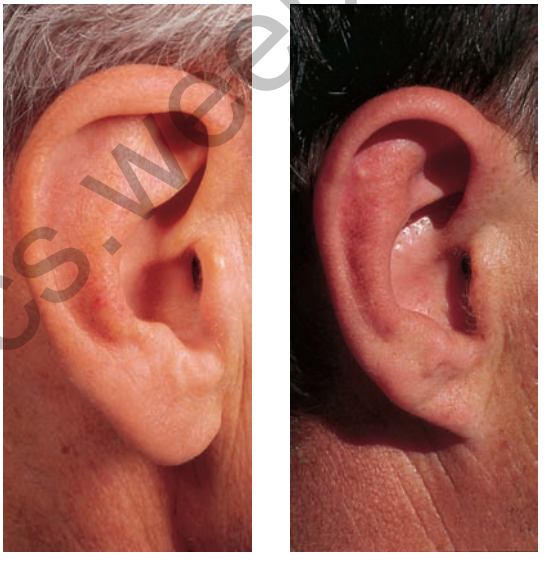
This chapter introduces another way to think about a gene. A gene is related to a characteristic of an organism, such as a color, a shape, or even the ability to break down a chemical. The characteristics usually result from the actions of proteins in the cell.

What Is an Allele?

Recall from chapter 9 that an allele is a specific version of a gene. Consider a characteristic such as earlobe shape. Some earlobes are free and some are attached (figure 10.1). These types of earlobes are two versions, or alleles, of the "earlobe-shape" gene. The two different alleles of this gene produce different versions of the same type of protein. The effect of these different proteins results in different earlobe shapes. Thus, there is an allele for free earlobes and a different allele for attached earlobes.

Genomes and Meiosis

A **genome** is a set of all the genes necessary to code for all of an organism's characteristics. In sexually reproducing organisms, a genome is diploid ($2n$) when it has two copies of each gene. When two copies of a gene are present, the two copies need not be identical. The copies may be the same alleles, or they may be different alleles of the same gene.



(a) (b)

FIGURE 10.1 Genes Control Structural Features
Whether your earlobe is *(a)* free or *(b)* attached depends on the alleles you have inherited. As genes express themselves, their actions affect the development of various tissues and organs. In some people the expression results in the earlobe being separated from the side of the face during fetal development, forming a "free" lobe. In others, the lobe remains "attached."

The genome of a haploid (n) cell has only one copy of each gene. Sex cells, such as eggs and sperm, are haploid. Because sperm and eggs are haploid, they have only one allele of a gene (review meiosis in chapter 9). If the parent has two different alleles of a gene, the parent's sperm or eggs can have either version of the alleles, but not both at the same time. When a haploid sperm (n) from a male and a haploid egg (n) from a female combine, they form a diploid ($2n$) cell, called a *zygote*. The alleles in the sperm and the alleles in the egg combine to form a new genome that is different from either of the parents. This means that each new zygote is a unique combination of genetic information.

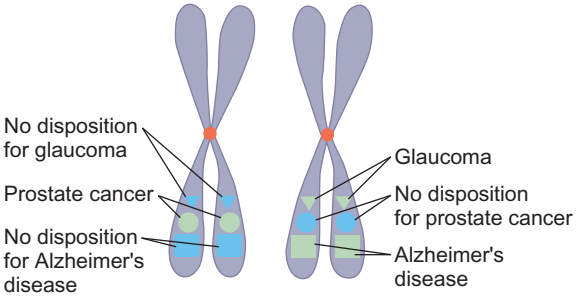


FIGURE 10.2 Homologous Chromosomes—Human Chromosome 1
Homologous chromosomes contain genes for the same characteristics at the same place. Different versions, or alleles, of the genes may be present on different chromosomes. This set of homologous chromosomes represents chromosome 1 in humans. Chromosome 1 is known to contain genes that play a role in glaucoma, prostate cancer, and Alzheimer's disease. The three genes shown here may be present in their normal form or in their altered, mutant form. Here, different genes are shown as specific shapes. The alleles for each gene are shown as different colors.

Meiosis is a cell's process of making haploid cells, such as eggs or sperm. Understanding the process of meiosis is extremely important to making genetic predictions. If you don't understand the cellular process of meiosis, your predictions will be less accurate. Figure 10.2 shows a pair of *homologous chromosomes* that have undergone DNA replication. After DNA replication, each homologous chromosome has two, exact copies of each allele, one on each chromatid.

When the cell undergoes meiosis I, the two homologous chromosomes go to different cells. This reduces the cell's genome from diploid to haploid. In meiosis II, the chromatids of each chromosome are separated into different daughter cells. The cells resulting from meiosis II mature to become sperm or eggs. The probability that an allele will be passed to a sperm or an egg is related to the number of times that allele is present in the cell before meiosis begins. These probabilities are used in making predictions in genetic crosses.

10.1 CONCEPT REVIEW

1. How does the term *gene* relate to the term *allele*?
2. Define the term *genome*.
3. What is meant by the symbols *n* and 2*n*?

10.2 The Fundamentals of Genetics

Three questions represent the biological principles behind understanding the genetics problems presented in this chapter:

1. What alleles do the parents have?
2. What alleles are present in the gametes that the parents produce?
3. What is the likelihood that gametes with specific combinations of alleles will be fertilized?

To solve genetics problems and understand biological inheritance, it is necessary to understand how to answer each of these questions and to understand how the answer to one of these questions can affect the others.

Phenotype and Genotype

The interaction of alleles determines the appearance of the organism. The **genotype** of an organism is the combination of alleles that are present in the organism's cells. The **phenotype** of an organism is how it appears outwardly and is a result of the organism's genotype.

Reconsider the example of earlobe type to explore the ideas of phenotype and genotype. Earlobes can be attached or free. If a person's earlobes are attached, the person's *phenotype* is "attached earlobes." Likewise, if a person's earlobes are free, his or her *phenotype* is "free earlobes." Each person has 2 alleles for earlobe type. However, the 2 alleles do not need to be identical.

To make understanding *genotype* easier, we can use a shorthand notation that is commonly used in genetics. The capital letter *E* can be used to represent the allele that codes for free earlobe development. A lowercase *e* can be used to refer to the allele that codes for attached earlobe development. Because each person has 2 alleles, a person can have one of these combinations of alleles:

- (*EE*)—2 alleles for free earlobes
- (*ee*)—2 alleles for attached earlobes
- (*Ee*)—1 allele for free earlobes and 1 allele for attached earlobes

The 2 alleles will interact with each other when they are in the same cell and their proteins are synthesized as described in chapter 9. Consider what happens in a cell when the allele combination is *EE*, *ee*, or even *Ee*. When the cell has *EE*, it is only capable of producing proteins associated with free earlobes. The organism will have free earlobes. When both alleles code for attached earlobe development (*ee*) then the person will develop attached earlobes. Continue reading to understand what happens when the cells are *Ee*.

Dominant and Recessive Alleles

What does the organism look like if it has 1 allele that codes for free earlobes and 1 allele that codes for attached earlobes—(*Ee*)? In this particular situation, the organism develops free earlobes. The *E* allele produces proteins for free earlobes that "outperforms" the *e* allele. Therefore, *E* is able to dominate the appearance of the organism. A **dominant allele** is one that masks another allele (called the recessive allele) in the phenotype of an organism. A **recessive allele** is one that is masked by another, the dominant allele. In the previous example, the free earlobes allele (*E*) is dominant and the attached earlobes allele (*e*) is recessive, because in an (*Ee*) individual the phenotype that develops is free earlobes. Geneticists use the capital letter to denote that an allele is dominant. The lowercase letter denotes the recessive allele.

Take a closer look at the genotypes for free and attached earlobes. Notice that organisms with attached earlobes

always have 2 *e* alleles (*ee*), whereas organisms with free earlobes might have 2 *E* alleles—(*EE*)—or both an *E* and an *e* allele—(*Ee*). A dominant allele may hide a recessive allele.

The term *recessive* has nothing to do with the significance or value of the allele—it simply describes how it is expressed when inherited with a dominant allele. The term *recessive* also has nothing to do with how frequently the allele is passed on to offspring.

In individuals with 2 different alleles, each allele has an equal chance of being passed on. The Gene Key that immediately follows this text organizes the information about how earlobe shape is inherited. This format will also be used later in this chapter to summarize information about other genes.

Gene Key
Gene or Condition: earlobe shape

Allele Symbols	Possible Genotypes	Phenotype
E = free	*EE*	Free earlobes
	Ee	Free earlobes
e = attached	*ee*	Attached earlobes

Summary: Geneticists describe an organism by its genotype and its phenotype. One rule that describes how the genotype of an organism influences its phenotype involves the principle of dominant and recessive interaction.

Application: Use the dominant and recessive principle to infer information that is not provided. Example: If a person has attached earlobes, you can infer that his or her genotype is *ee*. If a person has free earlobes, you can infer that he or she has at least 1 *E* allele. The second allele is uncertain without additional information.

Predicting Gametes from Meiosis

To predict the types of offspring that parents may produce, it is important to predict the kinds of alleles that may be in the sex cells produced by each parent. Remember that during meiosis the 2 alleles will end up in different sex cells. If an organism contains two copies of the same allele, such as in *EE* or *ee*, it can produce sex cells with only one type of allele. *EE* individuals can produce sex cells with only the *E* allele, likewise *ee* individuals can produce sex cells with only the *e* allele. The *Ee* individual can produce two different types of sex cells. Half of the sex cells carry the *E* allele. The other half carry the *e* allele. If an organism has 2 identical alleles for a characteristic and can produce sex cells with only one type of allele, the genotype of the organism is **homozygous** (*homo* = same or like). If an organism has 2 different alleles for a characteristic and can produce two kinds of sex cells with different alleles, the organism is **heterozygous** (*hetero* = different). This is summarized in the Gene Key at the bottom of this page.

Notice that the 2 alleles separate into different sex cells. This is true whether the cell is homozygous or heterozygous. The **Law of Segregation** states that in a diploid organism the alleles exist as two separate pieces of genetic information, and that these two different pieces of genetic information are on different chromosomes and are separated into different cells during meiosis.

Summary: When sex cells form, they receive only 1 allele for each characteristic. Homozygous organisms can produce only one kind of sex cell. In heterozygous organisms, meiosis produces two genetically different sex cells. The 2 different alleles are represented equally in the sex cells that are produced. Half the cells contain 1 of the alleles and half the cells contain the other.

Application: Make two predictions using the Law of Segregation. The first prediction describes the genetic information a sex cell can carry. The second prediction describes the expected ratios of these sex cells. If the organism is homozygous, then all sex cells will be the same. If the organism is heterozygous, half of the sex cells will carry one allele (one out of two). The other allele will be in the other half of the sex cells.

Fertilization

Recall from chapter 9 that **fertilization** is the process of two haploid (*n*) sex cells joining to form a zygote (2*n*). The zygote divides by mitosis to produce additional diploid cells as the new organism grows. The diploid genotype of all the cells of that organism is determined by the alleles carried by the two sex cells that joined to form the zygote.

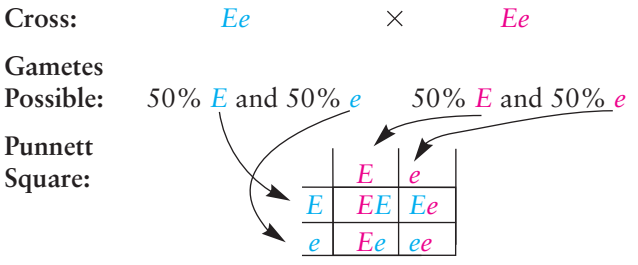
A **genetic cross** is a planned breeding or mating between two organisms. Although the cross is planned, the exact sperm and egg that join when fertilization occurs are not entirely predictable, because the process of fertilization is random. Any one of the many different sperm produced by meiosis may fertilize a given egg. Despite this element of randomness, generalizations can be made about possible results from two parents. These generalizations can be seen by drawing a diagram called a *Punnett square*. A **Punnett square** shows the possible offspring of a particular genetic cross.

Genetic crosses can be designed to investigate one or more characteristics. A **single-factor cross** is designed to look at how one genetically determined characteristic is inherited. A unique single factor cross is a *monohybrid cross*. A **monohybrid cross** is a cross between two organisms that are both heterozygous for the one observed gene. A **double-factor cross** is a genetic

Gene Key
Gene or Condition: earlobe type

Allele Symbols	Possible Genotype	Phenotype	Possible Sex Cells
E = free	*EE*-homozygous	Free earlobes	All sex cells have *E*.
	Ee-heterozygous	Free earlobes	Half of sex cells have *E* and half have *e*.
e = attached	*ee*-homozygous	Attached earlobes	All sex cells have *e*.

study in which two different genetically determined characteristics are followed from the parental generation to the offspring at the same time. Because double-factor crosses involve two genes, their outcomes are more complex than single-factor crosses. Let's look at the following single-factor cross where we observe earlobe attachment.



The cross shown is between two heterozygous (*Ee*) individuals. The individuals in this cross can each produce two types of sex cells, *E* and *e*. The colors (red and blue) used in this monohybrid cross and Punnett square allow us to trace what happens to the sex cells from each parent. The top row lists the sex cells that can be produced by one parent, and the left-most column of the Punnett square lists the sex cells that can be produced by the other parent. The letter combinations within the four boxes represent the possible genotypes of the offspring. Each combination of letters is simply the combination of the alleles listed at the top of each column and the left of each row.

Let's look at the type of offspring that can be produced by this cross. The Punnett square contains three genotypes: *EE, Ee,* and *ee*. Additionally, by counting how many times each genotype is shown in the Punnett square, we can predict how frequently we expect to observe each genotype in the offspring of these parents. Here, we expect to see *Ee* twice for every time we see *EE* or *ee*. Remember that a Punnet square only generalizes. If many *(at least 30 or more)* offspring are produced from the cross, we might expect to see nearly 1/4 *EE,* 2/4 *Ee,* and 1/4 *ee*. Geneticists may abbreviate this ratio as 1:2:1. These ratios can be written in a different manner but still mean the same thing:

1/4 *EE*, 1/2 *Ee*, 1/4 *ee*

Summary: The outcome of a genetic cross cannot be exactly determined. The outcome can only be described by general trends.

Application: The Punnett square can be used to predict the types and ratios of offspring.

10.2 CONCEPT REVIEW

4. Distinguish between phenotype and genotype.
5. What types of symbols are typically used to express genotypes?
6. How many kinds of games are possible with the genotype *Aa*?
7. What is the difference between a single-factor cross and double-factor cross?

10.3 Probability vs. Possibility

Your ability to understand genetics depends on your ability to work with probabilities. This section will help you understand what probability is.

Probability is the mathematical chance that an event will happen, and it is expressed as a percentage or a fraction, like the values that we identified using the Punnett square in the previous example. Probability is not the same as *possibility.* Consider the common phrase "almost anything is possible" when reading the following question: "It is possible for me to win the lottery, but how probable is it?" Although it is possible to win the lottery, it is extremely unlikely. When we talk about something being probable, we actually talk mathematically—in ratios and percentages—such as, "The probability of my winning the lottery is 1 in 250,000."

It is possible to toss a coin and have it come up heads, but the probability of getting a head is a more precise statement than just saying it is possible to do so. The probability of getting a head is 1 out of 2 (1/2, or 0.5, or 50%), because there are two sides to the coin, only one of which is a head. Probability can be expressed as a fraction:

$$\text{probability} = \frac{\text{the number of events that can produce a given outcome}}{\text{the total number of possible outcomes}}$$

What is the probability of cutting a standard deck of cards and getting the ace of hearts? The number of times the ace of hearts can occur in a standard deck is 1. The total number of different cards in the deck is 52. Therefore, the probability of cutting to an ace of hearts is 1/52. What is the probability of cutting to any ace? The total number of aces in the deck is 4, and the total number of cards is 52. Therefore, the probability of cutting an ace is 4/52, or 1/13.

It is also possible to determine the probability of two independent events occurring together. *The probability of two or more events occurring simultaneously is the product of their individual probabilities*. When two six-sided dice are thrown, it is possible that both will be 4s. What is the probability that both will be 4s? The probability of one die being a 4 is one out of the six sides of the die, or 1/6. The probability of the other die being a 4 is also 1/6. Therefore, the probability of throwing two 4s is

$$1/6 \times 1/6 = 1/36$$

The concepts of probability and possibility are frequently used in solving genetics problems (How Science Works 10.1). Consider describing the genetic contents of the sex cells an individual will produce. Assume that the individual's genotype is *AA*. It is only *possible* for this individual to produce sex cells that carry the *A* allele. The *probability* of this occurring is 100%. Now consider an individual with the *Aa* genotype.

HOW SCIENCE WORKS 10.1

Cystic Fibrosis—What Is the Probability?

Cystic fibrosis is among the most common lethal genetic disorders that affect Caucasians. An estimated 30,000 people are affected by cystic fibrosis in North America. One in every 20 persons has a defective recessive allele that causes cystic fibrosis, but most of these individuals display no cystic fibrosis symptoms, because they are heterozygous and the recessive allele is masked by a normal dominant allele. Only those with two copies of the defective recessive gene develop symptoms. About 1,000 new cystic fibrosis cases are identified in the United States each year. The gene for cystic fibrosis occurs on chromosome 7; it is responsible for the manufacture of **c**ystic **f**ibrosis **t**ransmembrane **r**egulator (CFTR) protein. The CFTR protein controls the movement of chloride ions across the cell membrane.

There are many possible types of mutations in the CFTR gene. The most common mutation results in a CFTR protein with a deletion of a single amino acid. As a result, CFTR protein is unable to control the movement of chloride ions across the cell membrane. The major result is mucus filling the bronchioles, resulting in blocked breathing and frequent respiratory infections. It is also responsible for other symptoms:

1. A malfunction of sweat glands in the skin and the secretion of excess chloride ions
2. Clogging of the bile duct, which interferes with digestion and liver function
3. Mucus clogging the pancreas ducts, preventing the flow of digestive enzymes into the intestinal tract
4. Bowel obstructions caused by thickened stools
5. Sterility in males that is due to the absence of vas deferens and, on occasion, female sterility due to the presence of dense mucus-blocking sperm from reaching eggs.

One in 20 people have a recessive allele for cystic fibrosis. In this group, two or three individuals, on average, have the allele.

Consider the facts about the frequency of the cystic fibrosis gene in the population. What is the probability that any set of parents will have a child with cystic fibrosis? What is the probability that a person who carries the cystic fibrosis allele will marry someone who also has the allele?

It is *possible* for the *Aa* individual to produce *A* or *a* sex cells. The *probability* of a sex cell having *A* is 50%; only one of the two possibilities is *A*. Likewise, the probability of a sex cell having *a* is 50%; only one of the two possibilities is *a*.

In a genetics problem, the frequency with which alleles are present in gametes determines the likelihood that a couple will have children with a particular characteristic. Consider the possible fertilization events that *could* occur between an individual with the genotype *AA* and an individual with the genotype *aa* (the genetic cross *AA* × *aa*). To do this, use a Punnett square. First, predict the possible sex cells produced by each individual.

Genotype	Possible Sex Cells
AA	*A*
aa	*a*

Then, set up a Punnett square that shows the possible fertilization events between the sex cells shown.

	a
A	*Aa*

The only possible offspring is *Aa*. The probability of obtaining an offspring with this genotype is 100%.

10.3 CONCEPT REVIEW

8. What is the difference between probability and possibility?
9. In what mathematical forms might probability be expressed?

10.4 The First Geneticist: Gregor Mendel

The inheritance patterns discussed in the section "Probability vs. Possibility" were initially described by Gregor Mendel—a member of the religious order of Augustinian monks. Mendel's (1822–1884) work was not generally accepted until the 1900s, when three men, working independently, rediscovered some of

(a) (b)

FIGURE 10.3 Gregor Mendel and His Pea Plant Garden
(a) Gregor Mendel was an Augustinian monk who used statistics to describe the inheritance patterns he observed in pea plants. *(b)* He carried out his investigations in this small garden of his monastery in Brno, Czech Republic where Mendel did his experiments.

the ideas that Mendel had formulated more than 30 years earlier. Because of his early work, the study of the pattern of inheritance that follows the laws formulated by Gregor Mendel is often called **Mendelian genetics** (figure 10.3).

Mendel's work established basic principles that allowed him and others to solve heredity problems. Heredity problems are concerned with determining which alleles are passed from parents to offspring and how likely it is that various types of offspring will be produced. Mendel performed experiments concerning the inheritance of certain characteristics in garden pea plants (*Pisum sativum*). From his work, Mendel developed the ideas of a genetic characteristic being dominant or recessive and categorized the inheritance patterns for a number of garden pea alleles by using rules of probability. Some of the phenotypes he used in his experiments are shown in table 10.1.

What made Mendel's work unique was that he initially studied only one trait at a time. In addition, he grouped the offspring by phenotype and counted them. Previous investigators tried to follow numerous traits at the same time. This made it very difficult to follow characteristics, and they did not determine the frequency of phenotypic groups. Therefore, they were unable to see any patterns in their data.

Mendel was very lucky to have chosen pea plants in his study because they naturally *self-pollinate*. This means that pea plants produce both pollen and eggs and that the eggs can be fertilized by haploid nuclei from their own pollen. When self-pollination occurs in pea plants over many generations, it is easier to develop a population of plants that is homozygous for a number of characteristics. Such a population is known as a *pure line*.

TABLE 10.1 Dominant and Recessive Traits in Pea Plants

Gene	Dominant Allele Phenotype	Recessive Allele Phenotype
Plant height	Tall	Dwarf
Pod shape	Full	Constricted
Pod color	Green	Yellow
Seed surface texture	Round	Wrinkled
Seed color	Yellow	Green
Flower color	Purple	White

The following gene key organizes some of Mendel's findings. Remember that Mendel didn't know about DNA or even chromosomes! Mendel developed this way of thinking about genetics to explain the data he collected. He did this from the perspective of a mathematician—not a biologist.

Gene Key
Gene or Condition: flower color

Allele Symbols	Possible Genotypes	Phenotype	Possible Sex Cells
C = Purple	*CC* = homozygous	Purple	All sex cells have *C* (*pure line*)
	Cc = heterozygous	Purple	Half of sex cells have *C* and half have *c*
c = white	*cc* = homozygous	White	All sex cells have *c* (*pure line*)

In one experiment, Mendel took a pure line of pea plants having purple flower color, removed the male parts (anthers), and discarded them, so that the plants could not self-pollinate. He then took anthers from a pure-breeding white-flowered plant and pollinated the antherless purple flower. These plants are called the parent generation, or P_0. When the pollinated flowers produced seeds, Mendel collected, labeled, and planted them. When these seeds germinated and grew, they eventually produced flowers. The offspring of the P_0 generation are called the F_1 generation. The *F* stands for *filial*, which is Latin for relating to a son or daughter. F_1 is read as the "F-one" generation or the "first filial" generation.

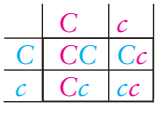
Mendel's First Cross

Observed	Genetic Notation
P_0 *pure breeding purple* × *pure breeding white*	$CC \times cc$
	
F_1 *100% produced purple flowers*	100% *Cc*

All the F_1 plants resulting from this cross had purple flowers. One of the popular ideas of Mendel's day would have predicted that the purple and white colors would have blended, resulting in flowers that were lighter than the purple parent flowers. Another hypothesis would have predicted that the offspring would have had a mixture of white and purple flowers. Neither of these two hypotheses was supported by Mendel's results. He observed only purple flowers from this cross.

Mendel then crossed the F_1 pea plants (all of which had purple flowers) with each other to see what the next generation would be like. Had the white-flowered characteristic been lost completely? The seeds from this mating were collected and grown. When these plants flowered, three-fourths of them produced purple flowers and one-fourth produced white flowers. This generation is called the F_2 generation.

Mendel's Second Cross

Observed	Genetic Notation
F_1 *Offspring from* P_0 *(purple)* × *offspring from* P_0 *(purple)*	$Cc \times Cc$
	
F_2 *75% produced purple flowers*	*25% CC* + *50% Cc* = *75% produced purple flowers*
25% produced white flowers	*25% cc produced white flowers*

His experiments used similar strategies to investigate other traits. Pure-breeding tall pea plants were crossed with pure-breeding dwarf plants. Pure-breeding plants with yellow pods were crossed with pure-breeding plants with green pods. Mendel recognized the same pattern for each characteristic in the F_1 generation: All the offspring showed the characteristics of one parent and not the other with no blending.

After analyzing these data, Mendel identified several genetic principles:

1. Organisms have two pieces of genetic information for each trait. It is now recognized that these are different alleles for each characteristic.
2. Because organisms have two pieces of genetic information for each characteristic, the alleles can be different. Mendel's **Law of Dominance** states that some alleles interact with each other in a dominant and recessive manner whereby the dominant allele masks the recessive allele.
3. Gametes fertilize randomly.
4. Mendel's Law of Segregation states that, when a diploid organism forms gametes, the two alleles for a characteristic separate from one another. In doing this, they move to different gametes and retain their individuality.

The application of Mendel's Law of Segregation may not be as apparent as the application of the Law of Dominance. The movements of chromosomes during meiosis separate the four copies (one on each chromatid) of each allele into four different sex cells. This causes only 1 allele of each gene to be present in each sex cell. We first observed this law in this chapter when we discussed sex cells and how alleles separate in both homozygous and heterozygous organisms. Finally, this law is the basis for the Punnett square, in which the possible alleles from each parent are placed in a separate row or column.

10.4 CONCEPT REVIEW

10. In your own words, describe Mendel's Law of Segregation.
11. Define *self-pollination*.
12. What is the "F_1 generation"?

10.5 Solving Genetics Problems

Many students become confused when they try to solve genetics problems because they are not sure where to begin or when it is appropriate to apply a principle. As a result, they move directly to drawing a Punnett square and begin to incorrectly fill it with letters. Developing an organized and consistent strategy will help solve such problems.

Single-Factor Crosses

Problem Type: Single-Factor Cross

INTRODUCTORY PRINCIPLES: Genetics problems can vary greatly in complexity and in the type of information that is provided. Let's start with a genetics problem that considers a single trait for which there are two alleles.

Cross 1: The pod color of some pea plants is inherited so that green pods are dominant to yellow pods. A pea plant that is heterozygous for green pods is crossed to a pea plant that produces yellow pods. What proportion of the offspring will have green pods?

Gene Key
Gene or Condition: pod color

Allele Symbols	Possible Genotypes	Phenotype
G = green	*GG*	Green
	Gg	Green
g = yellow	*gg*	Yellow

The question describes a gene affecting pea pod color. The two different phenotypes are green and yellow. The question also states that "green pods are dominant to yellow pods." Because of this statement, use a capital letter to represent the *green* allele and a lowercase letter to represent the *yellow* allele. We are using the letter *G*, but any other letter would work. The only requirement is to use the same letter for both alleles. The gene key table shows the type of information needed to describe how the alleles for a characteristic work together. A gene key is a reference that will help solve the problem.

Now, organize the actual genetic cross. Table 10.2 shows each step in a simple genetics problem and skills that may be necessary to move from one step to the next. This problem starts at the top row and works toward the bottom of the table. There are several steps in this process. The steps are represented by each row in the table. The rows are titled. "Parental phenotypes," "Parental genotypes," "Possible sex cells," "Offspring genotype," and "Offspring phenotype."

First, determine what information is provided in the question about the organisms that are involved in this cross. Identify the following pieces of information in the question.

- A pea plant with green pods is crossed to a pea plant with yellow pods.
- The green pea plant is heterozygous.
- The yellow pea plant is homozygous.

The question we are trying to answer is, "What proportion of the offspring will have green pods?" Solve the problem by using the table as a guide. These steps describe the process:

1. The first statement about the organisms being crossed is shown in the "Parental phenotypes" row as Green × Yellow. Using this information, the gene key, and the remaining two statements, we determine the parental genotypes. The reasoning described in this process is in the "Parental genotypes" row of table 10.2.

TABLE 10.2 Steps in Solving a Genetics Problem

Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	By reading the problem, determine that one parent has green pods and the other yellow. Green × Yellow
Parental genotypes	Organisms are diploid, so 2 alleles are needed for each parent. The green parent can be either *GG* or *Gg* (gene key). However, the problem states that this parent is heterozygous. The allele combination of *Gg* is the only green heterozygous combination. The gene key shows that the only genotype that produces yellow is *gg*. *Gg* × *gg*
Possible sex cells	Because of the Law of Segregation, the alleles separate from each other when sex cells are formed in the parents. The *Gg* parent can produce two types of sex cells, *G* and *g*. The *gg* parent can produce only *g* sex cells. *G* *g* *g*
Offspring genotype	Set up a Punnett square to show the possible fertilization events. This square will have one column and two rows, because one parent produces only one type of gamete and the other parent produces two types. *g* *G* *Gg* *g* *gg* 50% *Gg* 50% *gg*
Offspring phenotype	Now, use the information in the gene key to determine the phenotypes of the offspring genotypes. *Gg* will appear as green. Yellow can be produced only by *gg*. 50% produce green pea pods (*Gg*). 50% produce yellow pea pods (*gg*).

2. The next step is to use the parental genotypes to determine the parents' possible sex cells. It is necessary to apply Mendel's Law of Segregation to do this correctly. This process is described in the "Possible sex cells" row.
3. Now that the parents' gametes are identified, use a Punnett Square to predict the genotypes of the offspring. Create a Punnett square so that there is one row or column for each gamete. This process is shown in the "Offspring genotype" row.
4. Return to the gene key to determine the offspring phenotypes from the genotypes just produced with the Punnett square.
5. Finally, remember to look at the question that was asked. In this example, the question is what proportion of the offspring will produce green pea pods. The answer is 50%.

In this example, all the information from the problem fits into the gene key and the first rows of table 10.2. Not all problems are like this. Sometimes, a problem provides information about the offspring and requests information about the parents. Table 10.2 will help you do this as well. The principles that applied as you worked down the table still apply as you go the other direction.

Problem Type: Single-Factor Cross

INTRODUCTORY PRINCIPLES: When both parents are heterozygous and the alleles are completely dominant and recessive to each other, the predicted offspring ratio is always 3:1 (75% of the dominant phenotype to 25% of the recessive phenotype.) If the genotypes of parents are not known and the offspring have a 3:1 ratio, then geneticists frequently infer that the parents are both heterozygous for the trait being considered.

To illustrate this 3:1 pattern of inheritance, consider the disorder phenylketonuria (PKU). People with phenylketonuria are unable to convert the amino acid phenylalanine into the amino acid tyrosine. The buildup of phenylalanine in the body prevents the normal development of the nervous system. Such individuals may become mentally retarded if their disease is not controlled.

Figure 10.4 shows the metabolic pathway in which the amino acid phenylalanine is converted to the amino acid tyrosine by the enzyme phenylalanine hydroxylase. Tyrosine is then used as a substrate by other enzymes. In the abnormal pathway, the substrate phenylalanine builds up, because the enzyme phenylalanine hydroxylase does not function correctly in people with PKU. As phenylalanine levels rise, it is converted to phenylpyruvic acid, which kills nerve cells.

CROSS 2: The normal condition is to convert phenylalanine to tyrosine. It is dominant over the condition for PKU. If both parents are heterozygous for PKU, what is the probability that they will have a child who is normal? A child with PKU?

As in the previous example, use the gene key to summarize this problem:

- There are 2 alleles. One is responsible for the normal condition and the other is for PKU.
- The normal condition is dominant over PKU. From this statement, infer that individuals with a normal phenotype can be either *PP* or *Pp*.

Gene Key

Gene or Condition: Phenylketonuria

Allele Symbols	Possible Genotypes	Phenotype
P = normal	*PP*	Normal
	Pp	Normal
p = phenylketonuria	*pp*	Phenylketonuria

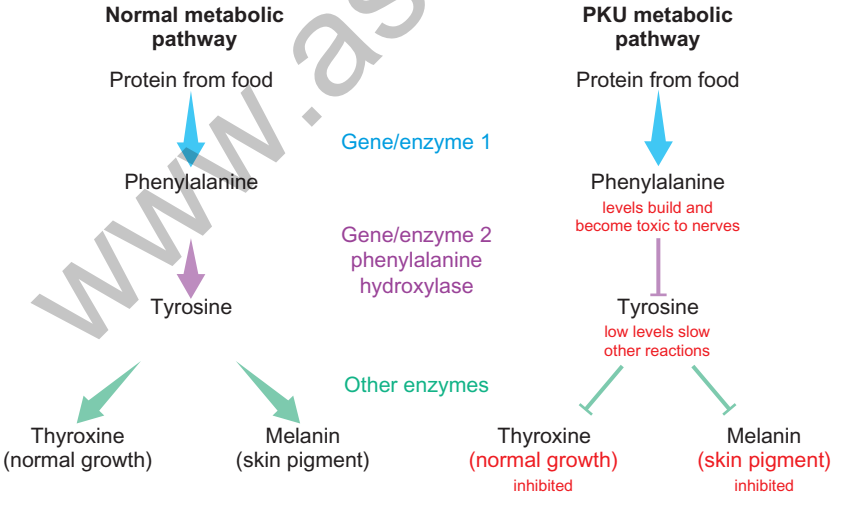


FIGURE 10.4 Phenylketonuria (PKU)
PKU is a recessive disorder located on chromosome 12. The diagram on the left shows how the normal pathway works. The diagram on the right shows an abnormal pathway. If the enzyme phenylalanine hydroxylase is not produced because of a mutated gene, the amino acid phenylalanine cannot be converted to tyrosine and is converted into phenylpyruvic acid, which accumulates in body fluids. The buildup of phenylpyruvic acid causes the death of nerve cells and ultimately results in mental retardation. Because phenylalanine is not converted to tyrosine, subsequent reactions in the pathway are also affected.

1. The problem states that "both parents are heterozygous for PKU." This describes the parental genotypes and determines the genotypes for both parents to be *Pp*. Enter this information on the "Parental Genotypes" row. Although it is not necessary to solve the problem, you can use the gene key to determine the parental phenotypes. *Pp* individuals are normal. *Note: This genetic problem does not start with the first row of table 10.3. A genetics problem can start at any point in the table and require that you determine things about either the parents or the offspring.*
2. Determine the possible sex cells. *Pp* individuals will have gametes that are *P* and *p*.
3. Determine the offspring genotypes using a Punnett square. Create your Punnett square so that there is one row or column for each gamete. Note that, in this situation, three different genotypes are produced—*PP, Pp,* and *pp*.
4. Determine the offspring phenotypes by using the gene key and combining genotypes with similar phenotypes.
5. Finally, answer the question that was asked from the problem. In this case, two questions were asked. The probability of having a normal child is 75%. The probability of having a child with PKU is 25%.

TABLE 10.3 Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	**Father × Mother** Normal × Normal
Parental genotypes	*Pp* × *Pp*
Possible sex cells	*P* *P* *p* *p*
Offspring genotype	

	P	*p*
P	*PP*	*Pp*
p	*Pp*	*pp*

Offspring phenotype		
Normal	Phenylketonuria	
25% *PP*	25% Total	
50% *Pp*		
75% Total		

Double-Factor Crosses

Up to this point, we have worked only with single-factor crosses. Now we will consider how to handle genetics problems that involve following two distinct characteristics—double-factor crosses. In solving double-factor crosses, it is important to consider the principle Mendel identified as the *Law of Independent Assortment*. The **Law of Independent Assortment** states that alleles of one characteristic separate independently of the alleles of another. *This law is applied only when working with two genes for different characteristics that are on different chromosomes.* This is an important distinction, because genes that are positioned near each other on a chromosome tend to stay together during meiosis and therefore tend to be inherited together. If genes are inherited together, they are not assorting in a random manner. Their assortment is not independent of each other.

In genetics problems, the process of predicting the sex cells that can be produced in double-factor crosses is affected by independent assortment. The following example illustrates how independent assortment works. Recall that if an individual has the genotype *Aa,* we predict that 50% of his or her reproductive cells have the *A* allele and 50% have the *a* allele. This is an application of the Law of Segregation. If an individual has the genotype *Bb,* we can make a similar prediction with regard to the *B* and *b* alleles. What happens when we want to look simultaneously at both sets of alleles when the "A" characteristic is on a different chromosome from the "B" characteristic? What are the possible sex cells that could be produced for an individual that is *AaBb?*

In order to answer this question, we have to apply both the Law of Segregation *and* the Law of Independent Assortment. For now, we will assume that the two genes are on different chromosomes. As mentioned earlier, the law of segregation predicts that 50% of the gametes will have *A* and 50% will have *a*. Likewise 50% of the gametes will have *B* and 50% *b*. The Law of Independent Assortment says that, if a gamete receives an *A* allele, it has an equal chance of also receiving a *B* allele or a *b* allele. Thus, the sex cells that are predicted are *AB, Ab, aB,* and *ab*. Notice that

- every sex cell has either an *A* or an *a* but not both. Every sex cell has either a *B* or a *b* but not both. This means that all the sex cells have 1 and only 1 of the 2 alleles for each characteristic.
- each allele is found in 50% of the sex cells.
- the alleles for one characteristic are inherited independently from the other.

You can check to see if you have made correct choices by making sure that only one allele for each characteristic is present in a sex cell. Note that sex cells with allele combinations such as *AA* or *AaB* are incorrect. Both of these incorrect examples have more than 1 allele for a gene. The first example (*AA*) should have only a single *A* and is missing a copy of

the *B* gene altogether. The second example (*AaB*) should have either the *A* or the *a* allele, but not both.

Problem Type: Double-Factor Cross

Cross 3: In humans, the allele for free earlobes is dominant over the allele for attached earlobes. The allele for dark hair dominates the allele for light hair. If both parents are heterozygous for earlobe shape and hair color, what types of offspring can they produce, and what is the probability for each type?

Just as in a single-factor cross, start by creating a gene key. You are working with two characteristics this time, so create a key for both. Remember that not all the information in the gene key is stated directly in the problem. From the problem, you should be able to identify that

- There are two genes—earlobe type and hair color.
- The free earlobe allele is dominant to the attached earlobe allele.
- The dark hair allele is dominant to the light hair allele.

From this information, you should be able to infer that

- Because the free earlobe allele is dominant, it can have two genotypes—*EE* and *Ee*.
- Because dark hair is dominant, it can have two genotypes—*HH* and *Hh*.

Gene Key

Gene or Condition: earlobe type

Allele Symbols	Possible Genotypes	Phenotype
E = free	*EE*	Free earlobes
	Ee	Free earlobes
e = attached	*ee*	Attached earlobes

Gene or Condition: hair color

Allele Symbols	Possible Genotypes	Phenotype
H = dark hair	*HH*	Dark hair
	Hh	Dark hair
h = light hair	*hh*	Light hair

1. After you have the gene key complete, move on to the cross setup in table 10.4. The problem states that "both parents are heterozygous for earlobe shape and hair color." This is a description of the parents' genotypes. It means that both parents are *EeHh*. Place this information on the "Parental Genotypes" row. Although it is not necessary, you can use the gene key to determine what the parent's phenotypes are for earlobe type and hair color.
2. Determine the possible sex cells. *EeHh* individuals will have gametes that are *EH*, *Eh*, *eH*, and *eh*. This answer uses the Law of Segregation and the Law of Independent Assortment.
3. Determine the offspring genotypes using a Punnett square. Create your Punnett square so that there is one row or column for each gamete. Your Punnett square will create a 4 × 4 grid. Fill in the genotypes as shown.
4. Determine the offspring phenotypes by using the gene key and combining genotypes with similar phenotypes. In this problem, there will be four different groupings: (a) free earlobes and dark hair, (b) free earlobes and light hair, (c) attached earlobes and dark hair, and (d) attached earlobes and light hair.
5. Answer the question that was asked from the problem. The ratios are 9:3:3:1.

In cases where the alleles for each gene are completely dominant and recessive to each other and both parents are heterozygous for both characteristics, the predicted offspring ratio is 9:3:3:1. When scientists observe a 9:3:3:1 ratio, they suspect that both parents are heterozygous for both characteristics being considered.

10.5 CONCEPT REVIEW

13. What does it mean when geneticists use the term *independent assortment?*
14. What is a Punnett square?
15. What is the probability of each of the following sets of parents producing the given genotypes in offspring?

Parents	Offspring
a. *AA* × *aa*	*Aa*
b. *Aa* × *Aa*	*Aa*
c. *Aa* × *Aa*	*aa*
d. *AaBb* × *AaBB*	*AABB*
e. *AaBb* × *AaBB*	*AaBb*
f. *AaBb* × *AaBb*	*AABB*

16. What possible combinations of parental genotypes could produce an offspring with the genotype *Aa*?
17. In certain pea plants, the allele *T* for tallness is dominant over *t* for shortness.
    a. If a homozygous tall and homozygous short plant are crossed, what will be the phenotype and genotype of the offspring?
    b. If both individuals are heterozygous, what will be the phenotypic and genotypic ratios of the offspring?
18. Certain kinds of cattle have two alleles for coat color: R = red, and *r* = white. when an cow is heterozygous, it is spotted with red and white (roan). When two red alleles are present, it is red. When two white alleles are present it is white. The allele L, for lack of horns, is dominant over *l*, for presence of horns. If a bull and a cow both have the genotype R*r*L*l*, how many possible phenotypes of offspring can they have?

TABLE 10.4 Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	**Father × Mother** Free earlobes Free earlobes Dark hair Dark hair
Parental genotypes	The problem states that both parents are heterozygous for both characteristics. *EeHh* × *EeHh*
Possible sex cells	Notice that the Law of Independent Assortment has been added as a skill that should be used for a double-factor cross. Both parents have the same genotypes, so they each produce the same types of gametes. *EH* *EH* *Eh* *Eh* *eH* *eH* *eh* *eh*
Offspring genotype	Set up a Punnett square to show the possible fertilization events.

	EH	*Eh*	*eH*	*eh*
EH	*EEHH*	*EEHh*	*EeHH*	*EeHh*
Eh	*EEHh*	*EEhh*	*EeHh*	*Eehh*
eH	*EeHH*	*EeHh*	*eeHH*	*eeHh*
eh	*EeHh*	*Eehh*	*eeHh*	*eehh*

Offspring phenotype	Free Earlobes and Dark Hair	Free Earlobes and Light Hair	Attached Earlobes and Dark Hair	Attached Earlobes and Light Hair
	Count up the different genotypes and then combine them by similar phenotype using the information in the Gene Key. The Punnett square is 4 × 4, so each box counts for 1/16 of the possible offspring.			
	1/16—*EEHH* 2/16—*EEHh* 2/16—*EeHH* 4/16—*EeHh* 9/16	1/16—*EEhh* 2/16—*Eehh* 3/16	1/16—*eeHH* 2/16—*eeHh* 3/16	1/16—*eehh* 1/16

10.6 Modified Mendelian Patterns

Mendel's principles are most clearly observed under very select conditions in which alleles have consistent dominant/recessive interactions. So far, we have considered only a few straightforward cases. Most, however, may not fit these fundamental patterns. This section discusses several common inheritance patterns that do not fit the patterns that are generally associated with Mendelian genetics.

Codominance

In some inheritance situations, alleles lack total dominant and recessive relationships and are both observed phenotypically to some degree. This behavior is not consistent with Mendel's law of dominance. This inheritance pattern is called *codominance*. In **codominance,** the phenotype of both alleles is expressed in the heterozygous condition. Consequently, a person with the heterozygous genotype can have a phenotype very different from either of his or her homozygous parents. In problems involving codominant alleles, all capital symbols are used, and superscripts are added to represent the different alleles. The capital letters call attention to the fact that each allele can be detected phenotypically to some degree, even when in the presence of an alternative allele. For example, the coat colors (*C*) of shorthorn cattle are phenotypically red (C^RC^R), roan (C^RC^W), and white (C^WC^W). The roan coat is composed of individual hairs, which are either red or white. Together, they create the intermediate effect of roan.

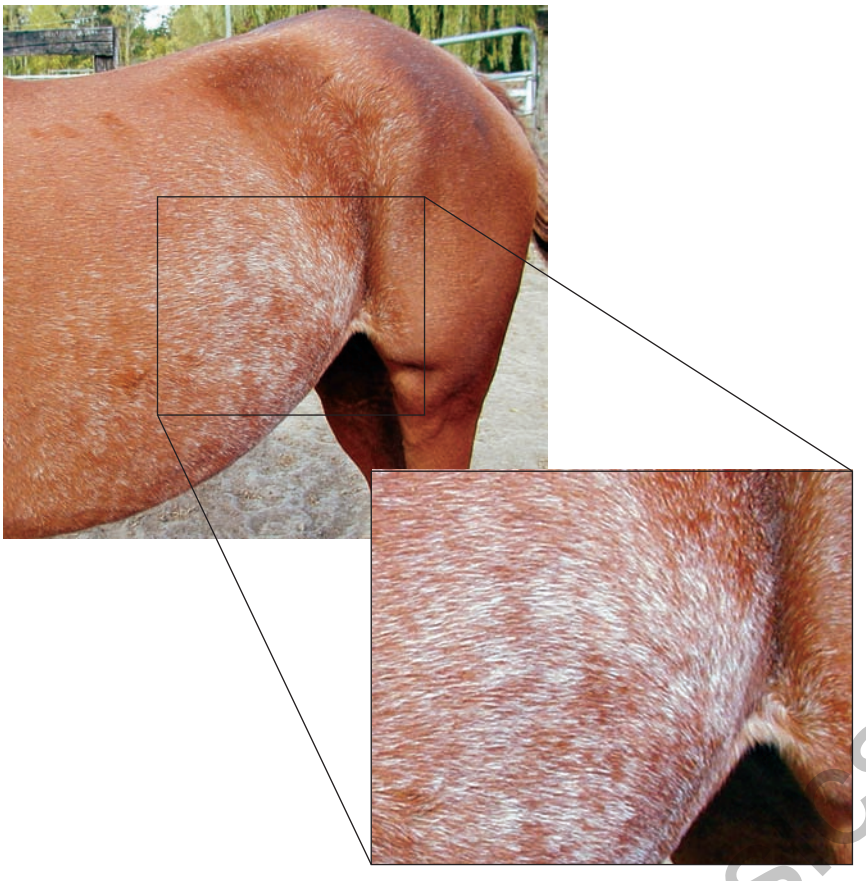


FIGURE 10.5 Codominance
The color of this breed of horse, an Arab, also displays the color called roan. Notice that there are places on the body where both white and red hairs are displayed.

Roan coat color can be seen in several other species, including horses (figure 10.5).

Another example of codominance occurs in certain horses. A pair of codominant alleles (D^R and D^W) is known to be involved in the inheritance of these coat colors. Genotypes homozygous (D^RD^R) for the D^R allele are chestnut-colored (reddish); heterozygous genotypes (D^RD^W) are palomino-colored (golden color with lighter mane and tail). Genotypes homozygous (D^WD^W) for the D^W allele are almost white and called cremello.

Incomplete Dominance

In **incomplete dominance,** the phenotype of a heterozygote is intermediate between the two homozygotes on a phenotypic gradient; that is, the phenotypes appear to be "blended" in heterozygotes. A classic example of incomplete dominance in plants is the color of the petals of snapdragons. There are 2 alleles for the color of these flowers. Because neither allele is recessive, we cannot use the traditional capital and lowercase letters as symbols for these alleles. Instead, the allele for white petals is the symbol F^W, and the one for red petals is F^R (figure 10.6).

There are three possible combinations of these 2 alleles:

Genotype	*Phenotype*
F^WF^W	White flower
F^RF^R	Red flower
F^RF^W	Pink flower

(a) F^RF^R (b) F^WF^W (c) F^WF^R

FIGURE 10.6 Incomplete Dominance
The colors of these snapdragons are determined by two alleles for petal color, F^W and F^R. There are three phenotypes because of the way in which the alleles interact with one another: *(a)* red, *(b)* white, and *(c)* pink. In the heterozygous condition, neither of the alleles dominates the other.

TABLE 10.5 Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	Pink × White
↕	
Parental genotypes	$F^RF^W \times F^WF^W$
↕	
Possible sex cells	F^R F^W F^W
↕	
Offspring genotype	F^W F^R F^RF^W F^W F^WF^W
↕	
Offspring phenotype	50% pink 50% white

Notice that there are only 2 different alleles, red and white, but there are three phenotypes—red, white, and pink. Both the red-flower allele and the white-flower allele partially express themselves when both are present, and this results in pink. The gene products of the 2 alleles interact to produce a blended result.

Problem Type: Incomplete Dominance

CROSS 4: *If a pink snapdragon is crossed with a white snapdragon, what phenotypes can result, and what is the probability of each phenotype?* Notice that the same principles used in earlier genetics problems still apply. Only the interpretation process between genotypes and phenotypes in the gene key is altered. (Table 10.5)

Gene Key
Gene: flower color

Allele Symbols	Possible Genotypes	Phenotype
F^W = White flowers	F^WF^W	White
F^R = Red flowers	F^RF^R	Red
	F^WF^R	Pink

This cross results in two different phenotypes—pink and white. No red flowers can result, because this would require that both parents be able to contribute at least 1 red allele. The white flowers are homozygous for white, and the pink flowers are heterozygous.

Multiple Alleles

So far, we have discussed only traits that are determined by only 2 alleles: for example, *A*, *a*. However, there can be more than 2 different alleles for a single trait. The term **multiple alleles** refers to situations in which there are more than 2 possible alleles that control a particular trait. However, an organism still can have only a maximum of 2 of the alleles for the characteristic because diploid organisms have only 2 copies of each gene. A good example of a characteristic that is determined by multiple alleles is the ABO blood type. There are 3 alleles for blood type:

Alleles*

I^A = **blood has type A antigens on red blood cell surface**
I^B = **blood has type B antigens on red blood cell surface**
i = **blood type O has neither type A nor type B antigens on red blood cell surface**

In the ABO system, A and B show *codominance* when they are together in an individual, but both alleles are dominant over the O allele. These 3 alleles can be combined as pairs in six ways, resulting in four phenotypes. Review the gene key and the following problem to further explore the genetics of blood type.

Problem Type: Multiple Alleles

CROSS 5: One aspect of blood type is determined by 3 alleles—A, B, and O. Allele A and allele B are codominant. Allele A and allele B are both dominant to allele O. A male heterozygous with blood type A and a female heterozygous with blood type B have a child. What are the possible phenotypes of their offspring?

Gene Key
Gene: blood type

Allele Symbols	Possible Genotypes	Phenotype
i = Type O	ii	Type O
I^A = Type A	I^AI^A	Type A
	I^Ai	Type A
I^B = Type B	I^BI^B	Type B
	I^Bi	Type B
	I^AI^B	Type AB

The solution for this problem is shown in Table 10.6.

*The symbols, *I* and *i* stand for the technical term referring to the antigenic carbohydrates attached to red blood cells, the immunogens. These alleles are located on human chromosome 9. The ABO blood system is not the only system used to type blood. Others include the Rh, MNS, and Xg systems.

TABLE 10.6 Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	Type A × Type B
Parental genotypes	$I^Ai \times I^Bi$
Possible sex cells	I^A I^B ; i i
Offspring genotype	I^B | i ; I^A | I^AI^B | I^Ai ; i | I^Bi | $i\,i$
Offspring phenotype	25% Type AB (I^AI^B) 25% Type A (I^Ai) 25% Type B (I^Bi) 25% Type O (ii)

Polygenic Inheritance

Thus far, we have considered phenotypic characteristics that are determined by single genes. However, some characteristics are determined by the interaction of several genes. This is called *polygenic inheritance*. In **polygenic inheritance,** a number of different pairs of alleles combine their efforts to determine a characteristic. Skin color in humans is a good example of this inheritance pattern. According to some experts, genes for skin color are located at a minimum of three chromosomal locations or loci. At each of these loci, the allele for dark skin is dominant over the allele for light skin. Therefore, a wide variety of skin colors is possible, depending on how many dark-skin alleles are present (figure 10.7). The number of total dark-skin alleles (capital *D* in figure 10.7) from all three genes determines skin color.

Polygenic inheritance is common with characteristics that show great variety within the population. Some obvious polygenic traits in humans are height, skin color, eye color, and intelligence. The many levels of height, skin color, eye color, and intelligence makes it difficult to separate individuals into meaningful categories. There is an entire range of expression for polygenic characteristics. For example, height in humans ranges from tall to short, with many intermediate heights. Eye color varies in some populations from deep brown to the lightest blue. Although it is still unclear how many genes are involved in determining these characteristics, at least two or three different genes have been identified. (Outlooks 10.1).

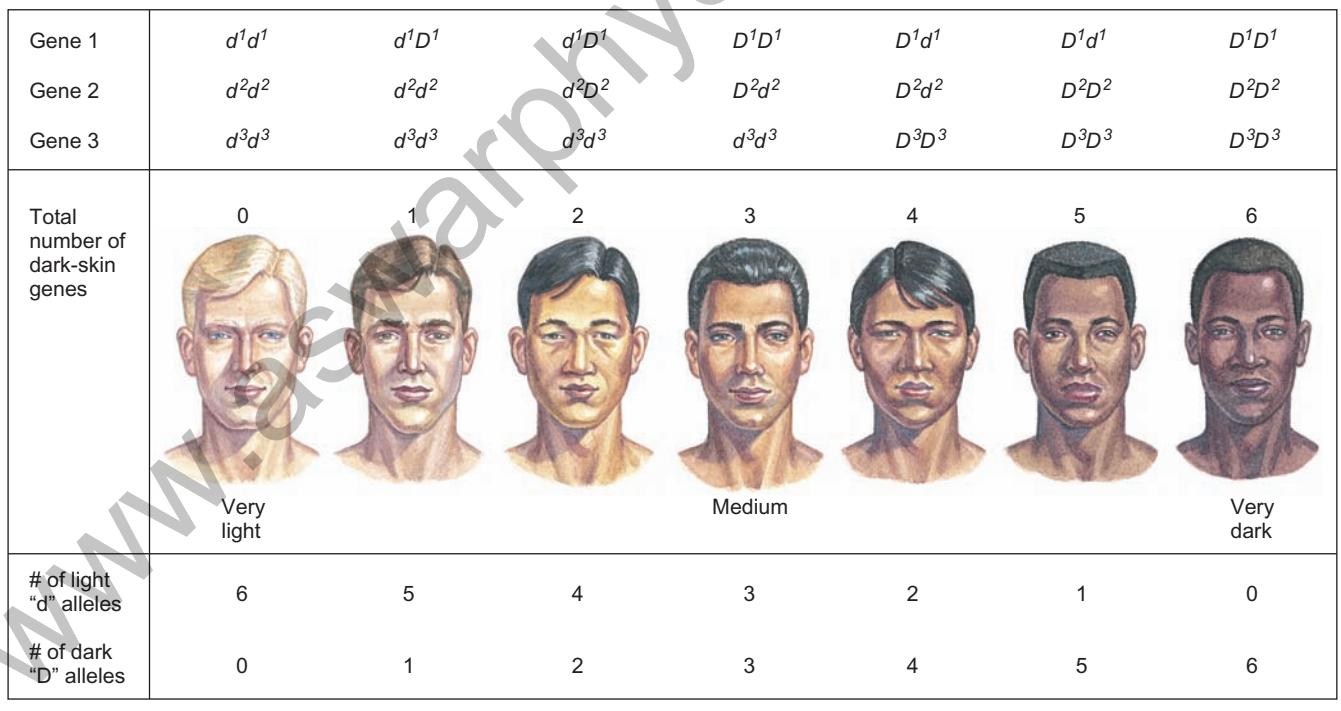


FIGURE 10.7 Polygenic Inheritance
Skin color in humans is an example of polygenic inheritance. There are several different genes for skin color located on different chromosomes, each with dark and light alleles. The total number of dark *D* alleles present have an additive effect on skin color. The top portion of the figure shows examples of genotypes that can produce the different skin colors. The number of dark *D* alleles is more important than how the *D* alleles are distributed in the different genes.

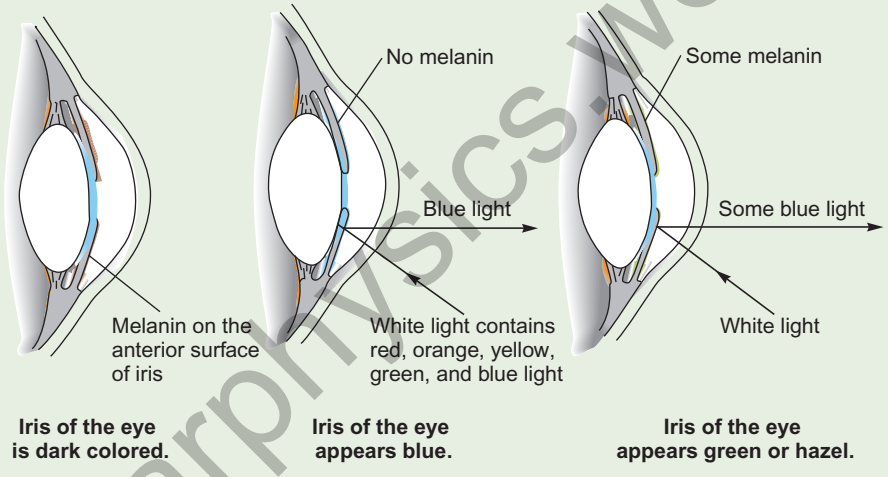
OUTLOOKS 10.1

The Inheritance of Eye Color

It is commonly thought that eye color is inherited in a simple dominant/recessive manner, in which brown eyes are considered dominant over blue eyes. However, the real pattern of inheritance is more complicated than this. Eye color is determined by the amount of a brown pigment, melanin, present in the iris of the eye. If there is a large quantity of melanin on the anterior surface of the iris, the eyes are dark. Black eyes have a greater quantity of melanin than do brown eyes.

If melanin is absent from the front surface of the iris, the eyes appear blue, not because of a blue pigment but because blue wavelengths of light are reflected from the iris. The iris appears blue for the same reason that deep bodies of water tend to appear blue. There is no blue pigment in the water, but blue wavelengths of light are returned to the eye from the water. Just as black and brown eyes are determined by the amount of pigment present, colors such as green, gray, and hazel are produced by the various amounts of melanin in the iris. If a very small amount of brown melanin is present in the iris, the eye tends to appear green, whereas relatively large amounts of melanin produce hazel eyes. If you examine the irises of people with green or hazel eyes, you will notice that specific parts of the iris have the brown pigment.

Several genes are probably involved in determining the quantity and placement of melanin. These genes interact in such a way that a wide range of eye color is possible. Eye color is probably determined by polygenic inheritance, just as skin color and height are. Some newborn babies have blue eyes that later become brown. This is because their irises have not yet begun to produce melanin.



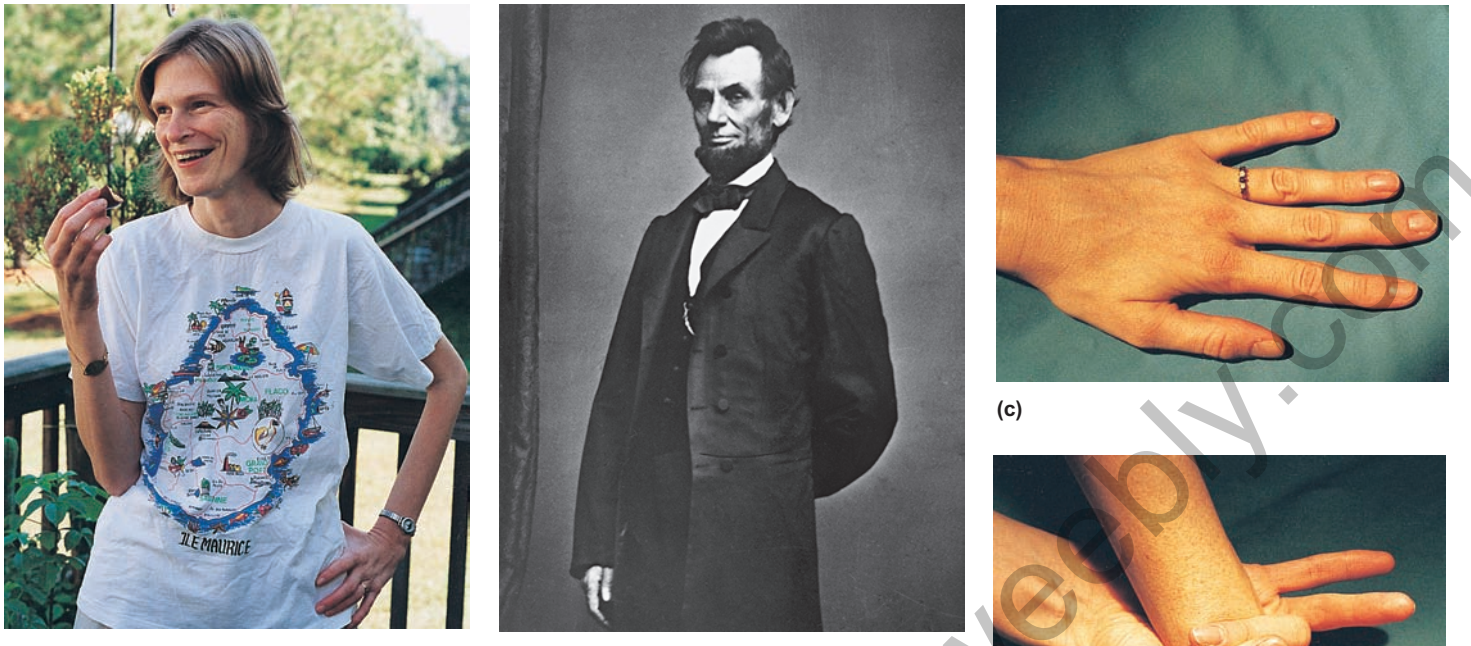
Blue eyes are due to a lack of pigment, not the presence of blue pigment. In blue eyes, blue light is reflected while other colors are absorbed. Green eyes absorb some blue light.

Polygenic traits are different from a characteristic such as blood type because blood type is determined by one gene locus; thus, there are a limited number of well-defined phenotypes (A, B, O, AB).

Pleiotropy

Even though a single gene may produce only one type of protein, it often has a variety of effects on the phenotype of a person. The term **pleiotropy** (*pleio* = changeable) describes the multiple effects a single gene has on a phenotype. A good example of pleiotropy—PKU—has already been discussed. In addition to the mental retardation phenotype, several other phenotypes are associated with PKU. Whereas mental retardation is caused by the buildup of phenylpyruvic acid, other phenotypes are caused by a lack of tyrosine, the next product in the pathway. Tyrosine is used by the human body to create two other important molecules—growth hormone and melanin. Growth hormone is needed for normal growth, and melanin is a skin pigment. Individuals with PKU have low levels of tyrosine because of the faulty enzyme; this results in abnormal growth and unusually pale skin, in addition to the presence of phenylpyruvic acid that can cause mental retardation.

Another example of pleiotropy is *Marfan syndrome*. This syndrome is a disorder of the body's connective tissue, but it can also have effects in many other organs. (Consider the phenotypic characteristics of the individual shown in figure 10.8.



(a) (b) (c) (d)

FIGURE 10.8 Marfan Syndrome
It is estimated that about 40,000 (1 out of 10,000) people in the United States have this autosomal dominant abnormality. Notice the common lanky appearance to the body and face of *(a)* this person with Marfan syndrome and *(b)* former U.S. president Abraham Lincoln. Photos *(c)* and *(d)* illustrate their unusually long fingers.

Some feel that the former U.S. president Abraham Lincoln also had Marfan syndrome. Do you see similarities?) The symptoms of Marfan syndrome generally include the following:

Skeletal
- Long arms and legs, disproportionate in length to the body
- Abnormally long fingers
- Skinniness
- Curvature of the spine
- Abnormally shaped chest, chest caves in or protrudes outward

Eye Problems
- Nearsightedness

Heart and Aortic Problems
- Weak or defective heart valves
- Weak blood vessels that rupture
- Inflammation of the heart

Lung and Breathing Problems
- Collapsed lungs
- Long pauses in breathing during sleep (sleep apnea)

Both PKU and Marfan syndrome are examples of alleles that have many different effects in an organism. Cystic fibrosis also shows pleiotropy. Review How Science Works 10.1—what information there supports this statement?

10.6 CONCEPT REVIEW

19. What is the difference between the terms *dominant* and *codominant*?
20. What is the probability of a child having type AB blood if one of the parents is heterozygous for type A blood and the other is heterozygous for type B? What other genotypes are possible in this child?

10.7 Linkage

Although Mendel's insight into the nature of inheritance was extremely important, there were many aspects of inheritance that Mendel did not explain. **Linkage** is a situation in which the genes for different characteristics are inherited together more frequently than would be predicted by probability. Linkage can be explained by examining chromosomes.

Linkage Groups

Each chromosome has many genes located along its length. Mendel's inheritance patterns don't really describe the inheritance patterns of individual genes; they describe the inheritance patterns of chromosomes. Homologous chromosomes separate from each other (segregation). Non-homologous chromosomes

separate from each other independently (independent assortment.) Because each chromosome has many genes on it, these genes tend to be inherited as a group. A **linkage group** is a set of genes located on the same chromosome. This means that they tend to be inherited together. The process of crossing-over, which occurs during prophase I of meiosis I, may split up these linkage groups. Crossing-over happens between homologous chromosomes donated by the mother and the father and results in a mixing of the allele combinations in gametes. This means that the child can have gene combinations not found in either parent alone. The closer two genes are to each other on a chromosome, the less likely crossing-over will occur between them and separate them.

Autosomal Linkage

People and many other organisms have two types of chromosomes—sex chromosomes and autosomes. **Sex chromosomes** control the sex of an organism. **Autosomes** are chromosomes that are not directly involved in sex determination; they have the same kinds of genes on both members of the homologous pair of chromosomes. Of the 23 pairs of human chromosomes, 22 are autosomes. An example of autosomal linkage is found in figure 10.9. The three genes listed in this figure are on the same chromosome. If the genes sit closely enough to each other, they are likely to be inherited together.

Sex Determination

Genes determine sexual characteristics in the same manner as other types of characteristics. In many organisms, special sex chromosomes carry sex-determining genes. Sex chromosomes are different between males and females of the same species. Autosomes carry the same genes in both sexes of a species. In humans, all other mammals, and some other organisms (e.g., fruit flies), the sex of an individual is determined by the presence of a certain chromosome combination. In mammals, the genes that determine maleness are located on a small chromosome known as the *Y chromosome*. The Y chromosome behaves as if it and another larger chromosome, known as the *X chromosome,* were homologous chromosomes. Males have one X and one Y chromosome. Females have two X chromosomes.

The sex of some animals is determined in a completely different way. In bees, for example, the females are diploid and the males are haploid. Other plants and animals have still other chromosomal mechanisms for determining their sex (Outlooks 10.2).

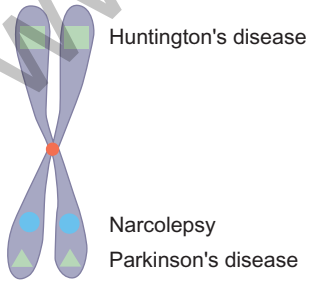


FIGURE 10.9 Chromosome
These are just three genes that are found on human chromosome number 4. Because all these genes are found on one chromosome or strand of DNA, they are considered to be members of one linkage group. Each chromosome represents a group of linked genes.

Sex Linkage

Sex linkage occurs when genes are located on the chromosomes that determine the sex of an individual. The Y chromosome is much shorter than the X chromosome and has fewer genes for traits than found on the X chromosome (figure 10.10). Therefore, the X chromosome has many genes for which there is no matching gene on the Y chromosome. Some genes appear on both the X chromosome and Y chromosome. Other genes, however, are found only on the X chromosome or only on the Y chromosome. Females have two copies of the genes that are found only on the X chromosomes. Because males have both a Y chromosome with few genes on it and the X chromosome, many of the recessive characteristics present on the X chromosome appear more frequently in males than in females, who have two X chromosomes. Unusual sex-linked inheritance patterns occur because certain genes are found on only one of the two sex chromosomes. Genes found only on the X chromosome are said to be **X-linked genes.** Genes found only on the Y chromosome are said to be **Y-linked genes.**

Female phenotypes can be affected by the dominant and recessive allele interactions that Mendel identified. Males present a different case. Males only have one copy of the genes that are found on the X chromosome, because they have only one X chromosome. This one allele determines the male's phenotype. Some X-linked genes can result in abnormal traits, such as *color deficiency, hemophilia, brown teeth,* and at least two forms of *muscular dystrophy* (Becker's and Duchenne's).

Use the following problem as an example of how to work with X-linked genes. Notice that the same basic format is followed as in previous genetics problems. The major difference is that chromosomes are represented in this problem. Here, an *X* represents the X chromosome and a *Y* represents the Y chromosome. Genes that are linked to the X chromosome are shown as superscripts. The *X* and its superscript should be treated as a single allele. You have used superscripts before in a genetics problem to look at incomplete dominance and codominance.

Problem Type: X-Linked

Cross 6: In humans, the allele for normal color vision is dominant and the allele for color deficiency is recessive. Both alleles are X-linked. People who cannot detect the difference between certain colors, such as between red and green, are described as having "color-defective vision." A male who has normal vision mates with a female who is heterozygous for normal color vision. What type of children can they have in terms of these traits, and what is the probability for each type?

Gene Key
Gene or Condition: color vision

Allele Symbols	Possible Genotypes	Phenotype
X^B = normal color vision	Females (X^BX^B or X^BX^b)	Female with normal color vision
X^b = color-deficient vision	Males (X^BY)	Male with normal color vision
Y = no gene for color vision	Females (X^bX^b)	Female with color-defective vision
	Males (X^bY)	Male with color-defective vision

Note that, in solving sex-linked problems, the general process is the same as that for other genetics problems (table 10.7). The only significant difference is that the alleles are listed as superscripts to the chromosomes, so that the gender and phenotypes can be determined in the last few steps of the problem.

10.7 CONCEPT REVIEW

21. What is a linkage group?
22. Provide examples of genes that are linked.

10.8 Other Influences on Phenotype

You might assume that the dominant allele is always expressed in a heterozygous individual; however, it is not that simple. As in other areas of biology, there are exceptions. For example, the allele for six fingers (*polydactylism*) is dominant over the allele for five fingers in humans. Some people who have received the allele for six fingers have a fairly complete sixth finger; in others, it may appear as a little stub. In some cases, this dominant characteristic is not expressed or perhaps shows on only one hand. Thus, there may be variation in the degree to which an allele expresses

OUTLOOKS 10.2

The Birds and the Bees . . . and the Alligators

The determination of sex depends on the kind of organism it is. For example, in humans, the physical features that result in maleness are triggered by a gene on the Y chromosome. The lack of a Y chromosome results in a female individual. In other organisms, sex is determined by other combinations of chromosomes or environmental factors.

Organism	Sex Determination
Mammals	Sex is chromosomally determined: XY individuals are male.
Birds	Sex is chromosomally determined: XY individuals are female. Rather than XY the letters WZ are used in birds.
Bees	Males (drones) are haploid and females (workers or queens) are diploid.
Certain species of alligators, turtles, and lizards	Egg incubation temperatures cause hormonal changes in the developing embryo; higher incubation temperatures cause the developing brain to shift sex in favor of the individual becoming a female.
Boat shell snails	Males can become females but will remain male if they mate and remain in one spot.
Shrimp, orchids, and some tropical fish	Males convert to females; on occasion, females convert to males, probably to maximize breeding.
African reed frog	Females convert to males, probably to maximize breeding.

TABLE 10.7 Solution Pathway

Steps in Information Flow	The Problem
Parental phenotypes	Father normal vision × Mother heterozygote for color vision
Parental genotypes	$X^BY \times X^BX^b$
Possible sex cells	X^B X^B Y X^b
Offspring genotype	X^B / X^B: X^BX^B; X^b: X^BX^b Y: X^BY; X^bY
Offspring phenotype	50% normal females (½ of these are carriers) 25% normal males 25% color-deficient males

itself *in an individual*. Geneticists refer to this as *variable expressivity*.

Both internal and external environmental factors can influence the expression of genes. A characteristic whose expression is influenced by internal gene-regulating mechanisms is that of male-pattern baldness (figure 10.11). In males with a genetic disposition to balding, the enzyme 5-alpha-reductase is produced in high levels. 5-alpha-reductase uses testosterone in males to produce dihydrotestosterone (DHT). DHT slows down blood supply to the hair follicle and causes baldness. In nonbalding males, 5-alpha-reductase is produced at lower levels, DHT is not produced, and baldness does not occur. The internal environment in females has lower levels of testosterone, so DHT is not produced at high levels even if the 5-alpha-reductase is expressed. Differences in the internal environment of males and females alter the phenotype. An example of external environmental factors that affect gene expression is sunlight. Genes for freckles do not show themselves fully unless a person's skin is exposed to sunlight (figure 10.12).

Diet is an external environmental factor that can influence the phenotype of an individual. *Diabetes mellitus*, a metabolic disorder in which glucose in the blood is not properly metabolized and is passed out of the body in the urine, has a genetic basis. Some people who have a family history of diabetes are thought to have inherited the trait for this disease. Evidence indicates that they can delay the onset of the disease by reducing the amount of sugar in their diet. This change in the external environment influences gene expression

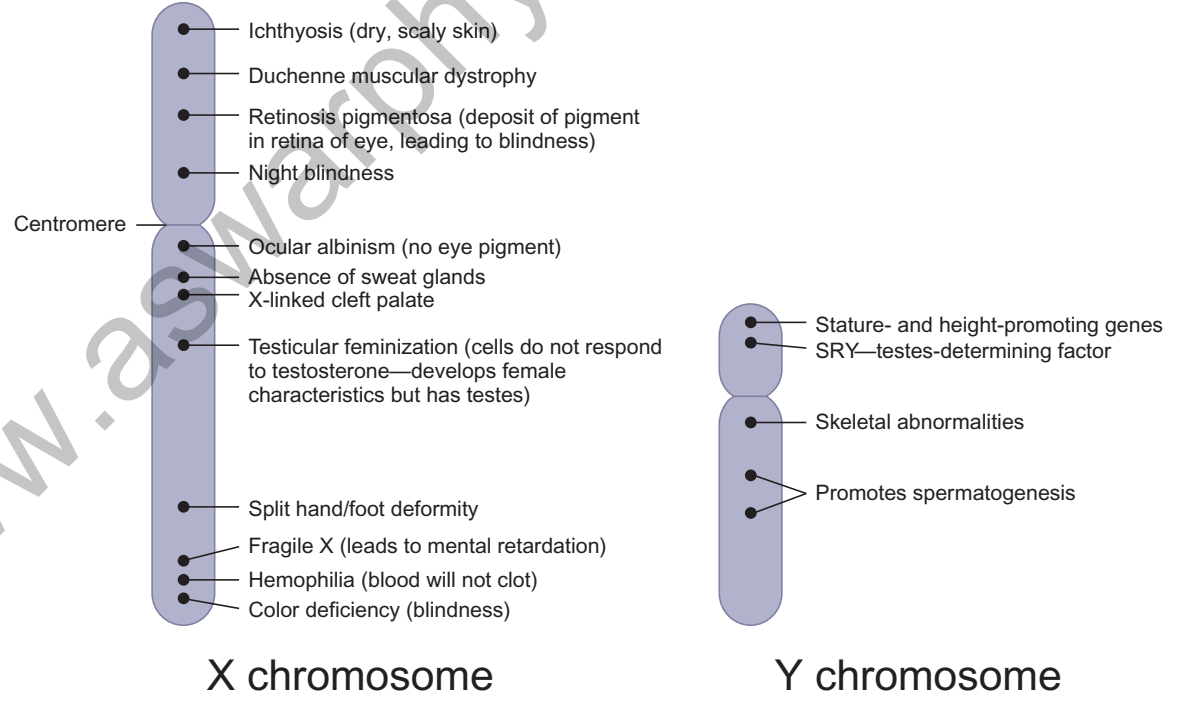


FIGURE 10.10 Sex Chromosomes
The human X chromosome contains over 1,400 genes and over 150 million base pairs, of which approximately 95% have been determined. The human Y chromosome contains about 200 genes and about 50 million base pairs, of which approximately 50% have been determined. A number of the genes linked on these chromosomes are listed.

FIGURE 10.11 Baldness and the Expression of Genes
It is a common misconception that males have genes for baldness and females do not. Male-pattern baldness is a sex-influenced trait, in which both males and females possess alleles coding for baldness. These genes are turned on by high levels of the hormone testosterone. This is an example of an internal gene-regulating mechanism.

in much the same way that sunlight affects the expression of freckles in humans. Similarly, diet is known to affect how the genes for intelligence, pigment production, and body height are expressed. Children who are deprived of protein during their growing years are likely to have reduced intelligence, lighter skin, and shorter overall height than children with adequate protein in their diet.

Whether a honeybee larva will become a worker or a queen is largely determined by its diet. Only larvae that are fed "royal jelly" mature into queen bees. Recent evidence indicates that royal jelly has the epigenetic effect of decreasing the expression of the gene that controls the transformation of larvae into workers.

10.8 CONCEPT REVIEW

23. What type of factor can cause a dominant allele to not be expressed?
24. Give two examples of environmentally influenced genetic traits.

FIGURE 10.12 The Environment and Gene Expression
The expression of many genes is influenced by the environment. The allele for dark hair in the cat is sensitive to temperature and expresses itself only in the parts of the body that stay cool. The allele for freckles expresses itself more fully when a person is exposed to sunlight.

Summary

Genes are units of heredity composed of specific lengths of DNA that determine the characteristics an organism displays. Specific genes are at specific loci on specific chromosomes. Mendel described the general patterns of inheritance in his Law of Dominance, his Law of Segregation, and his Law of Independent Assortment. Punnett squares help us predict graphically the results of a genetic cross. The phenotype displayed by an organism is determined by the alleles present and the ways the environment influences their expression. The alternative forms of genes for a characteristic are called alleles. There can be many different alleles for a particular characteristic. Diploid organisms have two alleles for each characteristic. Organisms with two identical alleles for a characteristic are homozygous; those with different alleles are heterozygous. Some alleles are dominant over other alleles, which are recessive. Sometimes, two alleles do not show dominance and recessiveness but, rather, both express themselves. Codominance and lack of dominance are examples. Often, a gene has more than one recognizable effect on the phenotype of the organism. This situation is called pleiotropy. Some characteristics are polygenic and are determined by several pairs of alleles acting together to determine one

recognizable characteristic. In humans and some other animals, males have an X chromosome with a normal number of genes and a Y chromosome with fewer genes. Although the X and Y chromosomes are not identical, they behave as a pair of homologous chromosomes. Because the Y chromosome is shorter than the X chromosome and has fewer genes, many of the recessive characteristics present on the X chromosome appear more frequently in males than in females, who have two X chromosomes. The degree of expression of many genetically determined characteristics is modified by the internal or external environment of the organism.

Key Terms

Use interactive flash cards, on the ***Concepts in Biology,*** *14/e website to help you learn the meaning of these terms.*

autosomes 219
codominance 213
dominant allele 203
double-factor cross 204
fertilization 204
genetic cross 204
genetics 202
genome 202
genotype 203
heterozygous 204
homozygous 204
incomplete dominance 214
Law of Dominance 208
Law of Independent Assortment 211
Law of Segregation 204
linkage 218
linkage group 219
Mendelian genetics 207
monohybrid cross 204
multiple alleles 215
offspring 202
phenotype 203
pleiotropy 217
polygenic inheritance 216
probability 205
Punnett square 204
recessive allele 203
sex chromosomes 219
sex linkage 219
single-factor cross 204
X-linked genes 219
Y-linked genes 219

Basic Review

1. Homologous chromosomes
   a. have the same genes in the same places.
   b. are identical.
   c. have the same alleles.
   d. All of the above are correct.
2. Phenotype is the combination of alleles that an organism has, whereas genotype is its appearance. (T/F)
3. A homozygous organism
   a. has the same alleles at a locus.
   b. has the same alleles at a gene.
   c. produces gametes that all carry the same allele.
   d. All of the above are correct.
4. Segregation happens during meiosis. (T/F)
5. The sex of an organism is determined by the number of chromosomes it possesses. (T/F)
6. Genes that are found only on the X chromosome in humans most consistently illustrate
   a. pleiotropy.
   b. the concept of diploid organisms.
   c. sex-linkage.
   d. All of the above are correct.
7. Double-factor crosses
   a. follow 2 alleles for 1 gene.
   b. follow the alleles for 2 genes.
   c. look at up to 4 alleles for 1 gene.
   d. None of the above are correct.
8. Mendelian principles apply when genes are found close to each other on the same chromosome. (T/F)
9. _____ occur when there are more than 2 alleles for a given gene.
10. Dominant alleles mask _____ alleles in heterozygous organisms.
11. The place where a gene is located on a chromosome is known as its _____.
12. The term _____ describes the multiple effects a gene has on a phenotype.
13. When a heterozygote appears to be a "blend" of the two parental phenotypes, the trait is considered to be exhibiting _____.
14. In the ABO system, A and B show _____ when they are together in an individual, but both alleles are dominant over the O allele.
15. What is the probability that parents heterozygous for a trait will have a homozygous offspring?

Answers
1. a 2. F 3. d 4. T 5. F 6. c 7. b 8. F 9. Multiple alleles 10. recessive 11. locus 12. pleiotropy 13. incomplete dominance 14. codominance 15. 50%

Thinking Critically

Nature vs. Nurture

The breeding of dogs, horses, cats, and many other domesticated animals is done with purposes in mind—that is, producing offspring that have specific body types, colors, behaviors, and athletic abilities. Cows are bred to produce more meat or milk. Many grain crops are bred to produce more grain per plant. Similarly, some people have the muscle development to be great baseball players, whereas others cannot hit the ball. Some have great mathematical skills, whereas others have a tough time adding 2 + 2. How do you think you have been genetically programmed? What are your strengths? As a parent or child, what frustrations have you experienced in teaching or learning? What are the difficulties in determining which of your traits are genetic and which are not?