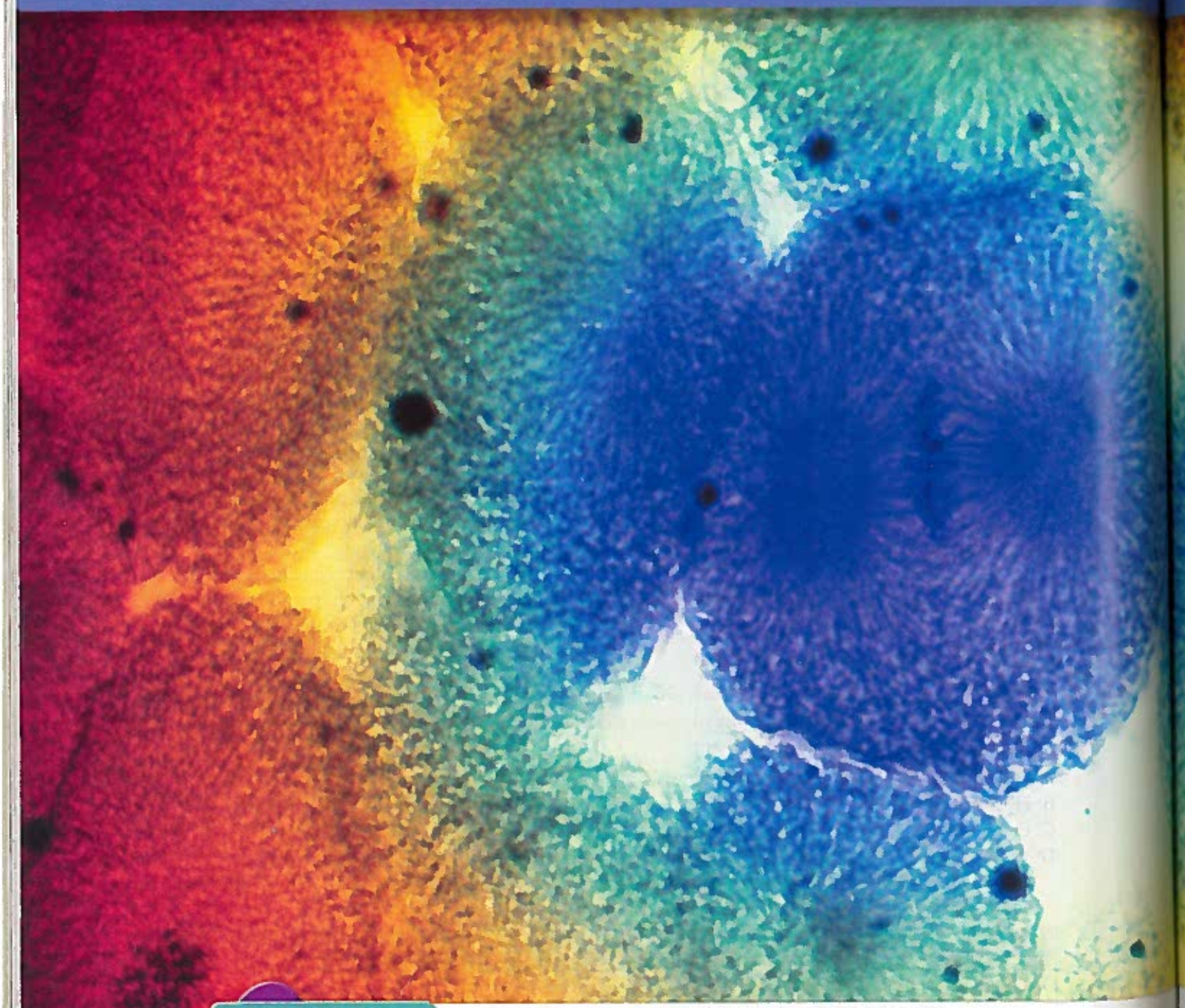
10 Cell Growth and Division

Big idea Growth, Development, and Reproduction

Q: How does a cell produce a new cell?



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10.1 Cell Growth, Division, and Reproduction

Key Questions

- ***What are some of the difficulties a cell faces as it increases in size?***
- ***How do asexual and sexual reproduction compare?***

Vocabulary

cell division
asexual reproduction
sexual reproduction

Taking Notes

Outline As you read, create an outline about cell growth, division, and reproduction. As you read, fill in key phrases or sentences about each heading.

THINK ABOUT IT When a living thing grows, what happens to its cells? Does an organism get larger because each cell increases in size or because it produces more of them? In most cases, living things grow by producing more cells. What is there about growth that requires cells to divide and produce more of themselves?

Limits to Cell Size

What are some of the difficulties a cell faces as it increases in size?

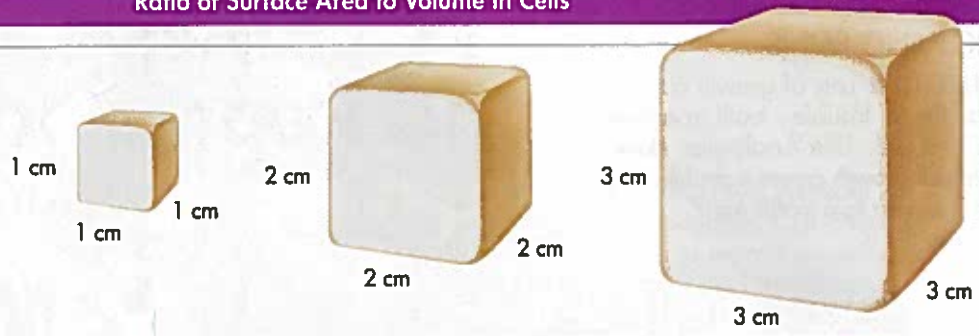
Nearly all cells can grow by increasing in size, but eventually, most cells divide after growing to a certain point. There are two main reasons why cells divide rather than continuing to grow. **The larger a cell becomes, the more demands the cell places on its DNA. In addition, a larger cell is less efficient in moving nutrients and waste materials across the cell membrane.**

Information "Overload" Living cells store critical information in a molecule known as DNA. As a cell grows, that information is used to build the molecules needed for cell growth. But as a cell increases in size, its DNA does not. If a cell were to grow too large, an "information crisis" would occur.

To get a better sense of information overload, compare a cell to a growing town. Suppose a small town has a library with a few thousand books. As more people move in, more people will borrow books. Sometimes, people may have to wait to borrow popular books. Similarly, a larger cell would make greater demands on its genetic "library." After a while, the DNA would no longer be able to serve the needs of the growing cell—it might be time to build a new library.

Exchanging Materials There is another critical reason why cell size is limited. Food, oxygen, and water enter a cell through its cell membrane. Waste products leave a cell in the same way. The rate at which this exchange takes place depends on the surface area of the cell, which is the total area of its cell membrane. The rate at which food and oxygen are used up and waste products are produced depends on the cell's volume. Understanding the relationship between a cell's surface area and its volume is the key to understanding why cells must divide rather than continue to grow.

Ratio of Surface Area to Volume in Cells

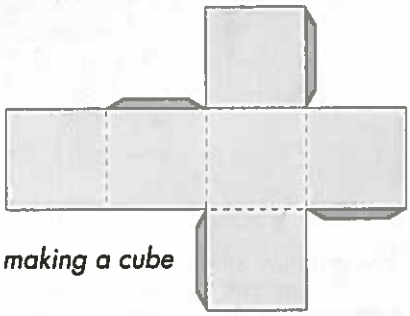


Surface Area (length × width) × 6 sides	1 cm × 1 cm × 6 = 6 cm^2	2 cm × 2 cm × 6 = 24 cm^2	3 cm × 3 cm × 6 = 54 cm^2
Volume (length × width × height)	1 cm × 1 cm × 1 cm = 1 cm^3	2 cm × 2 cm × 2 cm = 8 cm^3	3 cm × 3 cm × 3 cm = 27 cm^3
Ratio of Surface Area to Volume	6 / 1 = 6 : 1	24 / 8 = 3 : 1	54 / 27 = 2 : 1

FIGURE 10–1 Ratio of Surface Area to Volume As the length of the sides increases, the volume increases more than the surface area. **Interpret Tables** ***What are the ratios comparing?***

▶ ***Ratio of Surface Area to Volume*** Imagine a cell that is shaped like a cube, like those shown in **Figure 10–1.** The formula for area ($l \times w$) is used to calculate the surface area. The formula for volume ($l \times w \times h$) is used to calculate the amount of space inside. By using a ratio of surface area to volume, you can see how the size of the cell's surface area grows compared to its volume.

Notice that for a cell with sides that measure 1 cm in length, the ratio of surface area to volume is 6/1 or 6 : 1. Increase the length of the cell's sides to 2 cm, and the ratio becomes 24/8 or 3 : 1. What if the length triples? The ratio of surface area to volume becomes 54/27 or 2 : 1. Notice that the surface area is not increasing as fast as the volume increases. For a growing cell, a decrease in the relative amount of cell membrane available creates serious problems.



making a cube

Quick Lab
OPEN-ENDED INQUIRY

Modeling the Relationship Between Surface Area and Volume

❶ Use drawing or grid paper to make patterns for a 6-cm cube, a 5-cm cube, a 4-cm cube, and a 3-cm cube.

❷ Cut out your patterns and fold them. Then use the tabs to tape or glue the sides together. Don't tape down the top side.

❸ Construct a data table to compare the volume, the surface area, and the ratio of surface area to volume of each cube.

❹ Use your data to calculate the number of 3-cm cubes that would fit in the same volume as the 6-cm cube. Also calculate the total surface area for the smaller cubes. MATH

Analyze and Conclude

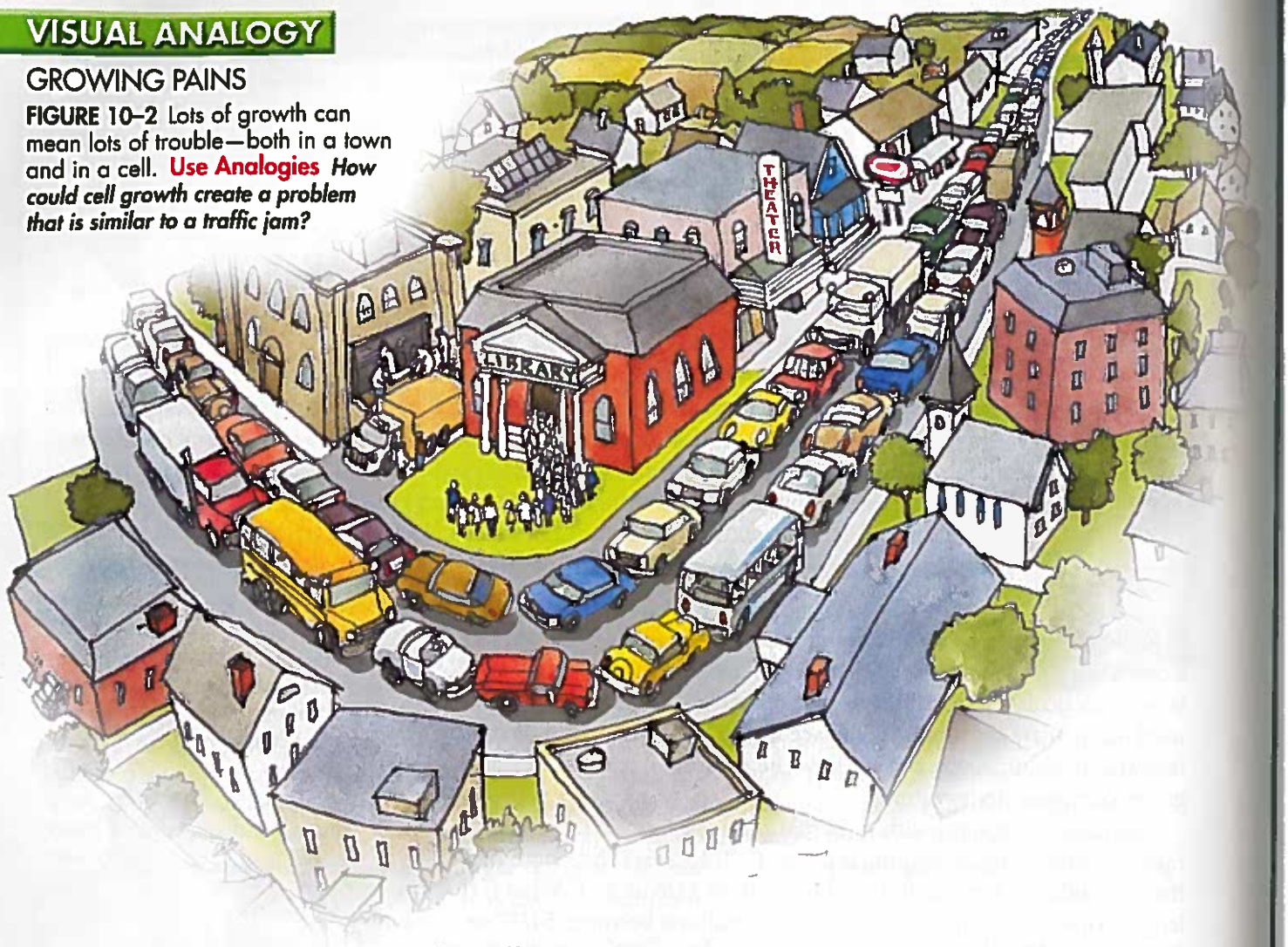
1. Review Describe the function of a cell membrane and its relationship to what happens inside a cell?

2. Apply Concepts How does the surface area change when a large cell divides into smaller cells that have the same total volume?

VISUAL ANALOGY

GROWING PAINS

FIGURE 10–2 Lots of growth can mean lots of trouble—both in a town and in a cell. **Use Analogies** *How could cell growth create a problem that is similar to a traffic jam?*



▶ ***Traffic Problems*** To use the town analogy again, suppose the town has just a two-lane main street leading to the center of town. As the town grows, more and more traffic clogs the main street. It becomes increasingly difficult to move goods in and out.

A cell that continues to grow would experience similar problems. If a cell got too large, it would be more difficult to get sufficient amounts of oxygen and nutrients in and waste products out. This is another reason why cells do not continue to grow larger even if the organism does.

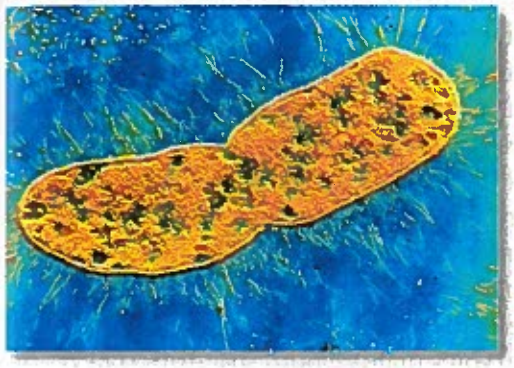
Division of the Cell Before it becomes too large, a growing cell divides, forming two "daughter" cells. The process by which a cell divides into two new daughter cells is called **cell division.**

Before cell division occurs, the cell replicates, or copies all of its DNA. This replication of DNA solves the problem of information overload because each daughter cell gets one complete copy of genetic information. Cell division also solves the problem of increasing size by reducing cell volume. Cell division results in an increase in the ratio of surface area to volume for each daughter cell. This allows for the efficient exchange of materials within a cell.

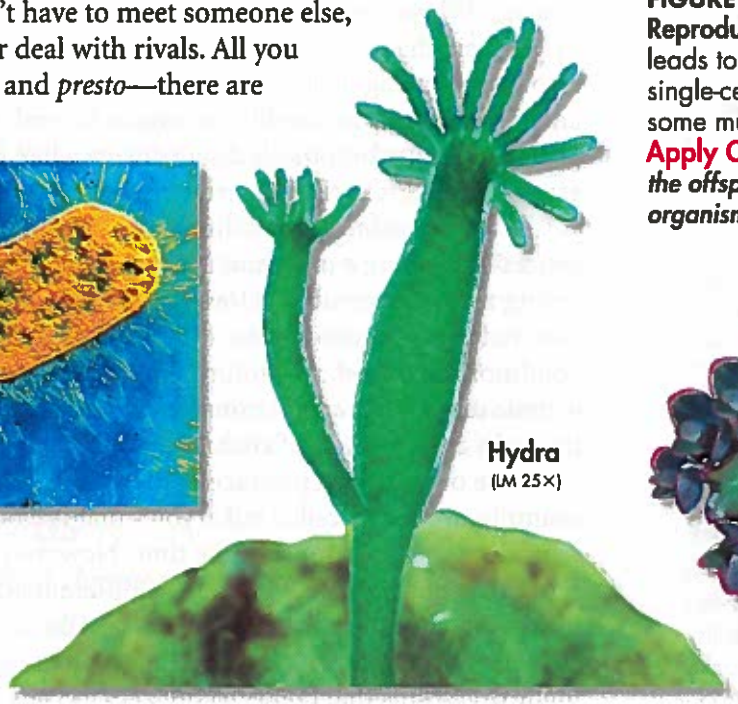
Cell Division and Reproduction

How do asexual and sexual reproduction compare?

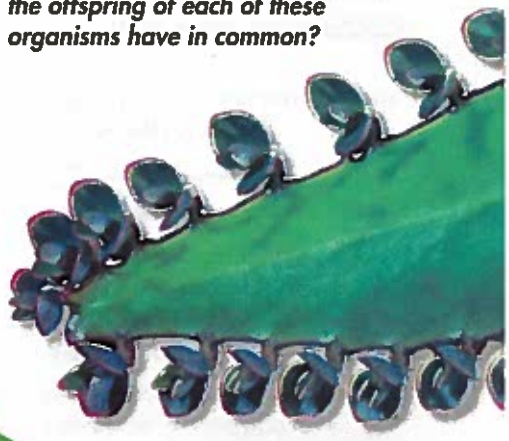
Reproduction, the formation of new individuals, is one of the most important characteristics of living things. For an organism composed of just one cell, cell division can serve as a perfectly good form of reproduction. You don't have to meet someone else, conduct a courtship, or deal with rivals. All you have to do is to divide, and *presto*—there are two of you!



Bacterium
(TEM 32,800×)



Hydra
(LM 25×)



Kalanchoe

FIGURE 10–3 Asexual Reproduction Cell division leads to reproduction in single-celled organisms and some multicellular organisms. **Apply Concepts** ***What do the offspring of each of these organisms have in common?***

Asexual Reproduction For many single-celled organisms, such as the bacterium in **Figure 10–3,** cell division is the only form of reproduction. The process can be relatively simple, efficient, and effective, enabling populations to increase in number very quickly. In most cases, the two cells produced by cell division are genetically identical to the cell that produced them. This kind of reproduction is called **asexual reproduction.** **The production of genetically identical offspring from a single parent is known as asexual reproduction.**

Asexual reproduction also occurs in many multicellular organisms. The small bud growing off the hydra will eventually break off and become an independent organism, an example of asexual reproduction in an animal. Each of the small shoots or plantlets on the tip of the kalanchoe leaf may also grow into a new plant.

Sexual Reproduction Unlike asexual reproduction, where cells separate to form a new individual, **sexual reproduction** involves the fusion of two cells. In sexual reproduction, offspring are produced by the fusion of special reproductive cells formed by each of two parents. **Offspring produced by sexual reproduction inherit some of their genetic information from each parent.** Most animals and plants reproduce sexually, and so do many single-celled organisms. You will learn more about the form of cell division that produces reproductive cells in Chapter 11.

In Your Notebook *Use a Venn diagram to compare asexual and sexual reproduction.*

BUILD Vocabulary

PREFIXES The prefix *a-* in *asexual* means "without." **Asexual reproduction** is reproduction without the fusion of reproductive cells.

MYSTERY CLUE

As its wound heals, the salamander's body cells are dividing to repair the damage. In what way is this type of cell division similar to asexual reproduction?

Comparing Asexual and Sexual Reproduction You can see that each type of reproduction has its advantages and disadvantages when you look at each one as a strategy for survival. Species survive by reproducing. The better suited a species is to its environment, the greater its chance of survival.

For single-celled organisms, asexual reproduction is a survival strategy. When conditions are right, the faster they reproduce, the better their chance of survival over other organisms using the same resources. Having offspring that are genetically identical is also an advantage as long as conditions remain favorable. However, a lack of genetic diversity becomes a disadvantage when conditions change in ways that do not fit the characteristics of an organism.

Sexual reproduction is a different type of survival strategy. The process of finding a mate and the growth and development of offspring require more time. However, this can be an advantage for species that live in environments where seasonal changes affect weather conditions and food availability. Sexual reproduction also provides genetic diversity. If an environment changes, some offspring may have the right combination of characteristics needed to survive.

Some organisms reproduce both sexually and asexually. Yeasts, for example, are single-celled eukaryotes that use both strategies. They reproduce asexually most of the time. However, under certain conditions, they enter a sexual phase. The different advantages of each type of reproduction may help to explain why the living world includes organisms that reproduce sexually, those that reproduce asexually, and many organisms that do both.

10.1 Assessment

Review Key Concepts

1. a. Review Identify two reasons why a cell's growth is limited.

b. Explain As a cell's size increases, what happens to the ratio of its surface area to its volume?

c. Applying Concepts Why is a cell's surface area-to-volume ratio important?

2. a. Review What is asexual reproduction? What is sexual reproduction?

b. Explain What types of organisms reproduce sexually?

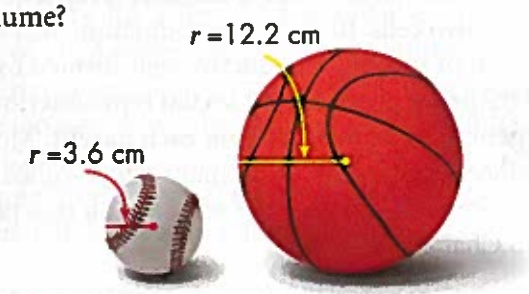
c. Summarize What are the advantages and disadvantages of both asexual and sexual reproduction?

VISUAL THINKING MATH

3. The formula for finding the surface area of a sphere, such as a baseball or a basketball, is $A = 4\pi r^2$, where r is the radius. The formula for finding the volume of a sphere is $V = 4/3\pi r^3$.

a. Calculate Calculate the surface area and the volume of the baseball and the basketball. Then, write the ratio of surface area to volume for each sphere.

b. Infer If the baseball and basketball were cells, which would possess a larger ratio of area of cell membrane to cell volume?



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10.2 The Process of Cell Division

THINK ABOUT IT What role does cell division play in your life? You know from your own experience that living things grow, or increase in size, during particular stages of life or even throughout their lifetime. This growth clearly depends on the production of new cells through cell division. But what happens when you are finished growing? Does cell division simply stop? Think about what must happen when your body heals a cut or a broken bone. And finally, think about the everyday wear and tear on the cells of your skin, digestive system, and blood. Cell division has a role to play there, too.

Chromosomes

What is the role of chromosomes in cell division?

What do you think would happen if a cell were simply to split in two, without any advance preparation? The results might be disastrous, especially if some of the cell's essential genetic information wound up in one of the daughter cells, and not in the other. In order to make sure this doesn't happen, cells first make a complete copy of their genetic information before cell division begins.

Even a small cell like the bacterium *E. coli* has a tremendous amount of genetic information in the form of DNA. In fact, the total length of this bacterium's DNA molecule is 1.6 mm, roughly 1000 times longer than the cell itself. In terms of scale, imagine a 300-meter rope stuffed into a school backpack. Cells can handle such large molecules only by careful packaging. Genetic information is bundled into packages of DNA known as **chromosomes.**

Prokaryotic Chromosomes Prokaryotes lack nuclei and many of the organelles found in eukaryotes. Their DNA molecules are found in the cytoplasm along with most of the other contents of the cell. Most prokaryotes contain a single, circular DNA chromosome that contains all, or nearly all, of the cell's genetic information.

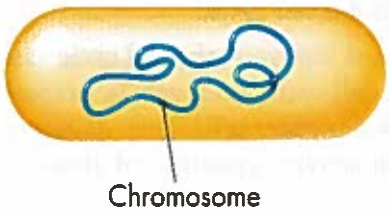


FIGURE 10–4 Prokaryotic Chromosome In most prokaryotes, a single chromosome holds most of the organism's DNA.

Key Questions

- ***What is the role of chromosomes in cell division?***
- ***What are the main events of the cell cycle?***
- ***What events occur during each of the four phases of mitosis?***
- ***How do daughter cells split apart after mitosis?***

Vocabulary

chromosome • chromatin • cell cycle • interphase • mitosis • cytokinesis • prophase • centromere • chromatid • centriole • metaphase • anaphase • telophase

Taking Notes

Two-Column Chart As you read, create a two-column chart. In the left column, make notes about what is happening in each stage of the cell cycle. In the right column, describe what the process looks like or draw pictures.

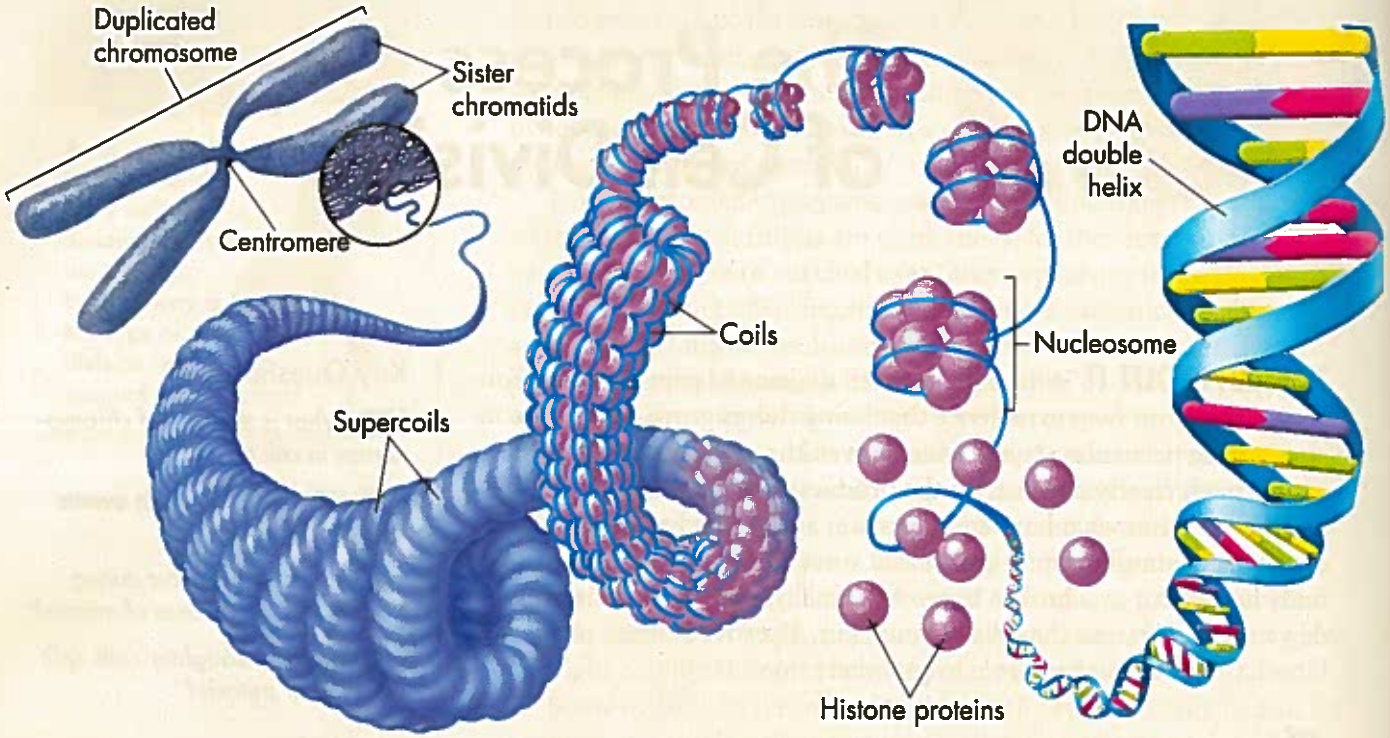


FIGURE 10–5 Eukaryotic Chromosome As a eukaryotic cell prepares for division, each chromosome coils more and more tightly to form a compact structure. **Interpret Visuals** ***Which side of the diagram, left or right, shows the smallest structures, and which shows the largest?***

Eukaryotic Chromosomes Eukaryotic cells generally have much more DNA than prokaryotes have and, therefore, contain multiple chromosomes. Fruit flies, for example, have 8 chromosomes per cell, human cells have 46, and carrot cells have 18. Eukaryotic chromosomes contain both DNA and protein, tightly associated to form a substance called **chromatin.** Chromatin consists of DNA tightly coiled around special proteins known as histones. Together, the DNA and histone molecules form beadlike structures called nucleosomes. Nucleosomes pack together to form thick fibers, which condense even further during cell division.

Why do cells go to such lengths to package their DNA into chromosomes? One of the principal reasons is to ensure equal division of DNA when a cell divides. **Chromosomes make it possible to separate DNA precisely during cell division.**

In Your Notebook *Write instructions to build a eukaryotic chromosome.*

The Cell Cycle

What are the main events of the cell cycle?

All cells go through a series of events known as the **cell cycle** as they grow and divide. **During the cell cycle, a cell grows, prepares for division, and divides to form two daughter cells.** Each daughter cell then moves into a new cell cycle of activity, growth, and division.

The Prokaryotic Cell Cycle The prokaryotic cell cycle is a regular pattern of growth, DNA replication, and cell division that can take place very rapidly under ideal conditions. Researchers are only just beginning to understand how the cycle works in prokaryotes, and relatively little is known about its details. It is known that most prokaryotic cells begin to replicate, or copy, their DNA chromosomes once they have grown to a certain size. When DNA replication is complete, or nearly complete, the cell begins to divide.

The process of cell division in prokaryotes is a form of asexual reproduction known as binary fission. Once the chromosome has been replicated, the two DNA molecules attach to different regions of the cell membrane. A network of fibers forms between them, stretching from one side of the cell to the other. The fibers constrict and the cell is pinched inward, dividing the cytoplasm and chromosomes between two newly formed cells. Binary fission results in the production of two genetically identical cells.

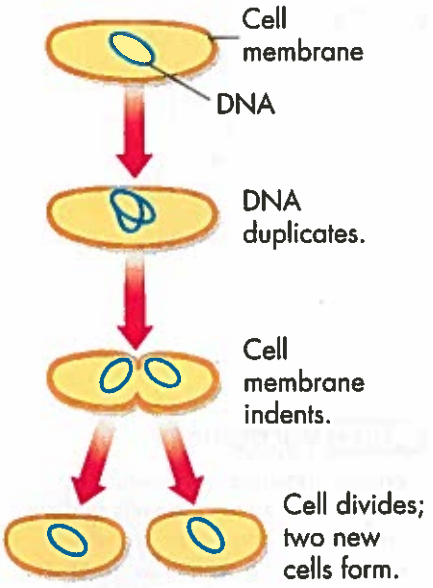


FIGURE 10–6 Binary Fission Cell division in a single-celled organism produces two genetically identical organisms.

The Eukaryotic Cell Cycle In contrast to prokaryotes, much more is known about the eukaryotic cell cycle. As you can see in **Figure 10–7,** the eukaryotic cell cycle consists of four phases: G_1, S, G_2, and M. The length of each part of the cell cycle—and the length of the entire cell cycle—varies depending on the type of cell.

At one time, biologists described the life of a cell as one cell division after another separated by an "in-between" period of growth called **interphase.** We now appreciate that a great deal happens in the time between cell divisions. Interphase is divided into three parts: G_1, S, and G_2.

▶ ***G_1 Phase: Cell Growth*** Cells do most of their growing during the G_1 phase. In this phase, cells increase in size and synthesize new proteins and organelles. The *G* in G_1 and G_2 stands for "gap," but the G_1 and G_2 phases are actually periods of intense growth and activity.

▶ ***S Phase: DNA Replication*** The G_1 phase is followed by the S phase. The *S* stands for "synthesis." During the S phase, new DNA is synthesized when the chromosomes are replicated. The cell at the end of the S phase contains twice as much DNA as it did at the beginning.

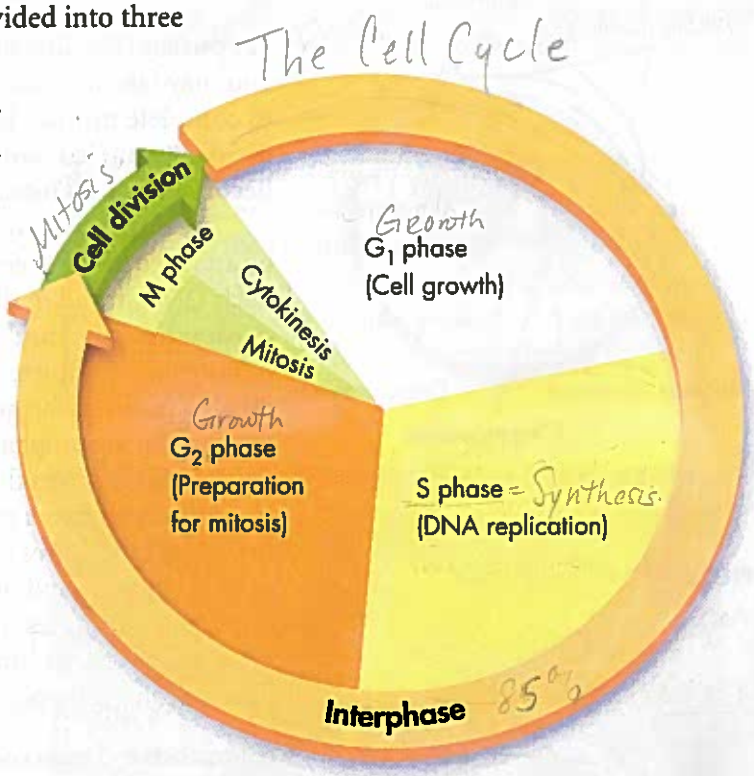


FIGURE 10–7 The Cell Cycle During the cell cycle, a cell grows, prepares for division, and divides to form two daughter cells. The cell cycle includes four phases—G_1, S, G_2, and M. **Infer** ***During which phase or phases would you expect the DNA content of the cell to change?***

▶ ***G_2 Phase: Preparing for Cell Division*** When DNA replication is completed, the cell enters the G_2 phase. G_2 is usually the shortest of the three phases of interphase. During the G_2 phase, many of the organelles and molecules required for cell division are produced. When the events of the G_2 phase are completed, the cell is ready to enter the M phase and begin the process of cell division.

▶ ***M Phase: Cell Division*** The M phase of the cell cycle, which follows interphase, produces two daughter cells. The M phase takes its name from the process of mitosis. During the normal cell cycle, interphase can be quite long. In contrast, the process of cell division usually takes place quickly.

In eukaryotes, cell division occurs in two main stages. The first stage of the process, division of the cell nucleus, is called **mitosis** (my TOH sis). The second stage, the division of the cytoplasm, is called **cytokinesis** (sy toh kih NEE sis). In many cells, the two stages may overlap, so that cytokinesis begins while mitosis is still taking place.

BUILD Vocabulary

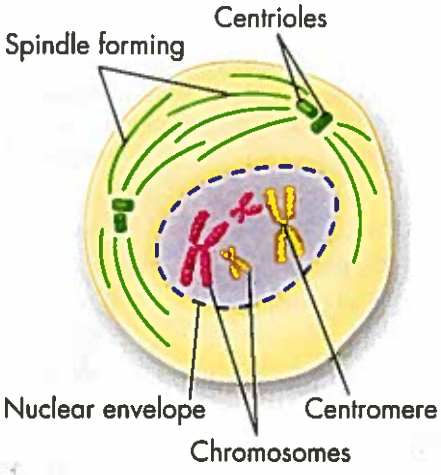
WORD ORIGINS The prefix *cyto-* in **cytokinesis** refers to cells and derives from the Greek word *kytos*, meaning "a hollow vessel." *Cytoplasm* is another word that has the same root.

Mitosis

What events occur during each of the four phases of mitosis?

Biologists divide the events of mitosis into four phases: prophase, metaphase, anaphase, and telophase. Depending on the type of cell, mitosis may last anywhere from a few minutes to several days. **Figure 10–8** through **Figure 10–11** show mitosis in an animal cell.

FIGURE 10–8 Prophase

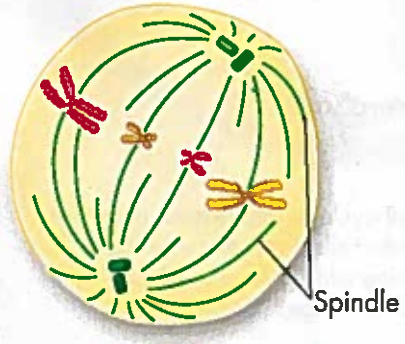


Prophase The first phase of mitosis, **prophase,** is usually the longest and may take as much as 50 to 60 percent of the total time required to complete mitosis. **During prophase, the genetic material inside the nucleus condenses and the duplicated chromosomes become visible. Outside the nucleus, a spindle starts to form.**

The duplicated strands of the DNA molecule can be seen to be attached along their length at an area called the **centromere.** Each DNA strand in the duplicated chromosome is referred to as a **chromatid** (KROH muh tid), or sister chromatid. When the process of mitosis is complete, the chromatids will have separated and been divided between the new daughter cells.

Also during prophase, the cell starts to build a spindle, a fanlike system of microtubules that will help to separate the duplicated chromosomes. Spindle fibers extend from a region called the centrosome, where tiny paired structures called **centrioles** are located. Centrioles, as you may recall, are found only in animal cells. The centrioles, which were duplicated during interphase, start to move toward opposite ends, or poles, of the cell. As prophase ends, the chromosomes coil more tightly, the nucleolus disappears, and the nuclear envelope breaks down.

FIGURE 10–9 Metaphase



Metaphase The second phase of mitosis, **metaphase,** often lasts only a few minutes. **During metaphase, the centromeres of the duplicated chromosomes line up across the center of the cell. Spindle fibers connect the centromere of each chromosome to the two poles of the spindle.**

Anaphase The third phase of mitosis, **anaphase,** begins when sister chromatids suddenly separate and begin to move apart. Once anaphase begins, each sister chromatid is now considered an individual chromosome. **During anaphase, the chromosomes separate and move along spindle fibers to opposite ends of the cell.** Anaphase comes to an end when this movement stops and the chromosomes are completely separated into two groups.

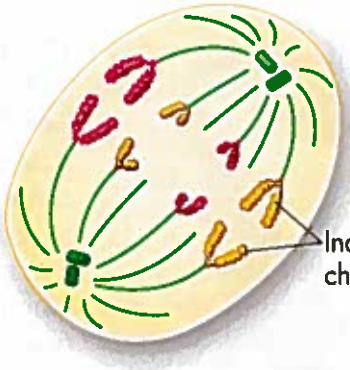


FIGURE 10–10
Anaphase

Telophase Following anaphase is **telophase,** the fourth and final phase of mitosis. **During telophase, the chromosomes, which were distinct and condensed, begin to spread out into a tangle of chromatin.** A nuclear envelope re-forms around each cluster of chromosomes. The spindle begins to break apart, and a nucleolus becomes visible in each daughter nucleus. Mitosis is complete. However, the process of cell division is not yet complete.

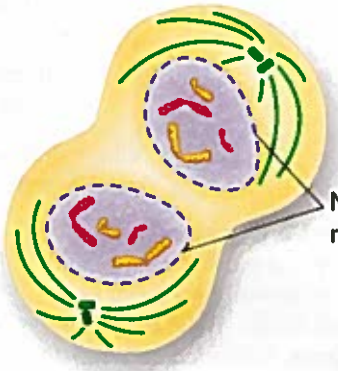


FIGURE 10–11
Telophase

In Your Notebook *Create a chart that lists the important information about each phase of mitosis.*

Quick Lab
GUIDED INQUIRY

Mitosis in Action

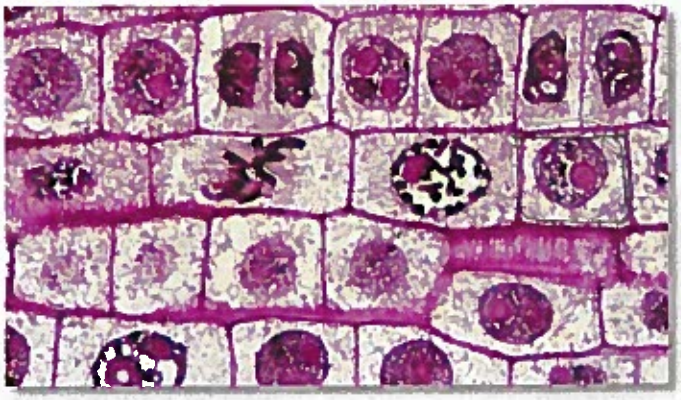
1. Examine a slide of a stained onion root tip under a microscope. Viewing the slide under low power, adjust the stage until you find the boxlike cells just above the root tip.
2. Switch the microscope to high power and locate cells that are in the process of dividing.
3. Find and sketch cells that are in each phase of mitosis. Label each sketch with the name of the appropriate phase.

Analyze and Conclude

1. Observe In which phase of the cell cycle were most of the cells you observed? Why do you think this is?

2. Draw Conclusions What evidence did you observe that shows mitosis is a continuous process, not a series of separate events?

3. Apply Concepts Cells in the root divide many times as the root grows longer and thicker. With each cell division, the chromosomes are divided between two daughter cells, yet the number of chromosomes in each cell does not change. What processes ensure that the normal number of chromosomes is restored after each cell division?



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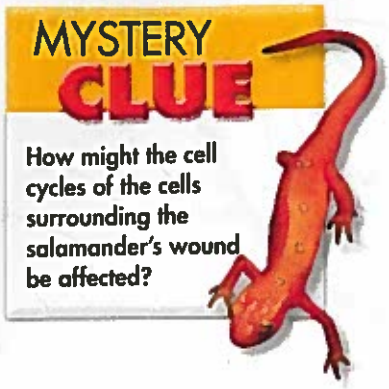

Cytokinesis

How do daughter cells split apart after mitosis?

As a result of mitosis, two nuclei—each with a duplicate set of chromosomes—are formed. All that remains to complete the M phase of the cycle is cytokinesis, the division of the cytoplasm itself. Cytokinesis usually occurs at the same time as telophase. **Cytokinesis completes the process of cell division—it splits one cell into two.** The process of cytokinesis differs in animal and plant cells.

Cytokinesis in Animal Cells During cytokinesis in most animal cells, the cell membrane is drawn inward until the cytoplasm is pinched into two nearly equal parts. Each part contains its own nucleus and cytoplasmic organelles.

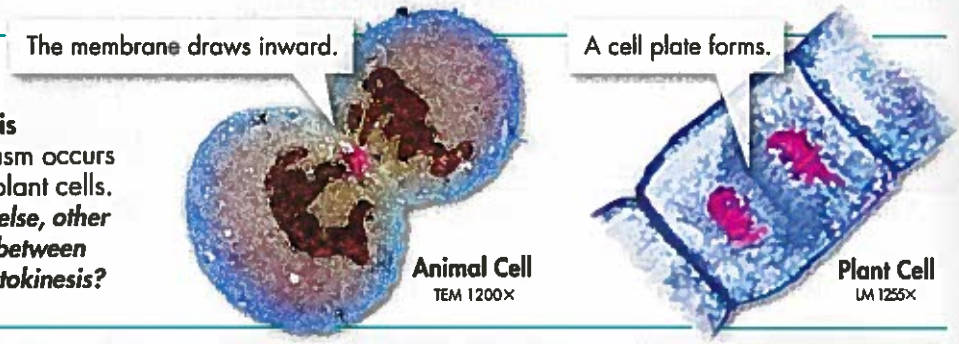

FIGURE 10–12 Cytokinesis
The division of the cytoplasm occurs differently in animal and plant cells.
Draw Conclusions ***What else, other than cytoplasm, is divided between the two new cells during cytokinesis?***

Cytokinesis in Plant Cells Cytokinesis in plant cells proceeds differently. The cell membrane is not flexible enough to draw inward because of the rigid cell wall that surrounds it. Instead, a structure known as the cell plate forms halfway between the divided nuclei. The cell plate gradually develops into cell membranes that separate the two daughter cells. A cell wall then forms in between the two new membranes, completing the process.

10.2 Assessment

Review Key Concepts

1. a. Review What are chromosomes?

b. Compare and Contrast How does the structure of chromosomes differ in prokaryotes and eukaryotes?

2. a. Review What is the cell cycle?

b. Sequence During which phase of the cell cycle are chromosomes replicated?

3. a. Review What happens during each of the four phases of mitosis? Write one or two sentences for each phase.

b. Predict What do you predict would happen if the spindle fibers were disrupted during metaphase?

4. a. Review What is cytokinesis and when does it occur?

b. Compare and Contrast How does cytokinesis differ in animal and plant cells?

WRITE ABOUT SCIENCE

Summary

5. Summarize what happens during interphase. Be sure to include all three parts of interphase. *Hint:* Include all of the main details in your summary.

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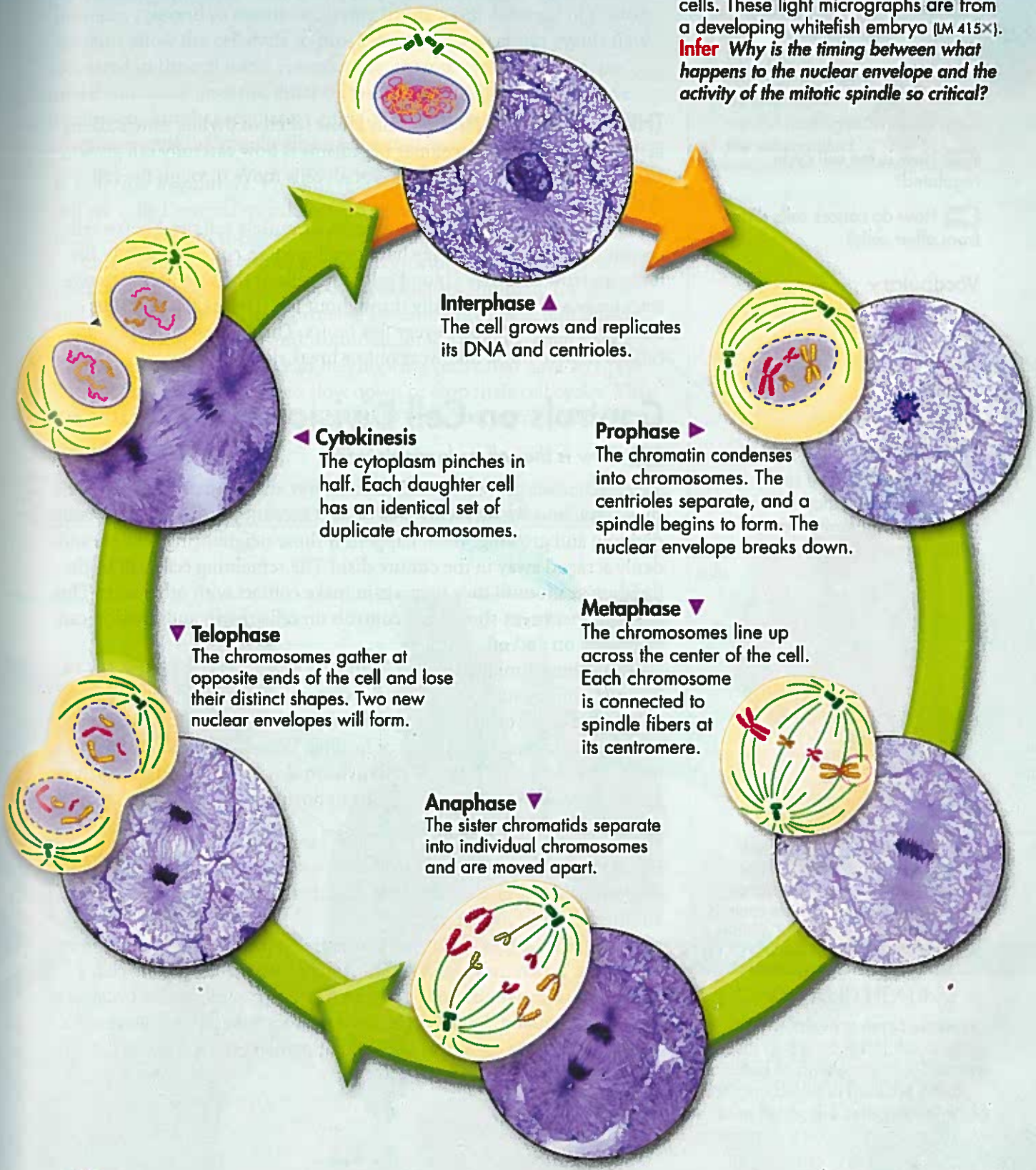
VISUAL SUMMARY

MITOSIS

FIGURE 10–13 The phases of mitosis shown here are typical of eukaryotic cells. These light micrographs are from a developing whitefish embryo (LM 415×).
Infer ***Why is the timing between what happens to the nuclear envelope and the activity of the mitotic spindle so critical?***



Interphase ▲
The cell grows and replicates its DNA and centrioles.

Prophase ►
The chromatin condenses into chromosomes. The centrioles separate, and a spindle begins to form. The nuclear envelope breaks down.

Metaphase ▼
The chromosomes line up across the center of the cell. Each chromosome is connected to spindle fibers at its centromere.

Anaphase ▼
The sister chromatids separate into individual chromosomes and are moved apart.

▼ Telophase
The chromosomes gather at opposite ends of the cell and lose their distinct shapes. Two new nuclear envelopes will form.

◄ Cytokinesis
The cytoplasm pinches in half. Each daughter cell has an identical set of duplicate chromosomes.

10.3 Regulating the Cell Cycle

Key Questions

- How is the cell cycle regulated?
- How do cancer cells differ from other cells?

Vocabulary

cyclin
growth factor
apoptosis
cancer
tumor

Taking Notes

Concept Map As you read, create a concept map to organize the information in this lesson.

THINK ABOUT IT How do cells know when to divide? One striking fact about cells in multicellular organisms is how carefully cell growth and cell division are controlled. Not all cells move through the cell cycle at the same rate.

In the human body, for example, most muscle cells and nerve cells do not divide at all once they have developed. In contrast, cells in the bone marrow that make blood cells and cells of the skin and digestive tract grow and divide rapidly throughout life. These cells may pass through a complete cycle every few hours. This process provides new cells to replace those that wear out or break down.

Controls on Cell Division

How is the cell cycle regulated?

When scientists grow cells in the laboratory, most cells will divide until they come into contact with each other. Once they do, they usually stop dividing and growing. What happens if those neighboring cells are suddenly scraped away in the culture dish? The remaining cells will begin dividing again until they once again make contact with other cells. This simple experiment shows that controls on cell growth and division can be turned on and off.

Something similar happens inside the body. Look at **Figure 10–14.** When an injury such as a cut in the skin or a break in a bone occurs, cells at the edges of the injury are stimulated to divide rapidly. New cells form, starting the process of healing. When the healing process nears completion, the rate of cell division slows, controls on growth are restored, and everything returns to normal.

BUILD Vocabulary

ACADEMIC WORDS The verb **regulate** means "to control or direct." Therefore, a substance that regulates the cell cycle controls when the cell grows and divides.

The Discovery of Cyclins

For many years, biologists searched for a signal that might regulate the cell cycle—something that would "tell" cells when it was time to divide, duplicate their chromosomes, or enter another phase of the cell cycle.

In the early 1980s, biologists discovered a protein in cells that were in mitosis. When they injected the protein into a nondividing cell, a mitotic spindle would form. They named this protein **cyclin** because it seemed to regulate the cell cycle. Investigators have since discovered a family of proteins known as cyclins that regulate the timing of the cell cycle in eukaryotic cells.

Regulatory Proteins The discovery of cyclins was just the start. Scientists have since identified dozens of other proteins that also help to regulate the cell cycle. **The cell cycle is controlled by regulatory proteins both inside and outside the cell.**

▶ ***Internal Regulators*** One group of proteins, internal regulatory proteins, respond to events occurring inside a cell. Internal regulatory proteins allow the cell cycle to proceed only when certain events have occurred in the cell itself. For example, several regulatory proteins make sure a cell does not enter mitosis until its chromosomes have replicated. Another regulatory protein prevents a cell from entering anaphase until the spindle fibers have attached to the chromosomes.

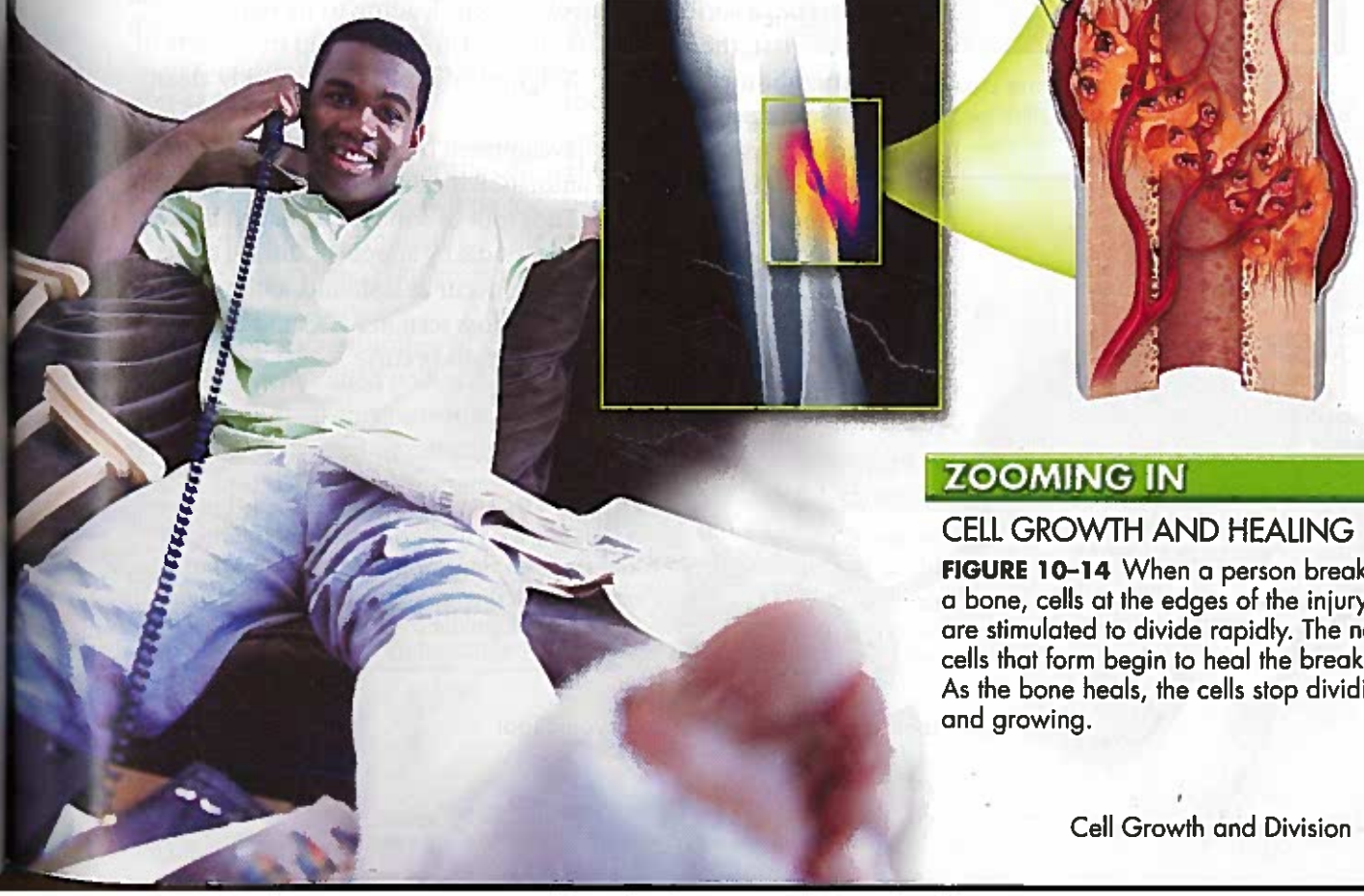
▶ ***External Regulators*** Proteins that respond to events outside the cell are called external regulatory proteins. External regulatory proteins direct cells to speed up or slow down the cell cycle.

One important group of external regulatory proteins is the group made up of the growth factors. **Growth factors** stimulate the growth and division of cells. These proteins are especially important during embryonic development and wound healing. Other external regulatory proteins on the surface of neighboring cells often have an opposite effect. They cause cells to slow down or stop their cell cycles. This prevents excessive cell growth and keeps body tissues from disrupting one another.

In Your Notebook *Use a cause-and-effect diagram to describe how internal and external regulators work together to control the cell cycle.*

MYSTERY CLUE

How might regulatory proteins be involved in wound healing in the salamander?



ZOOMING IN

CELL GROWTH AND HEALING

FIGURE 10–14 When a person breaks a bone, cells at the edges of the injury are stimulated to divide rapidly. The new cells that form begin to heal the break. As the bone heals, the cells stop dividing and growing.

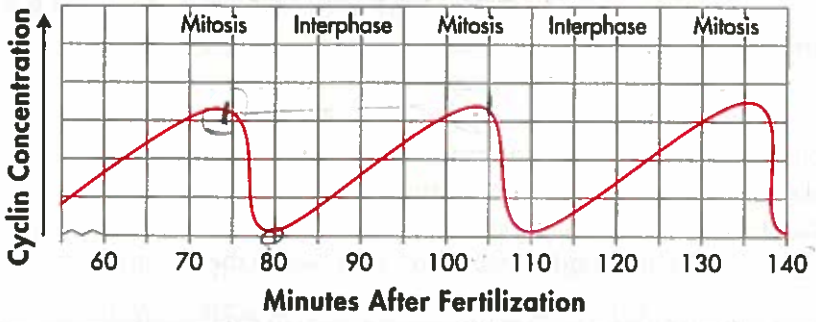
Analyzing Data

The Rise and Fall of Cyclins

Scientists measured cyclin levels in clam egg cells as the cells went through their first mitotic divisions after fertilization. The data are shown in the graph.

Cyclins are continually produced and destroyed within cells. Cyclin production signals cells to enter mitosis, while cyclin destruction signals cells to stop dividing and enter interphase.

Cyclin Levels in Fertilized Clam Eggs



1. Interpret Graphs How long does cyclin production last during a typical cell cycle in fertilized clam eggs?

2. Infer During which part of the cell cycle does cyclin production begin? How quickly is cyclin destroyed?

3. Predict Suppose that the regulators that control cyclin production are no longer produced. What are two possible outcomes?

Apoptosis Just as new cells are produced every day in a multicellular organism, many other cells die. Cells end their life cycle in one of two ways. A cell may die by accident due to damage or injury, or a cell may actually be "programmed" to die. **Apoptosis** (AYP up TOH sis) is a process of programmed cell death. Once apoptosis is triggered, a cell undergoes a series of controlled steps leading to its self-destruction. First, the cell and its chromatin shrink, and then parts of the cell's membranes break off. Neighboring cells then quickly clean up the cell's remains.

Apoptosis plays a key role in development by shaping the structure of tissues and organs in plants and animals. For example, look at the photos of a mouse foot in **Figure 10–15.** Each foot of a mouse is shaped the way it is partly because cells between the toes die by apoptosis during tissue development. When apoptosis does not occur as it should, a number of diseases can result. For example, the cell loss seen in AIDS and Parkinson's disease can result if too much apoptosis occurs.

FIGURE 10–15 Apoptosis The cells between a mouse's toes undergo apoptosis during a late stage of development. **Predict** ***What is one way the pattern of apoptosis would differ in foot development for a duck?***

Cancer: Uncontrolled Cell Growth

How do cancer cells differ from other cells?

Why is cell growth regulated so carefully? The principal reason may be that the consequences of uncontrolled cell growth in a multicellular organism are very severe. **Cancer,** a disorder in which body cells lose the ability to control growth, is one such example.

Cancer cells do not respond to the signals that regulate the growth of most cells. As a result, the cells divide uncontrollably. Cancer cells form a mass of cells called a **tumor.** However, not all tumors are cancerous. Some tumors are benign, or noncancerous. A benign tumor does not spread to surrounding healthy tissue or to other parts of the body. Cancerous tumors, such as the one in **Figure 10–16,** are malignant. Malignant tumors invade and destroy surrounding healthy tissue.

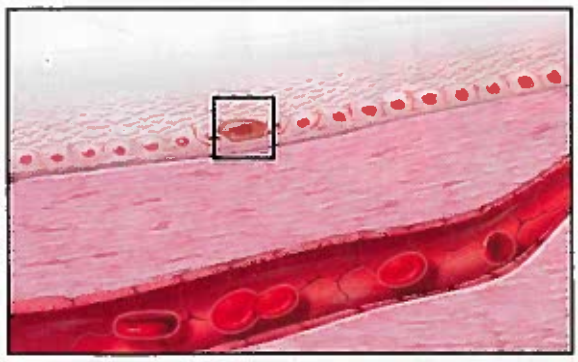
As the cancer cells spread, they absorb the nutrients needed by other cells, block nerve connections, and prevent the organs they invade from functioning properly. Soon, the delicate balances that exist in the body are disrupted, and life-threatening illness results.

What Causes Cancer? Cancers are caused by defects in the genes that regulate cell growth and division. There are several sources of such defects, including: smoking or chewing tobacco, radiation exposure, other defective genes, and even viral infection. All cancers, however, have one thing in common: The control over the cell cycle has broken down. Some cancer cells will no longer respond to external growth regulators, while others fail to produce the internal regulators that ensure orderly growth.

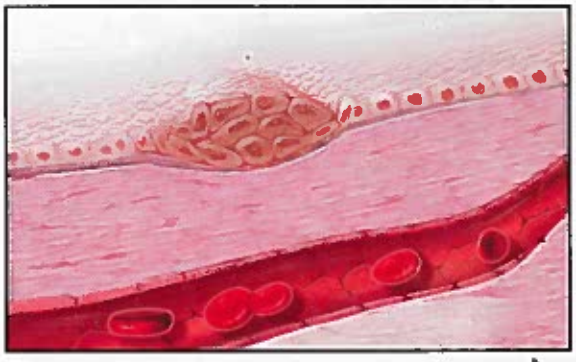
An astonishing number of cancer cells have a defect in a gene called p53, which normally halts the cell cycle until all chromosomes have been properly replicated. Damaged or defective p53 genes cause cells to lose the information needed to respond to signals that normally control their growth.

In Your Notebook *Use a two-column chart to compare the controls that regulate normal cell growth to the lack of control seen in cancer cells.*

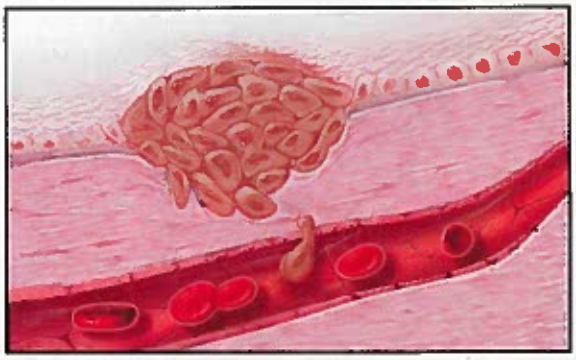
FIGURE 10–16 Growth of Cancer Cells Normal cells grow and divide in a carefully controlled fashion. Cells that are cancerous lose this control and continue to grow and divide, producing tumors.



1 A cell begins to divide abnormally.



2 The cancer cells produce a tumor, which begins to displace normal cells and tissues.



3 Cancer cells are particularly dangerous because of their tendency to spread once they enter the bloodstream or lymph vessels. The cancer then moves into other parts of the body and forms secondary tumors, a process called metastasis.

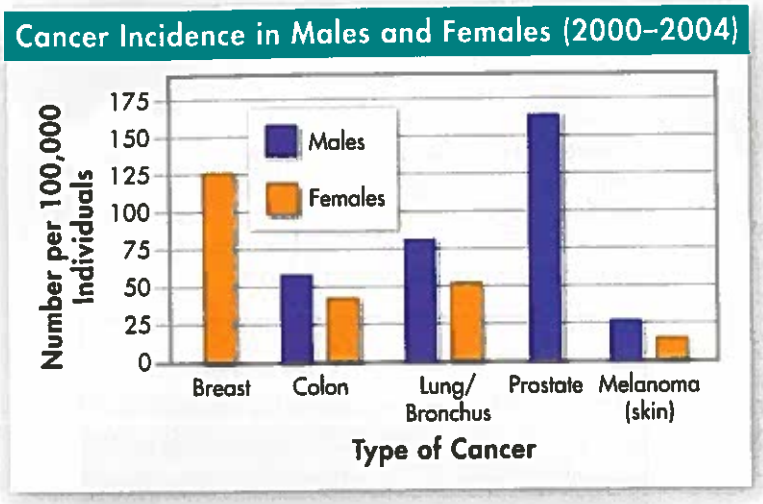


FIGURE 10–17 Cancer Incidence Cancer can affect almost every organ in the body. **Interpret Graphs** ***How many cases of breast cancer were reported compared to prostate cancer for the time period shown?***

Treatments for Cancer When a cancerous tumor is localized, it can often be removed by surgery. Skin cancer, the most common form of the disease, can usually be treated this way. Melanomas, the most serious form of skin cancer, can be removed surgically, but only if spotted very early.

Other forms of treatment make use of the fact that cancer cells grow rapidly and, therefore, need to copy their DNA more quickly than do most normal cells. This makes them especially vulnerable to damage from radiation. As a result, many tumors can be effectively treated with carefully targeted beams of radiation.

Medical researchers have worked for years to develop chemical compounds that would kill cancer cells, or at least slow their growth. The use of such compounds against cancer is known as chemotherapy. Great advances in chemotherapy have taken place in recent years and have even made it possible to cure some forms of cancer. However, because most chemotherapy compounds target rapidly dividing cells, they also interfere with cell division in normal, healthy cells. This produces serious side effects in many patients, and it is one of the reasons why scientists are so interested in gaining a better understanding of the role of cell cycle proteins in cancer. The goal of many researchers is to find highly specific ways in which cancer cells can be targeted for destruction while leaving healthy cells unaffected.

Cancer is a serious disease. Understanding and combating cancer remains a major scientific challenge, but scientists at least know where to start. Cancer is a disease of the cell cycle, and conquering cancer will require a much deeper understanding of the processes that control cell division.

10.3 Assessment

Review Key Concepts

1. a. Review Name the two types of proteins that regulate the cell cycle. How do these proteins work?

b. Form a Hypothesis Write a hypothesis about what you think would happen if cyclin were injected into a cell during mitosis. How could you test your hypothesis?

2. a. Review Why is cancer considered a disease of the cell cycle?

b. Compare and Contrast How are the growth of a tumor and the repair of a scrape on your knee similar? How are they different?

Apply the Big idea

Growth, Development, and Reproduction

3. Why do you think it is important that cells have a "control system" to regulate the timing of cell division?

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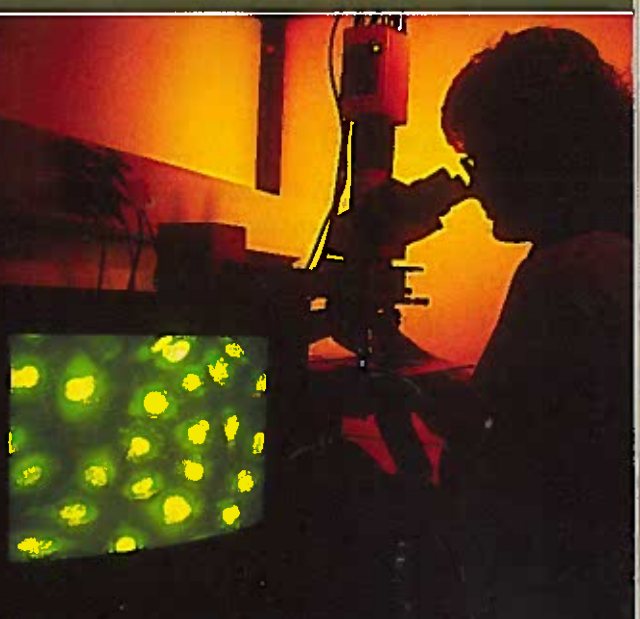
Technology & BIOLOGY

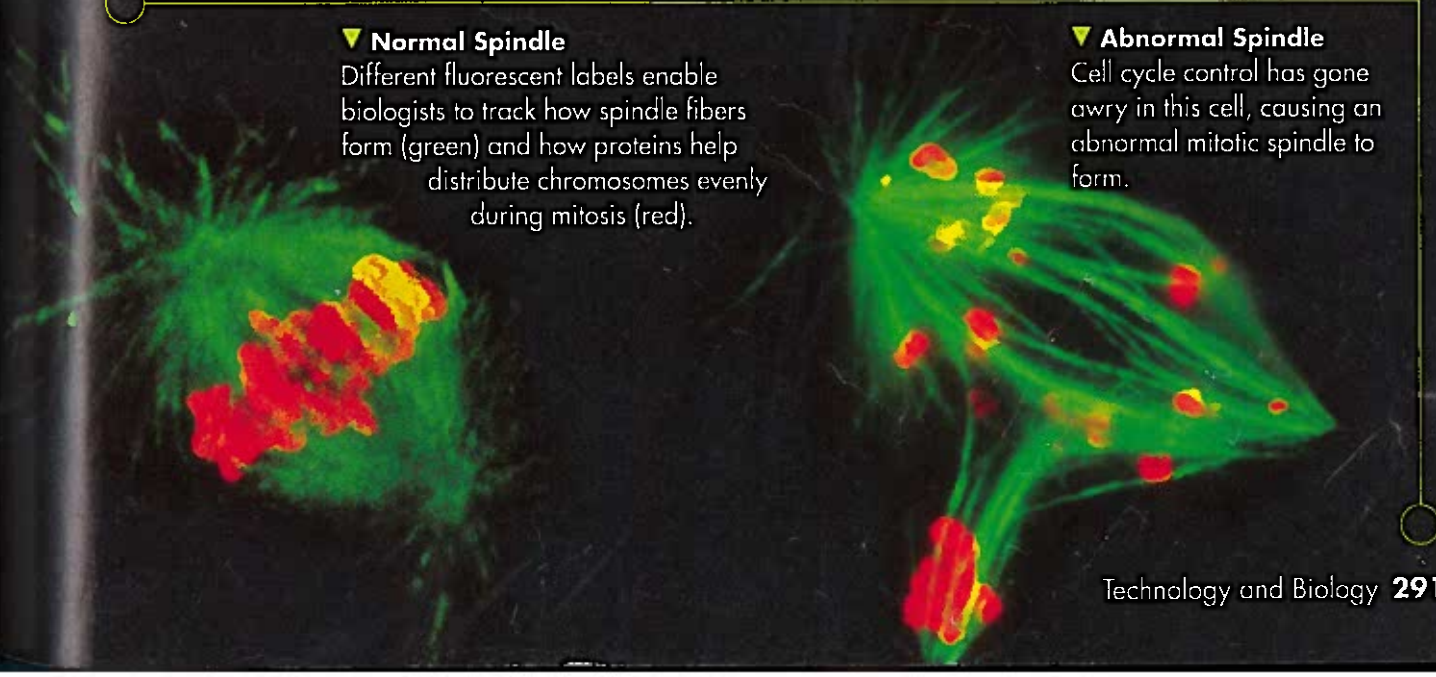
Fluorescence Microscopy

Imagine being able to "see" proteins at work inside a cell, or to track proteins from where they are made to where they go. Scientists can now do all of these things, thanks to advances in fluorescence microscopy. One advance came from the discovery that crystal jellyfish, properly known as *Aequorea victoria*, produce a protein that glows. By fusing the gene for this protein to other genes, scientists can label different parts of the cell with fluorescence. Other advances include the development of additional highly specific fluorescent labels and the invention of powerful laser microscopes. As the images on this page show, the view is clearly amazing.



▲ **Viewing Labeled Specimens**
In fluorescence microscopy, a specimen is labeled with a molecule that glows under a specific wavelength of light. Different fluorescent labels give off different colors. This way, biologists can easily see exactly where a protein is located within a cell or tissue.

WRITING **Suppose you are a cell biologist studying cell division and cancer. What might you use a fluorescence microscope to study? Describe your ideas in a paragraph.**



▼ **Normal Spindle**
Different fluorescent labels enable biologists to track how spindle fibers form (green) and how proteins help distribute chromosomes evenly during mitosis (red).

▼ **Abnormal Spindle**
Cell cycle control has gone awry in this cell, causing an abnormal mitotic spindle to form.

10.4 Cell Differentiation

Key Questions

- ***How do cells become specialized for different functions?***
- ***What are stem cells?***
- ***What are some possible benefits and issues associated with stem cell research?***

Vocabulary

embryo • differentiation • totipotent • blastocyst • pluripotent • stem cell • multipotent

Taking Notes

Compare/Contrast Table As you read, create a table comparing the ability of different cell types to differentiate.

THINK ABOUT IT The human body contains an estimated 100,000,000,000,000 (one hundred trillion) cells. That's a staggering number, but in one respect it's not quite as large as you might think. Why? Try to estimate how many times a single cell would have to divide through mitosis to produce that many cells. It may surprise you to learn that as few as 47 rounds of cell division can produce that many cells.

The results of those 47 cell cycles are truly amazing. The human body contains hundreds of distinctly different cell types, and every one of them develops from the single cell that starts the process. How do the cells get to be so different from each other?

From One Cell to Many

How do cells become specialized for different functions?

Each of us started life as just one cell. So, for that matter, did your pet dog, an earthworm, and the petunia on the windowsill. These living things pass through a developmental stage called an **embryo,** from which the adult organism is gradually produced. During the development process, an organism's cells become more and more differentiated and specialized for particular functions. **Figure 10–18** shows some of the specialized cells found in the roots, stems, and leaves of a plant.

FIGURE 10–18 Specialized Plant Cells

Defining Differentiation The process by which cells become specialized is known as **differentiation** (dif ur en shee AY shun). **During the development of an organism, cells differentiate into many types of cells.** A differentiated cell has become, quite literally, different from the embryonic cell that produced it, and specialized to perform certain tasks, such as contraction, photosynthesis, or protection. Our bodies, and the bodies of all multicellular organisms, contain highly differentiated cells that carry out the jobs we need to perform to stay alive.

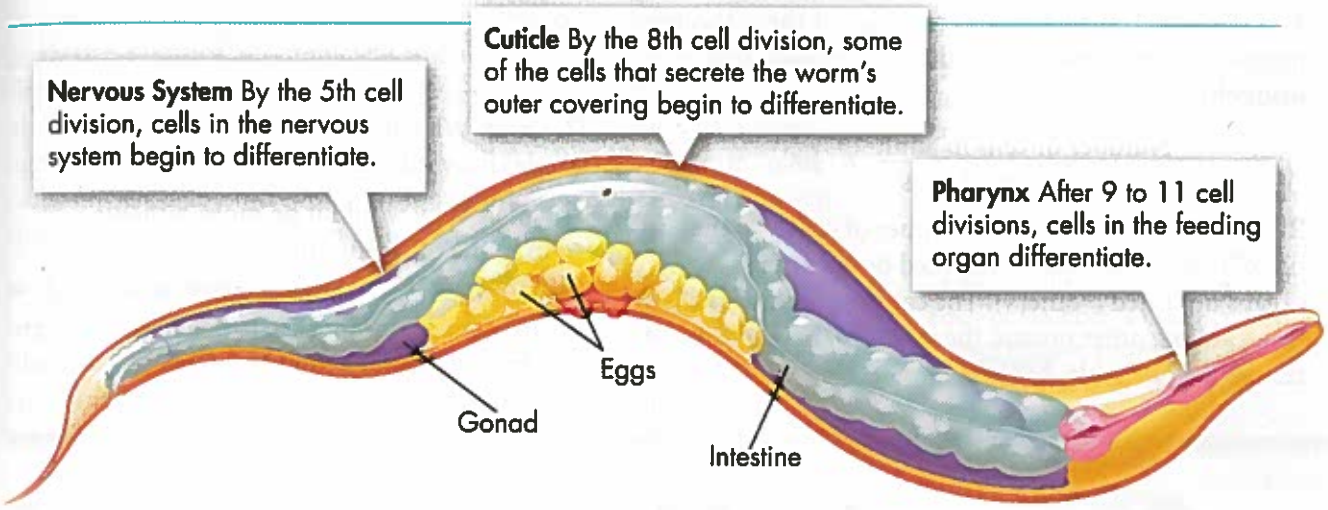


FIGURE 10–19 Differentiation in *C. elegans* A fertilized egg develops into an adult worm after many cell divisions. Daughter cells from each cell division follow a specific path toward a role as a particular kind of cell.

Mapping Differentiation The process of differentiation determines a cell's ultimate identity, such as whether it will spend its life as a nerve cell or a muscle cell. In some organisms, a cell's role is rigidly determined at a specific point in the course of development. In the microscopic worm *Caenorhabditis elegans*, for example, biologists have mapped the outcome of each and every cell division from fertilized egg to adult.

The process of cell differentiation in *C. elegans* begins with the very first division and continues throughout embryonic development. **Figure 10–19** shows when some of the cells found in the adult begin to differentiate during development. Each and every time a new worm develops, the process is the same, resulting in 959 cells with precisely determined functions.

Differentiation in Mammals Other organisms, including mammals like us, go through a more flexible process in which cell differentiation is controlled by a number of interacting factors in the embryo, many of which are still not well understood. What is known, however, is that adult cells generally do reach a point at which their differentiation is complete—when they can no longer become other types of cells.

In Your Notebook *Starting with a single cell, calculate how many cells might result after 4, 8, and 10 cell divisions.*

Analyzing Data

Cellular Differentiation of *C. elegans*

The adult microscopic worm *C. elegans* contains 959 cells. The data table shows some of the different cell types in this worm. Copy the data table into your notebook and answer the following questions.

1. Calculate Calculate the percentage of the total cell number represented by each tissue or organ listed by using this formula:

$$\frac{\text{Number of cells in adult}}{\text{Total number of cells}} \times 100$$

2. Calculate Find both the number of cells and the percentage of the total represented by cells in tissues or organs not listed ("other"). The category includes cells from, among other organs, the intestine. Record the results in your table. MATH

Cell Type	Number of Cells in Adult	Percent of Total
Cuticle	213	22%
Gonad (excluding germ line cells)	143	
Mesoderm muscle	81	
Pharynx	80	
Other		

3. Infer Why does *C. elegans* make an ideal model for studying cellular differentiation?

4. Infer Why would it be more difficult to map the differentiation patterns in a different organism, such as a mammal?

Stem Cells and Development

What are stem cells?

One of the most important questions in biology is how all of the specialized, differentiated cell types in the body are formed from just a single cell. Biologists say that such a cell is **totipotent** (toh TIP uh tunt), literally able to do everything, to develop into any type of cell in the body (including the cells that make up the extraembryonic membranes and placenta). Only the fertilized egg and the cells produced by the first few cell divisions of embryonic development are truly totipotent. If there is a "secret" by which cells start the process of differentiation, these are the cells that know that secret.

MYSTERY CLUE

Some adult salamander cells never completely differentiate. What ability do these cells retain?

Human Development After about four days of development, a human embryo forms into a **blastocyst,** a hollow ball of cells with a cluster of cells inside known as the inner cell mass. Even at this early stage, the cells of the blastocyst have begun to specialize. The outer cells form tissues that attach the embryo to its mother, while the inner cell mass becomes the embryo itself. The cells of the inner cell mass are said to be pluripotent (plu RIP uh tunt). Cells that are **pluripotent** can develop into most, but not all, of the body's cell types. They cannot form the tissues surrounding the embryo.

In Your Notebook *Look up the roots that form the words* totipotent, pluripotent, *and* multipotent. *How do the roots relate to each cell's ability to differentiate?*

Stem Cells **The unspecialized cells from which differentiated cells develop are known as stem cells.** As the name implies, **stem cells** sit at the base of a branching "stem" of development from which different cell types form. Because of their potential to develop into other cell types, stem cells are the subject of intense interest by researchers around the world.

▶ ***Embryonic Stem Cells*** As you have seen, the pluripotent stem cells of the inner cell mass eventually produce all of the cells of the body. Embryonic stem cells are pluripotent cells found in the early embryo. In 1998, researchers at the University of Wisconsin found a way to grow these embryonic stem cells in culture. Their experiments confirmed that such cells did indeed have the capacity to produce just about any cell type in the human body. In fact, scientists have managed to coax mouse embryonic stem cells to differentiate into nerve cells, muscle cells, and even into sperm and egg cells. Recently, sperm made from embryonic stem cells were used to generate live mice.

▶ ***Adult Stem Cells*** For years, biologists have suspected that adult organisms might also contain some types of stem cells. Cells in the blood and skin, for example, have a limited life span and must be constantly replaced. This suggests that the body contains pools of stem cells from which new skin and blood cells can be produced.

Adult stem cells are groups of cells that differentiate to renew and replace cells in the adult body. Because of their more limited potential, adult stem cells are referred to as **multipotent** (muhl TIP uh tunt), meaning that they can develop into many types of differentiated cells. Typically, stem cells of a given organ or tissue produce only the types of cells that are unique to that tissue. For example, adult stem cells in the bone marrow can develop into several different types of blood cells, while stem cells in the brain can produce neurons, or nerve cells.

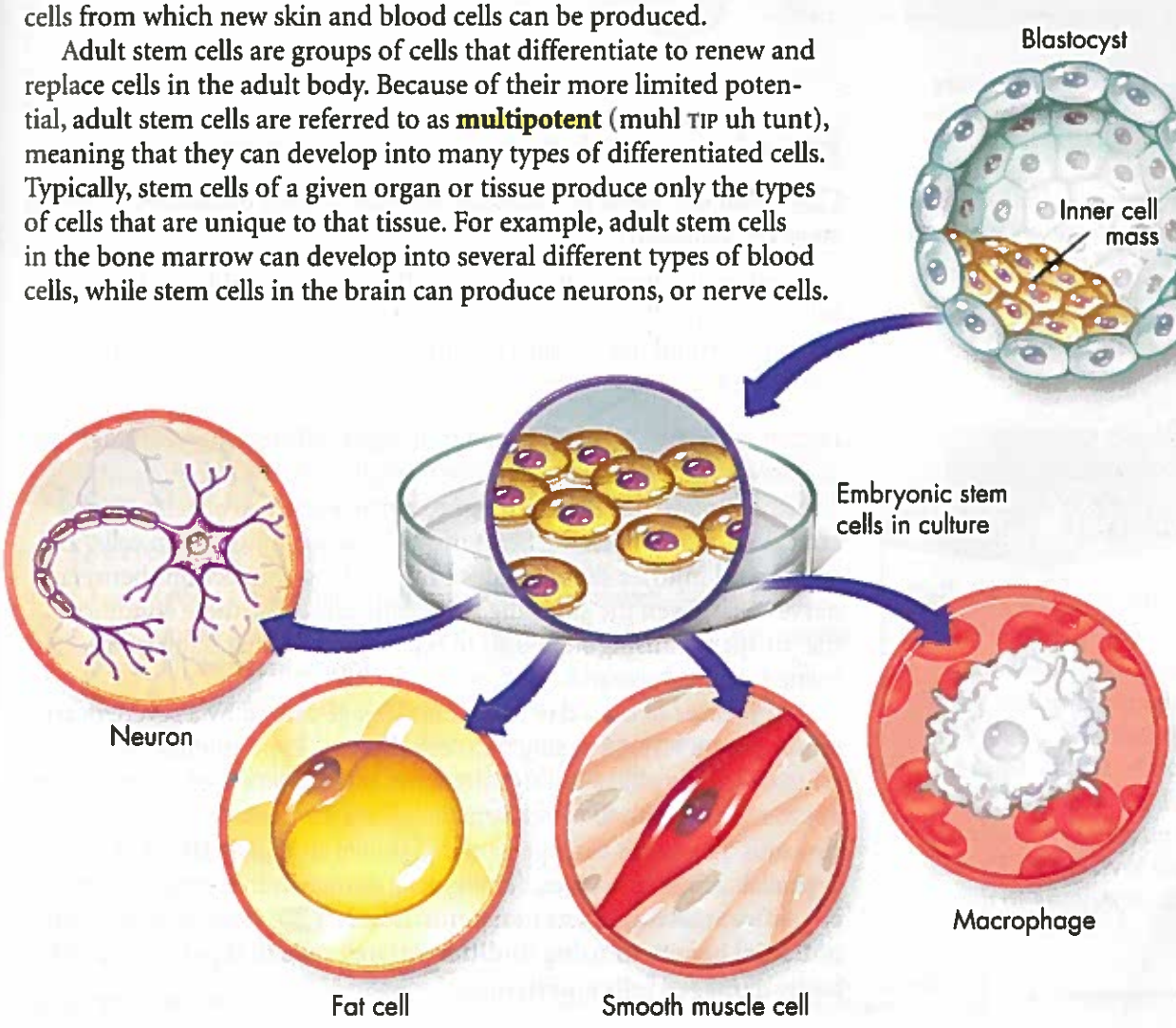


FIGURE 10–20 Embryonic Stem Cells After fertilization, the human embryo develops into a hollow ball of cells known as a blastocyst. The actual body of the embryo develops from the inner cell mass, a cluster of cells inside the blastocyst. Because of their ability to differentiate into each of the body's many cell types, these cells are known as embryonic stem cells.

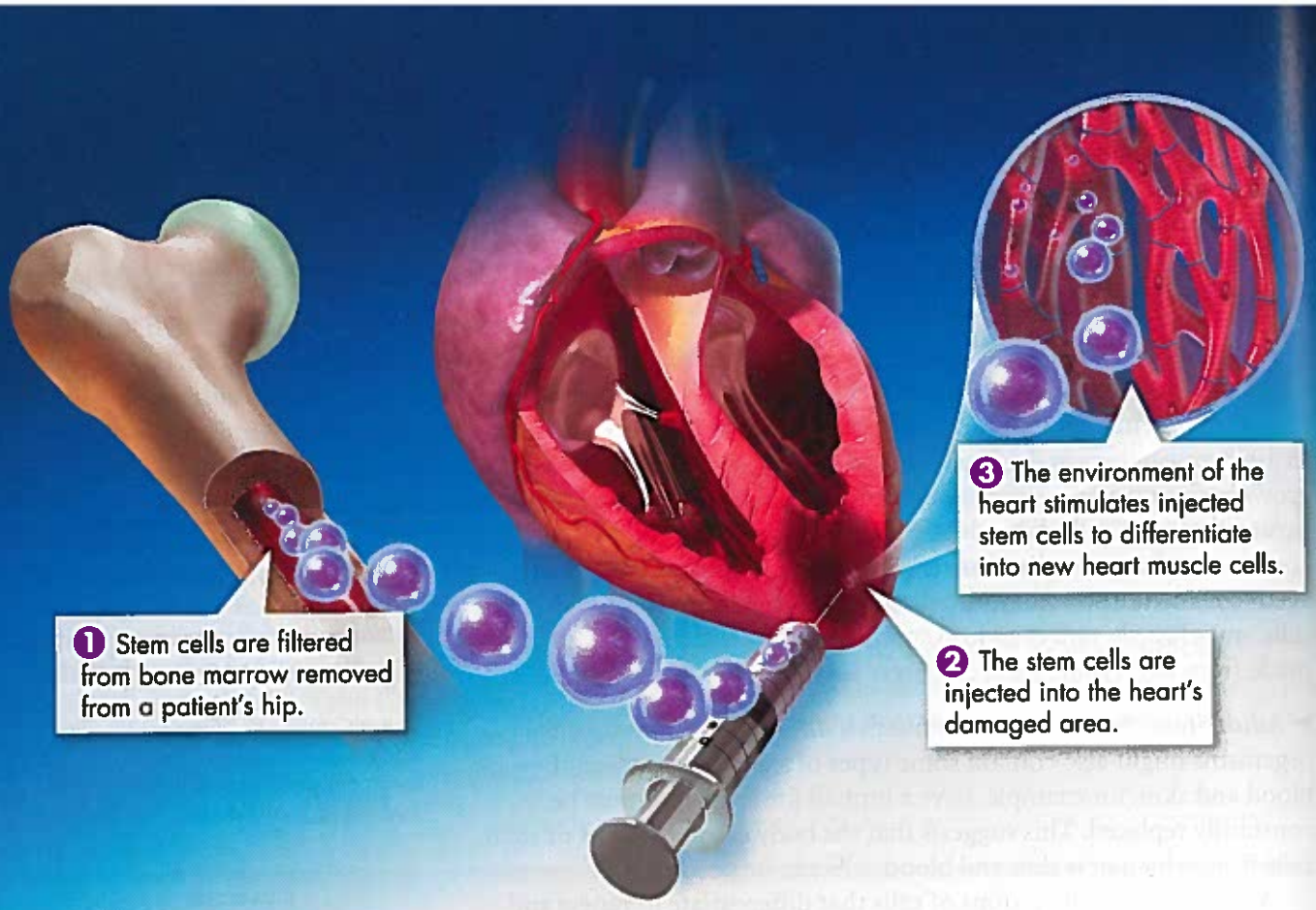


FIGURE 10–21 A Possible Future Treatment for Heart Disease? Stem cell research may lead to new ways to reverse the damage caused by a severe heart attack. The diagram shows one method currently being investigated. **Infer** ***How would the fate of the stem cells change after they are moved from the bone marrow to the heart?***

Frontiers in Stem Cell Research

What are some possible benefits and issues associated with stem cell research?

Understanding how stem cells retain the capacity to differentiate into so many cell types is an important unsolved problem in biology. Scientists would like to learn exactly which signals tell a cell to become specialized, and how other cells remain multipotent.

Potential Benefits Basic research on stem cells takes on a special urgency in light of the importance it might have for human health. There are many causes of damage to particular types of cells. Heart attacks destroy cells in the heart muscle, strokes injure brain cells, and spinal cord injuries cause paralysis by breaking connections between nerve cells. Given the suffering and death caused by these conditions, the prospect of using stem cells to repair such cellular damage has excited medical researchers.

Many hope to see a day when the damage caused by a severe heart attack can be reversed using stem cell therapy. Experiments using animals suggest that several approaches show promise of success. One approach might be to inject stem cells from the patient's bone marrow into the heart's damaged area, as shown in **Figure 10–21.** Another approach might be to inject embryonic stem cells that might eventually differentiate into new heart muscle cells. **Stem cells offer the potential benefit of using undifferentiated cells to repair or replace badly damaged cells and tissues.**

Ethical Issues Because adult stem cells can be obtained directly from the body of a willing donor, research with these cells has raised few ethical questions to date. This is not the case with embryonic stem cells, which are generally obtained from very early embryos.

Most techniques for harvesting embryonic stem cells cause the destruction of an embryo. For this reason, individuals who regard the embryo as entitled to the rights and protections of any human being object to such work. This concern has made government funding of embryonic stem cell research an important political issue. Groups seeking to protect embryos oppose such research as unethical. Other groups support such research as essential for saving human lives and argue that it would be unethical to restrict research. **Human embryonic stem cell research is controversial because the arguments for it and against it both involve ethical issues of life and death.**

It is possible, however, that in the not-too-distant future, both ethical concerns will be addressed with a technological solution. Some recent experiments have suggested that there may be ways to extract a small number of stem cells from an early embryo without damaging the embryo itself. Other experiments have shown that it may be possible to switch "on" a small number of genes that would then cause adult cells to mimic pluripotent embryonic stem cells. Such a technique would do away with the need to involve embryos at all. It also might make it possible to tailor specific therapies to the needs of each individual patient. Approaches like these, if successful, might allow potentially lifesaving research to go forward while avoiding any destruction of embryonic life.

In Your Notebook *Make a two-column chart that lists the benefits and issues related to stem cell research.*

BUILD Vocabulary

ACADEMIC WORDS The word **harvest** is the act or process of gathering. Scientists who harvest stem cells are gathering the cells.

10.4 Assessment

Review Key Concepts

1. **a. Review** What happens during differentiation?
   b. Apply Concepts What does "mapping" refer to in the process of cell differentiation?
2. **a. Review** What are stem cells?
   b. Compare and Contrast How are embryonic stem cells and adult stem cells alike? How are they different?
3. **a. Review** Summarize the potential benefits and issues of stem cell research.
   b. Form an Opinion How might technological advances help address the ethical concerns surrounding stem cell research?

Apply the Big idea

Cellular Basis of Life

4. Use what you learned in this lesson to discuss how cells become specialized for different functions. Include an explanation of how the potential for specialization varies with cell type and how it varies over the life span of an organism.

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11 Introduction to Genetics

Big idea

Information and Heredity

Q: How does cellular information pass from one generation to another?

Genetics is the study of biological inheritance. The different coat colors of these Labrador retrievers are an example of the inherited characteristics that geneticists try to understand.

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11.1 The Work of Gregor Mendel

Key Questions

- ***Where does an organism get its unique characteristics?***
- ***How are different forms of a gene distributed to offspring?***

Vocabulary

genetics • fertilization • trait • hybrid • gene • allele • principle of dominance • segregation • gamete

Taking Notes

Two-Column Chart Before you read, draw a line down the center of a sheet of paper. On the left side, write the main ideas in this lesson. On the right side, note the details and examples that support each of those ideas.

THINK ABOUT IT What is an inheritance? To many people, it is money or property left to them by relatives who have passed away. That kind of inheritance matters, of course, but there is another kind that matters even more. It is something we each receive from our parents—a contribution that determines our blood type, the color of our hair, and so much more. Most people leave their money and property behind by writing a will. But what kind of inheritance makes a person's face round or their hair curly?

The Experiments of Gregor Mendel

Where does an organism get its unique characteristics?

Every living thing—plant or animal, microbe or human being—has a set of characteristics inherited from its parent or parents. Since the beginning of recorded history, people have wanted to understand how that inheritance is passed from generation to generation. The delivery of characteristics from parent to offspring is called heredity. The scientific study of heredity, known as **genetics,** is the key to understanding what makes each organism unique.

The modern science of genetics was founded by an Austrian monk named Gregor Mendel. Mendel, shown in **Figure 11–1,** was born in 1822 in what is now the Czech Republic. After becoming a priest, Mendel spent several years studying science and mathematics at the University of Vienna. He spent the next 14 years working in a monastery and teaching high school. In addition to his teaching duties, Mendel was in charge of the monastery garden. In this simple garden, he was to do the work that changed biology forever.

Mendel carried out his work with ordinary garden peas, partly because peas are small and easy to grow. A single pea plant can produce hundreds of offspring. Today we call peas a "model system." Scientists use model systems because they are convenient to study and may tell us how other organisms, including humans, actually function. By using peas, Mendel was able to carry out, in just one or two growing seasons, experiments that would have been impossible to do with humans and that would have taken decades—if not centuries—to do with pigs, horses, or other large animals.

FIGURE 11–1 Gregor Mendel

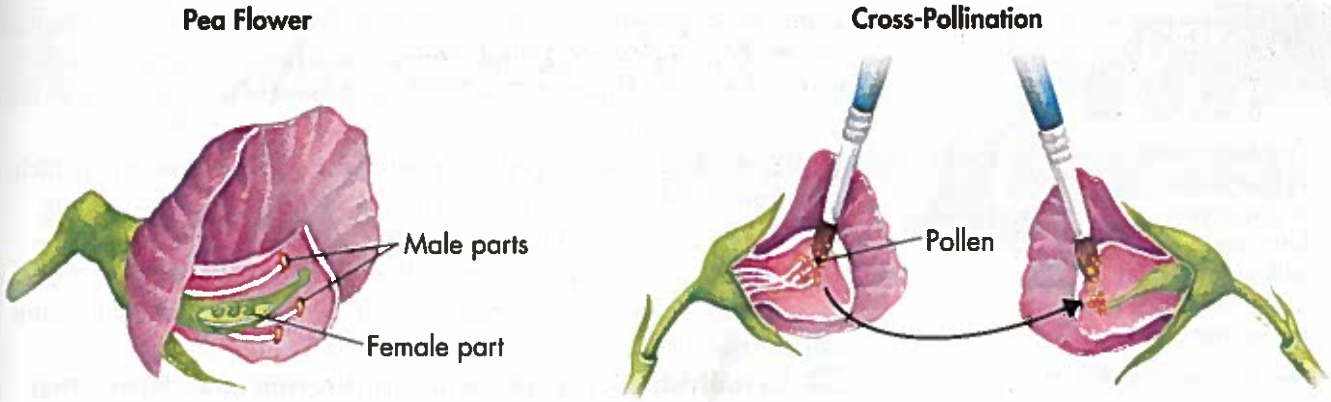

FIGURE 11–2 Cross-Pollination To cross-pollinate pea plants, Mendel cut off the male parts of one flower and then dusted the female part with pollen from another flower. **Apply Concepts** ***How did this procedure prevent self-pollination?***

The Role of Fertilization When Mendel began his experiments, he knew that the male part of each flower makes pollen, which contains the plant's male reproductive cells, called sperm. Similarly, Mendel knew that the female portion of each flower produces reproductive cells called eggs. During sexual reproduction, male and female reproductive cells join in a process known as **fertilization** to produce a new cell. In peas, this new cell develops into a tiny embryo encased within a seed.

Pea flowers are normally self-pollinating, which means that sperm cells fertilize egg cells from within the same flower. A plant grown from a seed produced by self-pollination inherits all of its characteristics from the single plant that bore it; it has a single parent.

Mendel's monastery garden had several stocks of pea plants. These plants were "true-breeding," meaning that they were self-pollinating, and would produce offspring identical to themselves. In other words, the traits of each successive generation would be the same. A **trait** is a specific characteristic, such as seed color or plant height, of an individual. Many traits vary from one individual to another. For instance, one stock of Mendel's seeds produced only tall plants, while another produced only short ones. One line produced only green seeds, another produced only yellow seeds.

To learn how these traits were determined, Mendel decided to "cross" his stocks of true-breeding plants—that is, he caused one plant to reproduce with another plant. To do this, he had to prevent self-pollination. He did so by cutting away the pollen-bearing male parts of a flower. He then dusted the pollen from a different plant onto the female part of that flower, as shown in **Figure 11–2.** This process, known as cross-pollination, produces a plant that has two different parents. Cross-pollination allowed Mendel to breed plants with traits different from those of their parents and then study the results.

Mendel studied seven different traits of pea plants. Each of these seven traits had two contrasting characteristics, such as green seed color or yellow seed color. Mendel crossed plants with each of the seven contrasting characteristics and then studied their offspring. The offspring of crosses between parents with different traits are called **hybrids.**

In Your Notebook *Explain, in your own words, what fertilization is.*

MYSTERY CLUE

Parakeets come in four colors: white, green, blue, and yellow. How many alleles might there be for feather color?

Genes and Alleles When doing genetic crosses, we call each original pair of plants the P, or parental, generation. Their offspring are called the F_1, or first filial, generation. (*Filius* and *filia* are the Latin words for "son" and "daughter.")

What were Mendel's F_1 hybrid plants like? To his surprise, for each trait studied, all the offspring had the characteristics of only one of its parents, as shown in **Figure 11–3.** In each cross, the nature of the other parent, with regard to each trait, seemed to have disappeared. From these results, Mendel drew two conclusions. His first conclusion formed the basis of our current understanding of inheritance.

An individual's characteristics are determined by factors that are passed from one parental generation to the next. Today, scientists call the factors that are passed from parent to offspring **genes.**

Each of the traits Mendel studied was controlled by one gene that occurred in two contrasting varieties. These variations produced different expressions, or forms, of each trait. For example, the gene for plant height occurred in one form that produced tall plants and in another form that produced short plants. The different forms of a gene are called **alleles** (uh LEELZ).

Dominant and Recessive Traits Mendel's second conclusion is called the **principle of dominance.** This principle states that some alleles are dominant and others are recessive. An organism with at least one dominant allele for a particular form of a trait will exhibit that form of the trait. An organism with a recessive allele for a particular form of a trait will exhibit that form only when the dominant allele for the trait is not present. In Mendel's experiments, the allele for tall plants was dominant and the allele for short plants was recessive. Likewise, the allele for yellow seeds was dominant over the recessive allele for green seeds.

FIGURE 11–3 Mendel's F_1 Crosses When Mendel crossed plants with contrasting traits, the resulting hybrids had the traits of only one of the parents.

Mendel's Seven F_1 Crosses on Pea Plants

	Seed Shape	Seed Color	Seed Coat	Pod Shape	Pod Color	Flower Position	Plant Height
P	Round X Wrinkled	Yellow X Green	Gray X White	Smooth X Constricted	Green X Yellow	Axial X Terminal	Tall X Short
F_1	Round	Yellow	Gray	Smooth	Green	Axial	Tall

Quick Lab
GUIDED INQUIRY

Classroom Variation

1. Copy the data table into your notebook.
2. Write a prediction of whether the traits listed in the table will be evenly distributed or if there will be more dominant than recessive traits.
3. Examine your features, using a mirror if necessary. Determine which traits you have for features A–E.
4. Interview at least 14 other students to find out which traits they have. Tally the numbers. Record the totals in each column.

Trait Survey				
Feature	**Dominant Trait**	**Number**	**Recessive Trait**	**Number**
A	Free ear lobes		Attached ear lobes	
B	Hair on fingers		No hair on fingers	
C	Widow's peak		No widow's peak	
D	Curly hair		Straight hair	
E	Cleft chin		Smooth chin	

Analyze and Conclude

1. **Calculate** Calculate the percentages of each trait in your total sample. How do these numbers compare to your prediction? MATH
2. **Form a Hypothesis** Why do you think recessive traits are more common in some cases?

In Your Notebook *Make a diagram that explains Mendel's principle of dominance.*

Segregation

How are different forms of a gene distributed to offspring?

Mendel didn't stop after one set of F_1 crosses, because he had another question: Had the recessive alleles simply disappeared, or were they still present in the new plants? To find out, he allowed all seven kinds of F_1 hybrids to self-pollinate. The offspring of an F_1 cross are called the F_2 (second filial) generation. In effect, Mendel crossed the F_1 generation with itself to produce the F_2 offspring, as shown in **Figure 11–4.**

The F_1 Cross When Mendel compared the F_2 plants, he made a remarkable discovery: The traits controlled by the recessive alleles reappeared in the second generation. Roughly one fourth of the F_2 plants showed the trait controlled by the recessive allele. Why, then, did the recessive alleles seem to disappear in the F_1 generation, only to reappear in the F_2 generation?

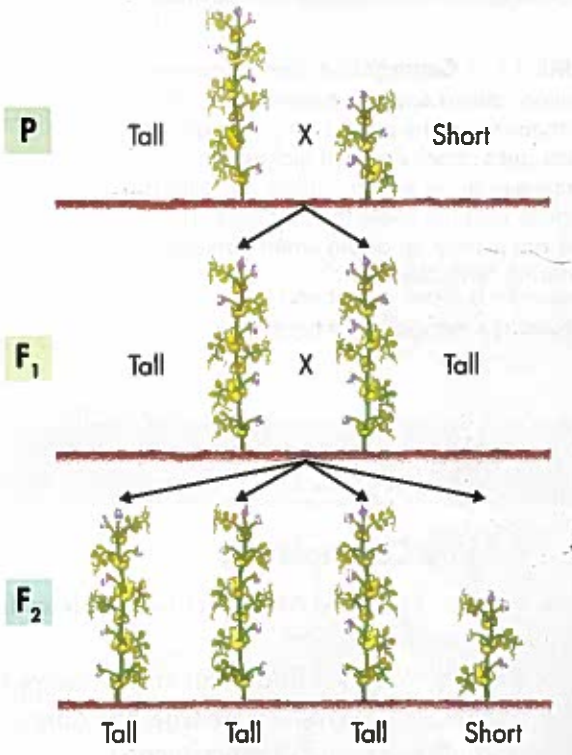

FIGURE 11–4 F_2 Cross When Mendel allowed the F_1 plants to reproduce by self-pollination, the traits controlled by recessive alleles reappeared in about one fourth of the F_2 plants in each cross. **Calculate** ***What proportion of the F_2 plants had a trait controlled by a dominant allele?*** MATH

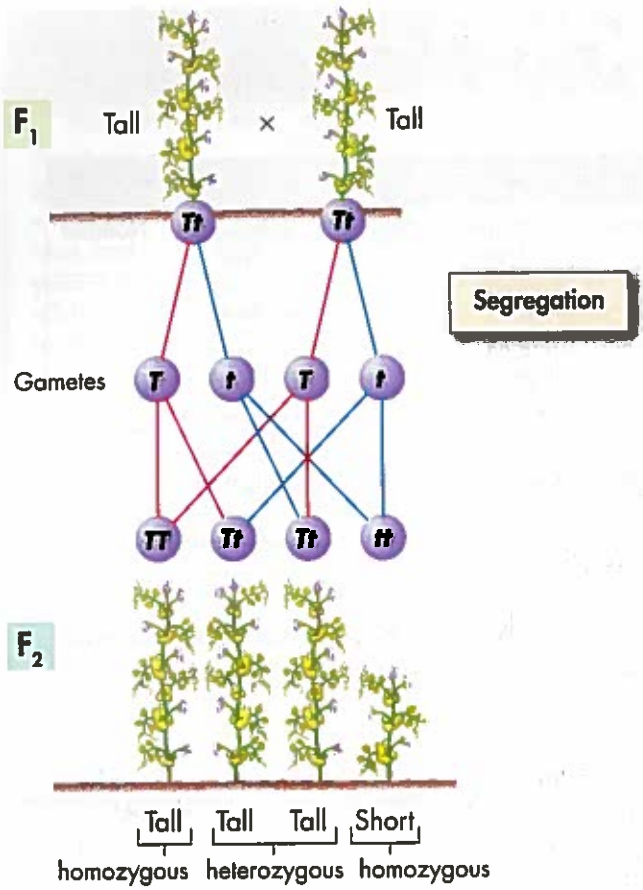

FIGURE 11–5 Segregation During gamete formation, alleles segregate from each other so that each gamete carries only a single copy of each gene. Each F_1 plant makes two types of gametes—those with the allele for tallness and those with the allele for shortness. The alleles are paired up again when gametes fuse during fertilization.

Explaining the F_1 Cross To begin with, Mendel assumed that a dominant allele had masked the corresponding recessive allele in the F_1 generation. However, the trait controlled by the recessive allele did show up in some of the F_2 plants. This reappearance indicated that, at some point, the allele for shortness had separated from the allele for tallness. How did this separation, or **segregation,** of alleles occur? Mendel suggested that the alleles for tallness and shortness in the F_1 plants must have segregated from each other during the formation of the sex cells, or **gametes** (GAM eetz). Did that suggestion make sense?

The Formation of Gametes Let's assume, as Mendel might have, that all the F_1 plants inherited an allele for tallness from the tall parent and one for shortness from the short parent. Because the allele for tallness is dominant, all the F_1 plants are tall. **During gamete formation, the alleles for each gene segregate from each other, so that each gamete carries only one allele for each gene.** Thus, each F_1 plant produces two kinds of gametes—those with the tall allele and those with the short allele.

Look at **Figure 11–5** to see how alleles separate during gamete formation and then pair up again in the F_2 generation. A capital letter represents a dominant allele. A lowercase letter represents a recessive allele. Now we can see why the recessive trait for height, *t*, reappeared in Mendel's F_2 generation. Each F_1 plant in Mendel's cross produced two kinds of gametes—those with the allele for tallness and those with the allele for shortness. Whenever a gamete that carried the *t* allele paired with the other gamete that carried the *t* allele to produce an F_2 plant, that plant was short. Every time one or both gametes of the pairing carried the *T* allele, a tall plant was produced. In other words, the F_2 generation had new combinations of alleles.

11.1 Assessment

Review Key Concepts

1. a. Review What did Mendel conclude determines biological inheritance?

b. Explain What are dominant and recessive alleles?

c. Apply Concepts Why were true-breeding pea plants important for Mendel's experiments?

2. a. Review What is segregation?

b. Explain What happens to alleles between the P generation and the F_2 generation?

c. Infer What evidence did Mendel use to explain how segregation occurs?

VISUAL THINKING

3. Use a diagram to explain Mendel's principles of dominance and segregation. Your diagram should show how alleles segregate during gamete formation.

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11.2 Applying Mendel's Principles

THINK ABOUT IT *Nothing in life is certain.* There's a great deal of wisdom in that old saying, and genetics is a fine example. If a parent carries two different alleles for a certain gene, we can't be sure which of those alleles will be inherited by any one of the parent's offspring. However, think carefully about the nature of inheritance and you'll see that even if we can't predict the exact future, we can do something almost as useful—we can figure out the odds.

Key Questions

- ***How can we use probability to predict traits?***
- ***How do alleles segregate when more than one gene is involved?***
- ***What did Mendel contribute to our understanding of genetics?***

Vocabulary

probability • homozygous • heterozygous • phenotype • genotype • Punnett square • independent assortment

Taking Notes

Preview Visuals Before you read, preview **Figure 11–7.** Try to infer the purpose of this diagram. As you read, compare your inference to the text. After you read, revise your statement if needed or write a new one about the diagram's purpose.

Probability and Punnett Squares

How can we use probability to predict traits?

Whenever Mendel performed a cross with pea plants, he carefully categorized and counted the offspring. Consequently, he had plenty of data to analyze. For example, whenever he crossed two plants that were hybrids for stem height (*Tt*), about three fourths of the resulting plants were tall and about one fourth were short.

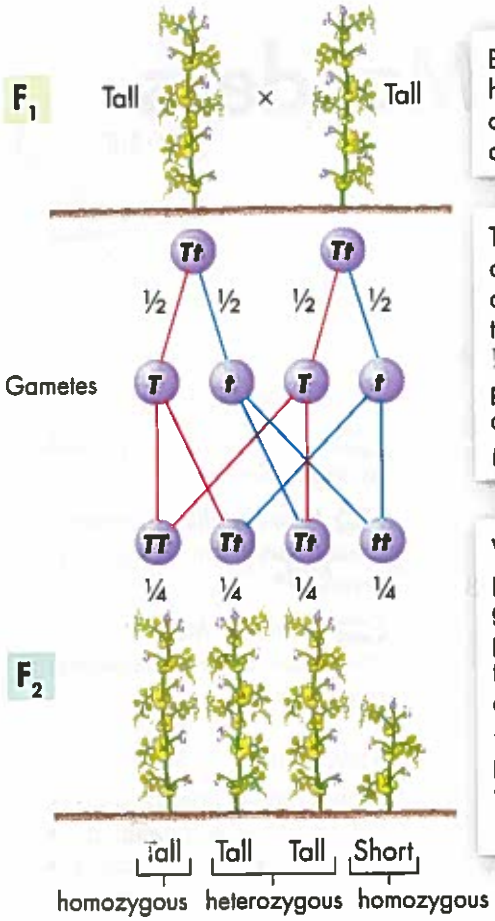
Upon analyzing his data, Mendel realized that the principles of probability could be used to explain the results of his genetic crosses. **Probability** is a concept you may have learned about in math class. It is the likelihood that a particular event will occur. As an example, consider an ordinary event, such as flipping a coin. There are two possible outcomes of this event: The coin may land either heads up or tails up. The chance, or probability, of either outcome is equal. Therefore, the probability that a single coin flip will land heads up is 1 chance in 2. This amounts to 1/2, or 50 percent.

If you flip a coin three times in a row, what is the probability that it will land heads up every time? Each coin flip is an independent event with a 1/2 probability of landing heads up. Therefore, the probability of flipping three heads in a row is:

$$1/2 \times 1/2 \times 1/2 = 1/8$$

As you can see, you have 1 chance in 8 of flipping heads three times in a row. The multiplication of individual probabilities illustrates an important point: Past outcomes do not affect future ones. Just because you've flipped three heads in a row does not mean that you're more likely to have a coin land tails up on the next flip. The probability for that flip is still 1/2.

FIGURE 11–6 Probability Probability allows you to calculate the likelihood that a particular event will occur. The probability that the coin will land heads up is ½, or 50 percent.



Both F_1 plants have the same set of alleles (*Tt*) and are tall.

The probability of each gamete acquiring the tall (*T*) allele is ½. Similarly, the probability of acquiring the short (*t*) allele is also ½.

When the alleles pair up in the F_2 generation, the probability of a tall offspring (*TT* or *Tt*) is ¼ + ¼ + ¼, or ¾. The probability that the offspring will be short (*tt*) is ¼.

FIGURE 11–7 Segregation and Probability In this cross, the *TT* and *Tt* allele combinations produced three tall pea plants, while the *tt* allele combination produced one short plant. These quantities follow the laws of probability. **Predict** ***If you crossed a TT plant with a Tt plant, would the offspring be tall or short?***

Using Segregation to Predict Outcomes

The way in which alleles segregate during gamete formation is every bit as random as a coin flip. Therefore, the principles of probability can be used to predict the outcomes of genetic crosses.

Look again at Mendel's F_1 cross, shown in **Figure 11–7.** This cross produced a mixture of tall and short plants. Why were just 1/4 of the offspring short? Well, the F_1 plants were both tall. If each plant had one tall allele and one short allele (*Tt*), and if the alleles segregated as Mendel thought, then 1/2 of the gametes produced by the plants would carry the short allele (*t*). Yet, the *t* allele is recessive. The only way to produce a short (*tt*) plant is for two gametes, each carrying the *t* allele, to combine.

Like the coin toss, each F_2 gamete has a one in two, or 1/2, chance of carrying the *t* allele. There are two gametes, so the probability of both gametes carrying the *t* allele is $1/2 \times 1/2 = 1/4$. In other words, roughly one fourth of the F_2 offspring should be short, and the remaining three fourths should be tall. This predicted ratio—3 offspring exhibiting the dominant trait to 1 offspring exhibiting the recessive trait—showed up consistently in Mendel's experiments. For each of his seven crosses, about 3/4 of the plants showed the trait controlled by the dominant allele. About 1/4 showed the trait controlled by the recessive allele. Segregation did occur according to Mendel's model.

As you can see in the F_2 generation, not all organisms with the same characteristics have the same combinations of alleles. Both the *TT* and *Tt* allele combinations resulted in tall pea plants, but only one of these combinations contains identical alleles. Organisms that have two identical alleles for a particular gene—*TT* or *tt* in this example—are said to be **homozygous** (hoh moh zy gus). Organisms that have two different alleles for the same gene—such as *Tt*—are **heterozygous** (het ur oh zy gus).

Probabilities Predict Averages Probabilities predict the average outcome of a large number of events. If you flip a coin twice, you are likely to get one heads and one tails. However, you might also get two heads or two tails. To get the expected 50 : 50 ratio, you might have to flip the coin many times. The same is true of genetics.

The larger the number of offspring, the closer the results will be to the predicted values. If an F_2 generation contains just three or four offspring, it may not match Mendel's ratios. When an F_2 generation contains hundreds or thousands of individuals, the ratios usually come very close to matching predictions.

Genotype and Phenotype One of Mendel's most revolutionary insights followed directly from his observations of F_1 crosses: Every organism has a genetic makeup as well as a set of observable characteristics. All of the tall pea plants had the same **phenotype,** or physical traits. They did not, however, have the same **genotype,** or genetic makeup. Look again at **Figure 11–7** and you will find three different genotypes among the F_2 plants: *TT*, *Tt*, and *tt*. The genotype of an organism is inherited, whereas the phenotype is formed as a result of both the environment and the genotype. This means that two organisms may share the same phenotype but have different genotypes.

Using Punnett Squares One of the best ways to predict the outcome of a genetic cross is by drawing a simple diagram known as a **Punnett square.** **Punnett squares use mathematical probability to help predict the genotype and phenotype combinations in genetic crosses.** Constructing a Punnett square is fairly easy. You begin with a square. Then, following the principle of segregation, all possible combinations of alleles in the gametes produced by one parent are written along the top edge of the square. The other parent's alleles are then segregated along the left edge. Next, every possible genotype is written into the boxes within the square, just as they might appear in the F_2 generation. **Figure 11–8** on the next page shows step-by-step instructions for constructing Punnett squares.

BUILD Vocabulary

PREFIXES The prefix *pheno-* in **phenotype** comes from the Greek word *phainein*, meaning "to show." *Geno-*, the prefix in **genotype,** is derived from the Greek word *genus*, meaning "race, kind."

In Your Notebook *In your own words, write definitions for the terms* homozygous, heterozygous, phenotype, *and* genotype.

Quick Lab
GUIDED INQUIRY

How Are Dimples Inherited?

1. Write the last four digits of any telephone number. These four random digits represent the alleles of a gene that determines whether a person will have dimples. Odd digits represent the allele for the dominant trait of dimples. Even digits represent the allele for the recessive trait of no dimples.
2. Use the first two digits to represent a father's genotype. Use the symbols *D* and *d* to write his genotype as shown in the example.

Father's genotype is *dd* (2 even digits). Mother's genotype is *Dd* (1 even digit and 1 odd digit).

46 | 38

3. Use the last two digits the same way to find the mother's genotype. Write her genotype.
4. Use **Figure 11–8** on the next page to construct a Punnett square for the cross of these parents. Then, using the Punnett square, determine the probability that their child will have dimples.
5. Determine the class average of the percent of children with dimples.

Analyze and Conclude

1. **Apply Concepts** How does the class average compare with the result of a cross of two heterozygous parents?
2. **Draw Conclusions** What percentage of the children will be expected to have dimples if one parent is homozygous for dimples (*DD*) and the other is heterozygous (*Dd*)?

VISUAL SUMMARY

HOW TO MAKE A PUNNETT SQUARE

FIGURE 11–8 By drawing a Punnett square, you can determine the allele combinations that might result from a genetic cross.

One-Factor Cross

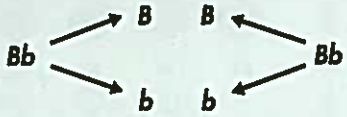
1 Start With the Parents

Write the genotypes of the two organisms that will serve as parents in a cross. In this example we will cross a male and female osprey, or fish eagle, that are heterozygous for large beaks. They each have genotypes of *Bb*.

Bb* and *Bb

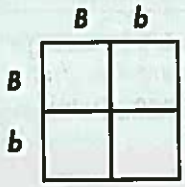
2 Figure Out the Gametes

Determine what alleles would be found in all of the possible gametes that each parent could produce.



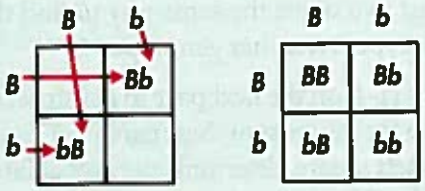
3 Line Them Up

Draw a table with enough squares for each pair of gametes from each parent. In this case, each parent can make two different types of gametes, *B* and *b*. Enter the genotypes of the gametes produced by both parents on the top and left sides of the table.



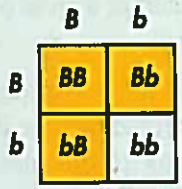
4 Write Out the New Genotypes

Fill in the table by combining the gametes' genotypes.



5 Figure Out the Results

Determine the genotype and phenotype of each offspring. Calculate the percentage of each. In this example, ¾ of the chicks will have large beaks, but only ½ will be heterozygous for this trait *(Bb)*.



Two-Factor Cross

1 Start With the Parents

In this example we will cross two pea plants that are heterozygous for size (tall and short alleles) and pod color (green and yellow alleles). The genotypes of the two parents are *TtGg* and *TtGg*.

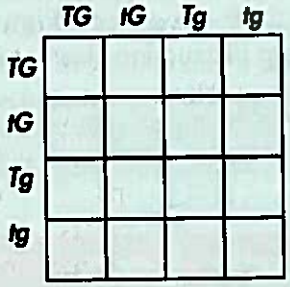
TtGg* and *TtGg

2 Figure Out the Gametes

Determine what alleles would be found in all of the possible gametes that each parent could produce.

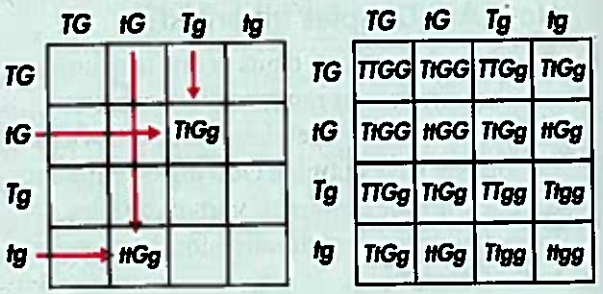
3 Line Them Up

In this case, each parent can make 4 different types of gametes, so the table needs to be 4 rows by 4 columns, or 16 squares.



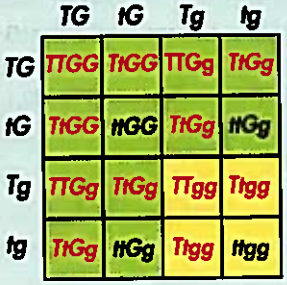
4 Write Out the New Genotypes

Fill in the table by combining the gametes' genotypes.



5 Figure Out the Results

In this example, the color of the squares represents pod color. Alleles written in black indicate short plants, while alleles written in red indicate tall plants.



Independent Assortment

How do alleles segregate when more than one gene is involved?

After showing that alleles segregate during the formation of gametes, Mendel wondered if the segregation of one pair of alleles affects another pair. For example, does the gene that determines the shape of a seed affect the gene for seed color? To find out, Mendel followed two different genes as they passed from one generation to the next. Because it involves two different genes, Mendel's experiment is known as a two-factor, or "dihybrid," cross. (Single-gene crosses are "monohybrid" crosses.)

The Two-Factor Cross: F_1 First, Mendel crossed true-breeding plants that produced only round yellow peas with plants that produced wrinkled green peas. The round yellow peas had the genotype *RRYY*, and the wrinkled green peas had the genotype *rryy*. All of the F_1 offspring produced round yellow peas. These results showed that the alleles for yellow and round peas are dominant. As the Punnett square in **Figure 11–9** shows, the genotype in each of these F_1 plants is *RrYy*. In other words, the F_1 plants were all heterozygous for both seed shape and seed color. This cross did not indicate whether genes assort, or segregate independently. However, it provided the hybrid plants needed to breed the F_2 generation.

The Two-Factor Cross: F_2 In the second part of this experiment, Mendel crossed the F_1 plants to produce F_2 offspring. Remember, each F_1 plant was formed by the fusion of a gamete carrying the dominant *RY* alleles with another gamete carrying the recessive *ry* alleles. Did this mean that the two dominant alleles would always stay together, or would they segregate independently, so that any combination of alleles was possible?

In Mendel's experiment, the F_2 plants produced 556 seeds. Mendel compared their variation. He observed that 315 of the seeds were round and yellow, while another 32 seeds were wrinkled and green—the two parental phenotypes. However, 209 seeds had combinations of phenotypes, and therefore combinations of alleles, that were not found in either parent. This clearly meant that the alleles for seed shape segregated independently of those for seed color. Put another way, genes that segregate independently (such as the genes for seed shape and seed color in pea plants) do not influence each other's inheritance.

Mendel's experimental results were very close to the 9 : 3 : 3 : 1 ratio that the Punnett square shown in **Figure 11–10** predicts. Mendel had discovered the principle of **independent assortment.**

The principle of independent assortment states that genes for different traits can segregate independently during the formation of gametes. Independent assortment helps account for the many genetic variations observed in plants, animals, and other organisms—even when they have the same parents.

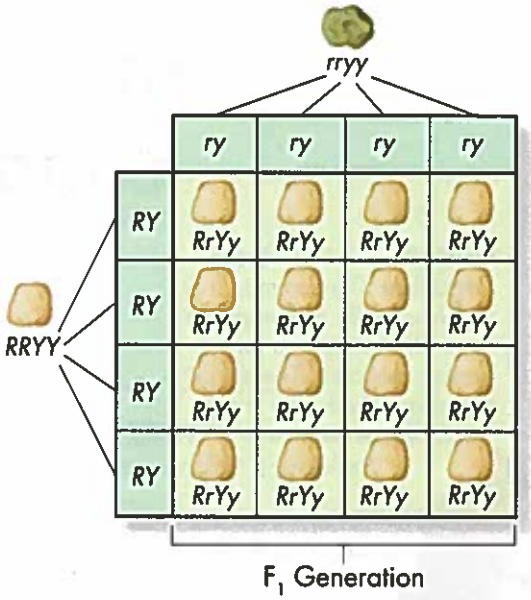


FIGURE 11–9 Two-Factor Cross: F_1 Mendel crossed plants that were homozygous dominant for round yellow peas with plants that were homozygous recessive for wrinkled green peas. All of the F_1 offspring were heterozygous dominant for round yellow peas. **Interpret Graphics** ***How is the genotype of the offspring different from that of the homozygous dominant parent?***

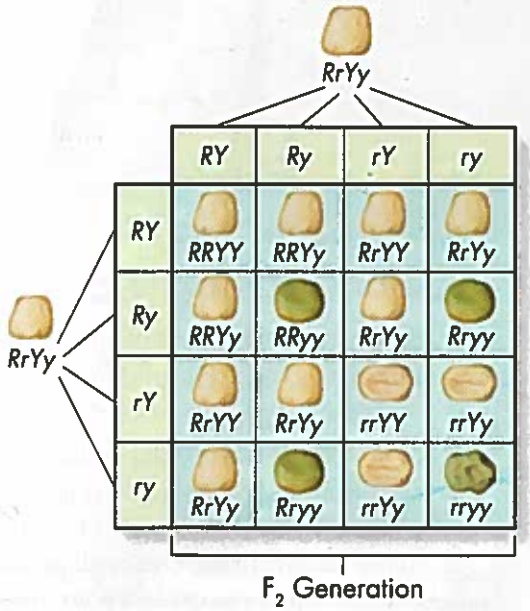


FIGURE 11–10 Two-Factor Cross: F_2 When Mendel crossed F_1 plants that were heterozygous dominant for round yellow peas, he found that the alleles segregated independently to produce the F_2 generation.

A Summary of Mendel's Principles

What did Mendel contribute to our understanding of genetics?

As you have seen, Mendel's principles of segregation and independent assortment can be observed through one- and two-factor crosses.

Mendel's principles of heredity, observed through patterns of inheritance, form the basis of modern genetics. These principles are as follows:

- The inheritance of biological characteristics is determined by individual units called genes, which are passed from parents to offspring.
- Where two or more forms (alleles) of the gene for a single trait exist, some alleles may be dominant and others may be recessive.
- In most sexually reproducing organisms, each adult has two copies of each gene—one from each parent. These genes segregate from each other when gametes are formed.
- Alleles for different genes usually segregate independently of each other.

Mendel's principles don't apply only to plants. At the beginning of the 1900s, the American geneticist Thomas Hunt Morgan wanted to use a model organism of another kind to advance the study of genetics. He decided to work on a tiny insect that kept showing up, uninvited, in his laboratory. The insect was the common fruit fly, *Drosophila melanogaster,* shown in **Figure 11–11.** *Drosophila* can produce plenty of offspring—a single pair can produce as many as 100 progeny. Before long, Morgan and other biologists had tested all of Mendel's principles and learned that they applied to flies and other organisms as well. In fact, Mendel's basic principles can be used to study the inheritance of human traits and to calculate the probability of certain traits appearing in the next generation. You will learn more about human genetics in Chapter 14.

FIGURE 11–11 A Model Organism The common fruit fly, *Drosophila melanogaster,* is an ideal organism for genetic research. These fruit flies are poised on a lemon.

11.2 Assessment

Review Key Concepts

1. a. Review What is probability?

b. Use Models How are Punnett squares used to predict the outcomes of genetic crosses?

2. a. Review What is independent assortment?

b. Calculate An F_1 plant that is homozygous for shortness is crossed with a heterozygous F_1 plant. What is the probability that a seed from the cross will produce a tall plant? Use a Punnett square to explain your answer and to compare the probable genetic variations in the F_2 plants. MATH

3. a. Review How did Gregor Mendel contribute to our understanding of inherited traits?

b. Apply Concepts Why is the fruit fly an ideal organism for genetic research?

Apply the Big idea

Information and Heredity

4. Suppose you are an avid gardener. One day, you come across a plant with beautiful lavender flowers. Knowing that the plant is self-pollinating, you harvest its seeds and plant them. Of the 106 plants that grow from these seeds, 31 have white flowers. Using a Punnett square, draw conclusions about the nature of the allele for lavender flowers.

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11.3 Other Patterns of Inheritance

THINK ABOUT IT Mendel's principles offer a tidy set of rules with which to predict various patterns of inheritance. Unfortunately, biology is not a tidy science. There are exceptions to every rule, and exceptions to the exceptions. What happens if one allele is not completely dominant over another? What if a gene has several alleles?

Key Questions

- ***What are some exceptions to Mendel's principles?***
- ***Does the environment have a role in how genes determine traits?***

Vocabulary

incomplete dominance • codominance • multiple allele • polygenic trait

Taking Notes

Outline Make an outline using the green and blue headings. As you read, write bulleted notes below each heading to summarize its topic.

Beyond Dominant and Recessive Alleles

What are some exceptions to Mendel's principles?

Despite the importance of Mendel's work, there are important exceptions to most of his principles. For example, not all genes show simple patterns of inheritance. In most organisms, genetics is more complicated, because the majority of genes have more than two alleles. In addition, many important traits are controlled by more than one gene. Mendel's principles alone cannot predict traits that are controlled by multiple alleles or multiple genes.

Incomplete Dominance

A cross between two four o'clock (*Mirabilis*) plants shows a common exception to Mendel's principles. **Some alleles are neither dominant nor recessive.** As shown in **Figure 11–12,** the F_1 generation produced by a cross between red-flowered (*RR*) and white-flowered (*WW*) *Mirabilis* plants consists of pink-colored flowers (*RW*). Which allele is dominant in this case? Neither one. Cases in which one allele is not completely dominant over another are called **incomplete dominance.** In incomplete dominance, the heterozygous phenotype lies somewhere between the two homozygous phenotypes.

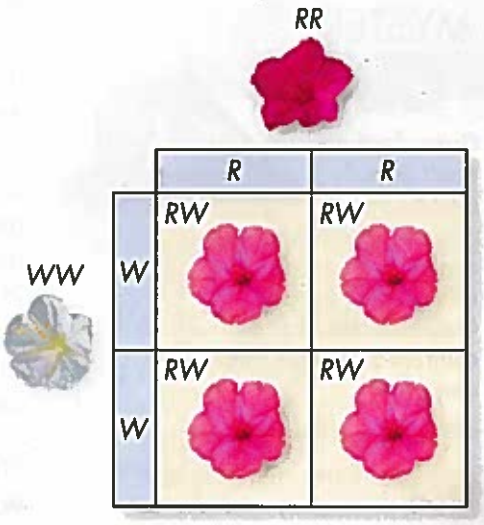


FIGURE 11–12 Incomplete Dominance In four o'clock plants, the alleles for red and white flowers show incomplete dominance. Heterozygous (*RW*) plants have pink flowers—a mix of red and white coloring.

Codominance

A similar situation arises from **codominance,** in which the phenotypes produced by both alleles are clearly expressed. For example, in certain varieties of chicken, the allele for black feathers is codominant with the allele for white feathers. Heterozygous chickens have a color described as "erminette," speckled with black and white feathers. Unlike the blending of red and white colors in heterozygous four o'clocks, black and white colors appear separately in chickens. Many human genes, including one for a protein that controls cholesterol levels in the blood, show codominance, too. People with the heterozygous form of this gene produce two different forms of the protein, each with a different effect on cholesterol levels.

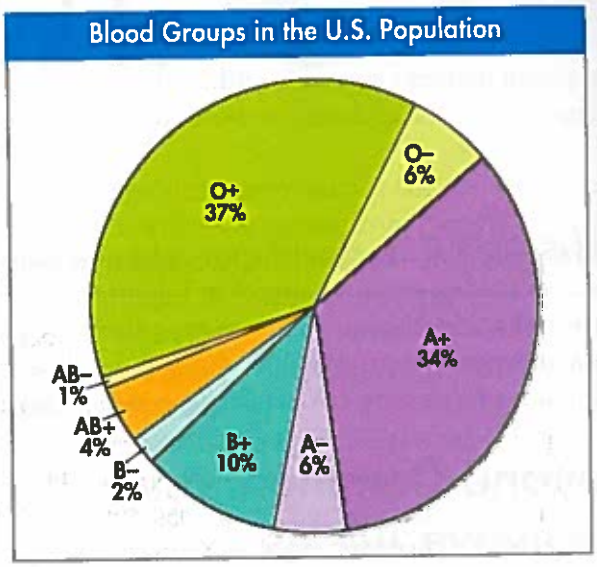
Analyzing Data

Human Blood Types

Red blood cells carry antigens, molecules that can trigger an immune reaction, on their surfaces. Human blood type A carries an A antigen, type B has a B antigen, type AB has both antigens, and type O carries neither antigen. The gene for these antigens has three alleles; A, B, and O.

For a transfusion to succeed, it must not introduce a new antigen into the body of the recipient. So, a person with type A blood may receive type O, but not vice versa.

Another gene controls a second type of antigen, known as Rh factor. Rh^+ individuals carry this antigen, while Rh^- ones don't. This chart of the U.S. population shows the percentage of each blood type.



1. **Interpret Graphs** Which blood type makes up the greatest percentage of the U.S. population?
2. **Calculate** What percentage of the total U.S. population has a positive Rh factor? What percentage has a negative Rh factor?
3. **Infer** Which blood type can be used for transfusion into the largest percentage of individuals? Which type has the smallest percentage of possible donors available?
4. **Predict** Could a person with O^+ blood have two parents with O^- blood? Could that person have a daughter with AB^+ blood? Explain your answers.

MYSTERY CLUE

Green feathers don't actually contain green pigments. Rather, they contain a mixture of blue and yellow pigments. Could feather color be controlled by more than one gene?

Multiple Alleles So far, our examples have described genes for which there are only two alleles, such as *a* and *A*. In nature, such genes are the exception rather than the rule. **Many genes exist in several different forms and are therefore said to have multiple alleles.** A gene with more than two alleles is said to have **multiple alleles.** An individual, of course, usually has only two copies of each gene, but many different alleles are often found within a population. One of the best-known examples is coat color in rabbits. A rabbit's coat color is determined by a single gene that has at least four different alleles. The four known alleles display a pattern of simple dominance that can produce four coat colors. Many other genes have multiple alleles, including the human genes for blood type.

Polygenic Traits **Many traits are produced by the interaction of several genes.** Traits controlled by two or more genes are said to be **polygenic traits.** *Polygenic* means "many genes." For example, at least three genes are involved in making the reddish-brown pigment in the eyes of fruit flies. Polygenic traits often show a wide range of phenotypes. The variety of skin color in humans comes about partly because more than four different genes probably control this trait.

In Your Notebook *In your own words, describe multiple alleles and polygenic traits. How are they similar? How are they different?*

Genes and the Environment

Does the environment have a role in how genes determine traits?

The characteristics of any organism—whether plant, fruit fly, or human being—are not determined solely by the genes that organism inherits. Genes provide a plan for development, but how that plan unfolds also depends on the environment. In other words, the phenotype of an organism is only partly determined by its genotype.

Consider the western white butterfly, *Pontia occidentalis*, shown in **Figure 11–13.** It is found throughout western North America. Butterfly enthusiasts had noted for years that western whites hatching in the summer (right) had different color patterns on their wings than those hatching in the spring (left). Scientific studies showed the reason—butterflies hatching in the shorter days of springtime had greater levels of pigment in their wings, making their markings appear darker than those hatching in the longer days of summer. In other words, the environment in which the butterflies develop influences the expression of their genes for wing coloration. **Environmental conditions can affect gene expression and influence genetically determined traits.** An individual's actual phenotype is determined by its environment as well as its genes.

In the case of the western white butterfly, these changes in wing pigmentation are particularly important. In order to fly effectively, the body temperature of the butterfly must be 28°C–40°C (about 84°F–104°F). Since the spring months are cooler in the west, greater pigmentation helps them reach the body temperature needed for flight. Similarly, in the hot summer months, less pigmentation enables the moths to avoid overheating.

Environmental Temperature and Butterfly Needs		
Temp. Needed for Flight	**Average Spring Temp.**	**Average Summer Temp.**
28–40°C	26.5°C	34.8°C

FIGURE 11–13 Temperature and Wing Color Western white butterflies that hatch in the spring have darker wing patterns than those that hatch in summer. The dark wing color helps increase their body heat. This trait is important because the butterflies need to reach a certain temperature in order to fly. **Calculate** ***What is the difference between the minimum temperature these butterflies need to fly and the average spring temperature? Would the same calculation apply to butterflies developing in the summer?*** MATH

11.3 Assessment

Review Key Concepts

1. a. Review What does *incomplete dominance* mean? Give an example.

b. Design an Experiment Design an experiment to determine whether the pink flowers of petunia plants result from incomplete dominance.

2. a. Review Describe two inheritance patterns besides simple dominance.

b. Compare and Contrast What is the difference between incomplete dominance and codominance?

PRACTICE PROBLEM

3. Construct a genetics problem to be given as an assignment to a classmate. The problem must test incomplete dominance, codominance, multiple alleles, or polygenic traits. Your problem must have an answer key that includes all of your work.

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11.4 Meiosis

THINK ABOUT IT As geneticists in the early 1900s applied Mendel's principles, they wondered where genes might be located. They expected genes to be carried on structures inside the cell, but *which* structures? What cellular processes could account for segregation and independent assortment, as Mendel had described?

Chromosome Number

How many sets of genes do multicellular organisms inherit?

To hold true, Mendel's principles require at least two events to occur. First, an organism with two parents must inherit a single copy of every gene from each parent. Second, when that organism produces gametes, those two sets of genes must be separated so that each gamete contains just one set of genes. As it turns out, chromosomes—those strands of DNA and protein inside the cell nucleus—are the carriers of genes. The genes are located in specific positions on chromosomes.

Diploid Cells Consider the fruit fly that Morgan used, *Drosophila*. A body cell in an adult fruit fly has eight chromosomes, as shown in **Figure 11–14.** Four of the chromosomes come from its male parent, and four come from its female parent. These two sets of chromosomes are **homologous** (hoh MAHL uh gus), meaning that each of the four chromosomes from the male parent has a corresponding chromosome from the female parent. A cell that contains both sets of homologous chromosomes is said to be **diploid,** meaning "two sets." **The diploid cells of most adult organisms contain two complete sets of inherited chromosomes and two complete sets of genes.** The diploid number of chromosomes is sometimes represented by the symbol 2N. Thus, for *Drosophila,* the diploid number is 8, which can be written as 2N = 8, where N represents the single set of chromosomes found in a sperm or egg cell.

Haploid Cells Some cells contain only a single set of chromosomes, and therefore a single set of genes. Such cells are **haploid,** meaning "one set." The gametes of sexually reproducing organisms, including fruit flies and peas, are haploid. For *Drosophila* gametes, the haploid number is 4, which can be written as N = 4.

Key Questions

- ***How many sets of genes do multicellular organisms inherit?***
- ***What events occur during each phase of meiosis?***
- ***How is meiosis different from mitosis?***
- ***How can two alleles from different genes be inherited together?***

Vocabulary

homologous • diploid • haploid • meiosis • tetrad • crossing-over • zygote

Taking Notes

Compare/Contrast Table Before you read, make a compare/contrast table to show the differences between mitosis and meiosis. As you read, complete the table.

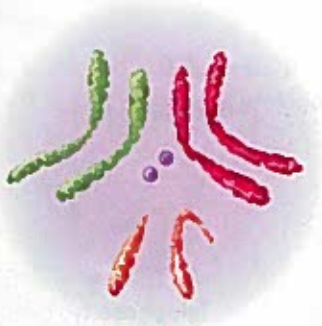
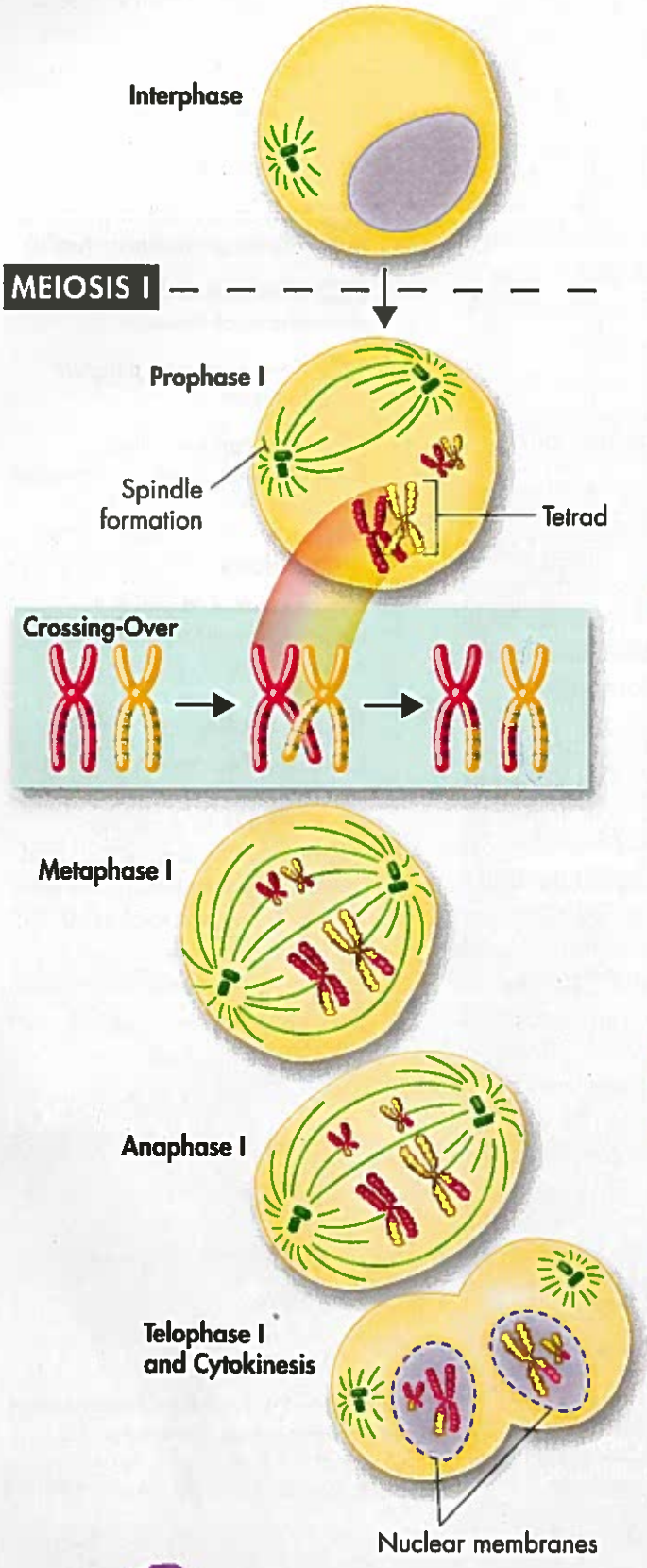


FIGURE 11–14 Fruit Fly Chromosomes These chromosomes are from a fruit fly. Each of the fruit fly's body cells is diploid, containing eight chromosomes.

FIGURE 11–15 Meiosis I During meiosis I, a diploid cell undergoes a series of events that results in the production of two daughter cells. Neither daughter cell has the same sets of chromosomes that the original diploid cell had. **Interpret Graphics** ***How does crossing-over affect the alleles on a chromosome?***



Phases of Meiosis

What events occur during each phases of meiosis?

How are haploid (N) gamete cells produced from diploid (2N) cells? That's where meiosis (my OH sis) comes in. **Meiosis** is a process in which the number of chromosomes per cell is cut in half through the separation of homologous chromosomes in a diploid cell. Meiosis usually involves two distinct divisions, called meiosis I and meiosis II. By the end of meiosis II, the diploid cell becomes four haploid cells. Let's see how meiosis takes place in a cell that has a diploid number of 4 (2N = 4).

Meiosis I Just prior to meiosis I, the cell undergoes a round of chromosome replication during interphase. As in mitosis, which was discussed in Chapter 10, each replicated chromosome consists of two identical chromatids joined at the center. Follow the sequence in **Figure 11–15** as you read about meiosis I.

▶ ***Prophase I*** After interphase I, the cell begins to divide, and the chromosomes pair up. **In prophase I of meiosis, each replicated chromosome pairs with its corresponding homologous chromosome.** This pairing forms a structure called a **tetrad,** which contains four chromatids. As the homologous chromosomes form tetrads, they undergo a process called **crossing-over.** First, the chromatids of the homologous chromosomes cross over one another. Then, the crossed sections of the chromatids—which contain alleles—are exchanged. Crossing-over therefore produces new combinations of alleles in the cell.

▶ ***Metaphase I and Anaphase I*** As prophase I ends, a spindle forms and attaches to each tetrad. **During metaphase I of meiosis, paired homologous chromosomes line up across the center of the cell.** As the cell moves into anaphase I, the homologous pairs of chromosomes separate. **During anaphase I, spindle fibers pull each homologous chromosome pair toward opposite ends of the cell.**

▶ ***Telophase I and Cytokinesis*** When anaphase I is complete, the separated chromosomes cluster at opposite ends of the cell. **The next phase is telophase I, in which a nuclear membrane forms around each cluster of chromosomes. Cytokinesis follows telophase I, forming two new cells.**

Meiosis I results in two cells, called daughter cells. Each cell has four chromatids, as it would after mitosis. However, because each pair of homologous chromosomes was separated, neither daughter cell has the two complete sets of chromosomes that it would have in a diploid cell. Those two sets have been shuffled and sorted almost like a deck of cards. The two cells produced by meiosis I have sets of chromosomes and alleles that are different from each other and from the diploid cell that entered meiosis I.

Meiosis II The two cells now enter a second meiotic division. Unlike the first division, neither cell goes through a round of chromosome replication before entering meiosis II.

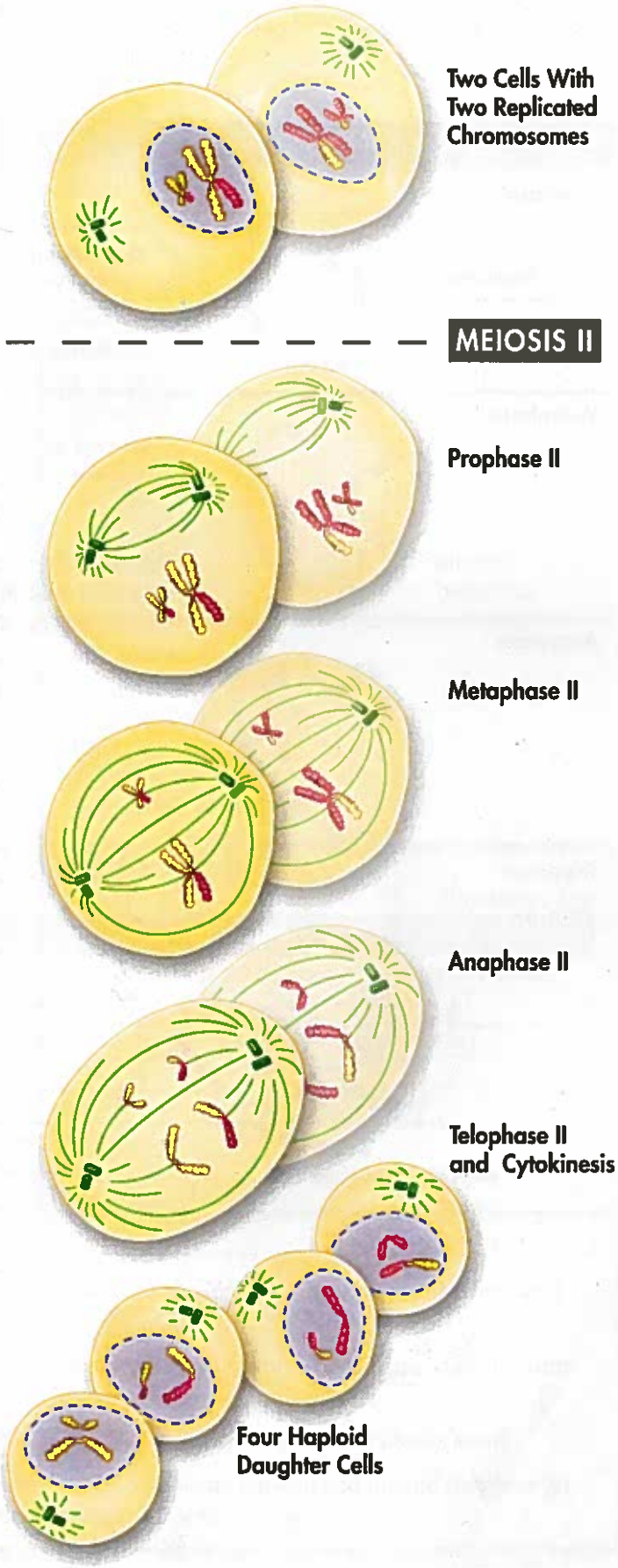
▶ ***Prophase II*** **As the cells enter prophase II, their chromosomes—each consisting of two chromatids—become visible.** The chromosomes do not pair to form tetrads, because the homologous pairs were already separated during meiosis I.

▶ ***Metaphase II, Anaphase II, Telophase II, and Cytokinesis*** During metaphase of meiosis II, chromosomes line up in the center of each cell. As the cell enters anaphase, the paired chromatids separate. **The final four phases of meiosis II are similar to those in meiosis I. However, the result is four haploid daughter cells.** In the example shown here, each of the four daughter cells produced in meiosis II receive two chromatids. These four daughter cells now contain the haploid number (N)—just two chromosomes each.

Gametes to Zygotes The haploid cells produced by meiosis II are the gametes that are so important to heredity. In male animals, these gametes are called sperm. In some plants, pollen grains contain haploid sperm cells. In female animals, generally only one of the cells produced by meiosis is involved in reproduction. The female gamete is called an egg in animals and an egg cell in some plants. Fertilization generates new combinations of alleles in a **zygote** (zy goht). The zygote undergoes cell division by mitosis and eventually forms a new organism.

In Your Notebook *Describe the difference between meiosis I and meiosis II. How are the end results different?*

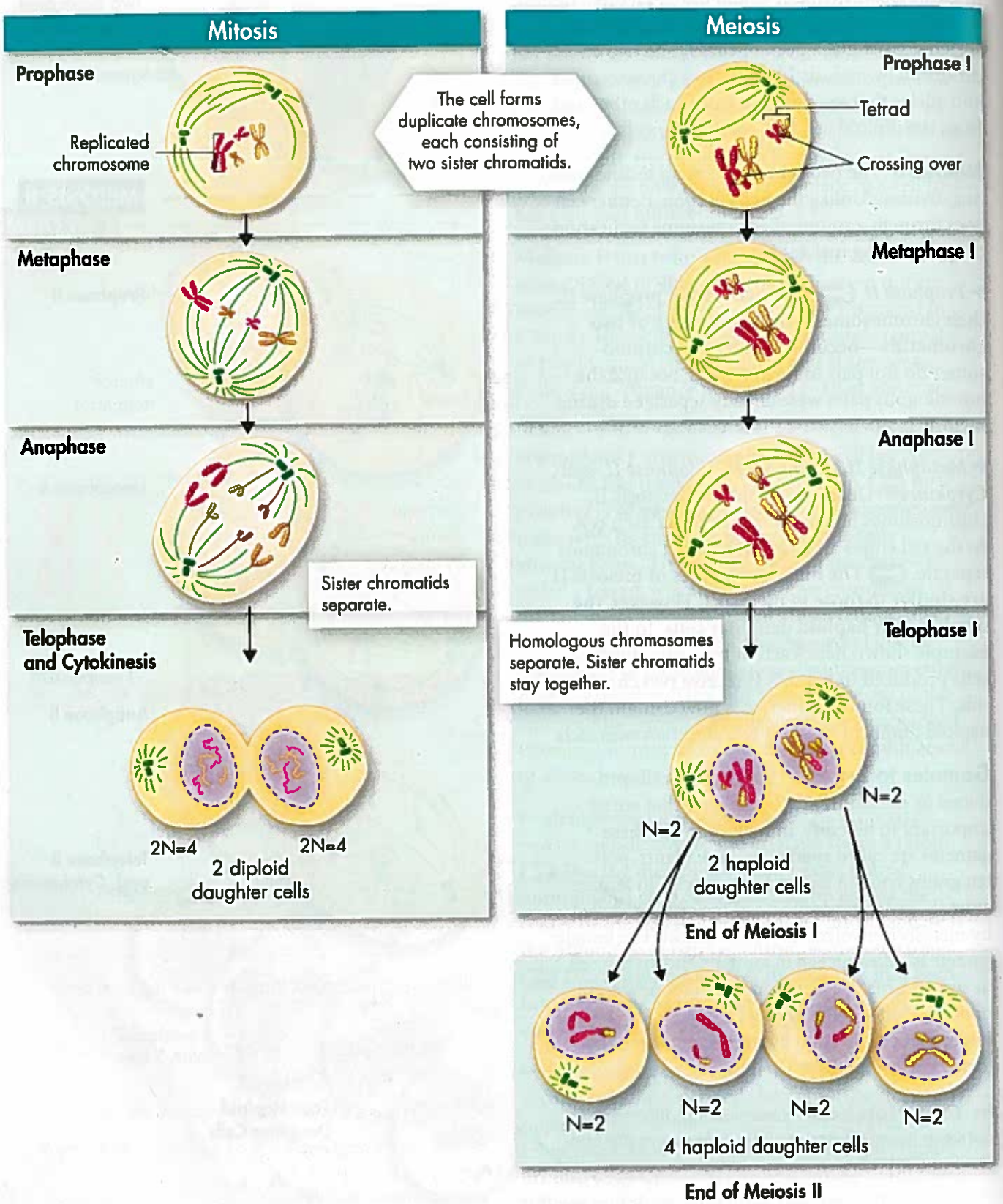
FIGURE 11–16 Meiosis II The second meiotic division, called meiosis II, produces four haploid daughter cells.



VISUAL SUMMARY

COMPARING MITOSIS AND MEIOSIS

FIGURE 11–17 Mitosis and meiosis both ensure that cells inherit genetic information. Both processes begin after interphase, when chromosome replication occurs. However, the two processes differ in the separation of chromosomes, the number of cells produced, and the number of chromosomes each cell contains.



Comparing Meiosis and Mitosis

How is meiosis different from mitosis?

The words *mitosis* and *meiosis* may sound similar, but the two processes are very different, as you can see in **Figure 11–17.** Mitosis is a form of asexual reproduction, whereas meiosis is an early step in sexual reproduction. There are three other ways in which these two processes differ.

Replication and Separation of Genetic Material Mitosis and meiosis are both preceded by a complete copying, or replication, of the genetic material of chromosomes. However, the next steps differ dramatically. **In mitosis, when the two sets of genetic material separate, each daughter cell receives one complete set of chromosomes. In meiosis, homologous chromosomes line up and then move to separate daughter cells.** As a result, the two alleles for each gene are segregated, and end up in different cells. The sorting and recombination of genes in meiosis result in a greater variety of possible gene combinations than could result from mitosis.

Changes in Chromosome Number **Mitosis does not normally change the chromosome number of the original cell. This is not the case for meiosis, which reduces the chromosome number by half.** A diploid cell that enters mitosis with eight chromosomes will divide to produce two diploid daughter cells, each of which also has eight chromosomes. On the other hand, a diploid cell that enters meiosis with eight chromosomes will pass through two meiotic divisions to produce four haploid gamete cells, each with only four chromosomes.

Analyzing Data

Calculating Haploid and Diploid Numbers

Haploid and diploid numbers are designated by the algebraic notations N and 2N, respectively. Either number can be calculated when the other is known. For example, if the haploid number (N) is 3, the diploid number (2N) is 2 × 3, or 6. If the diploid number (2N) is 12, the haploid number (N) is 12/2, or 6.

The table shows haploid or diploid numbers of a variety of organisms. Copy the table into your notebook and complete it. Then, use the table to answer the questions that follow.

Trait Survey

Organism	Haploid Number	Diploid Number
Amoeba	N=25	
Chimpanzee	N=24	
Earthworm	N=18	
Fern		2N=1010
Hamster	N=22	
Honeybee		2N=56
Human		2N=46
Onion		2N=16

1. **Calculate** What are the haploid numbers for the fern and onion plants? MATH
2. **Interpret Data** In the table, which organisms' diploid numbers are closest to that of a human?
3. **Apply Concepts** Why is a diploid number always even?
4. **Evaluate** Which organism's haploid and diploid numbers do you find the most surprising? Why?

Number of Cell Divisions Mitosis is a single cell division, resulting in the production of two identical daughter cells. On the other hand, meiosis requires two rounds of cell division, and, in most organisms, produces a total of four daughter cells. **Mitosis results in the production of two genetically identical diploid cells, whereas meiosis produces four genetically different haploid cells.**

Gene Linkage and Gene Maps

How can two alleles from different genes be inherited together?

If you think carefully about Mendel's principle of independent assortment in relation to meiosis, one question might bother you. Genes that are located on different chromosomes assort independently, but what about genes that are located on the same chromosome? Wouldn't they generally be inherited together?

Gene Linkage The answer to this question, as Thomas Hunt Morgan first realized in 1910, is yes. Morgan's research on fruit flies led him to the principle of gene linkage. After identifying more than 50 *Drosophila* genes, Morgan discovered that many of them appeared to be "linked" together in ways that, at first glance, seemed to violate the principle of independent assortment. For example, Morgan used a fly with reddish-orange eyes and miniature wings in a series of test crosses. His results showed that the genes for those two traits were almost always inherited together. Only rarely did the genes separate from each other. Morgan and his associates observed so many genes that were inherited together that, before long, they could group all of the fly's genes into four linkage groups. The linkage groups assorted independently, but all of the genes in one group were inherited together. As it turns out, *Drosophila* has four linkage groups and four pairs of chromosomes.

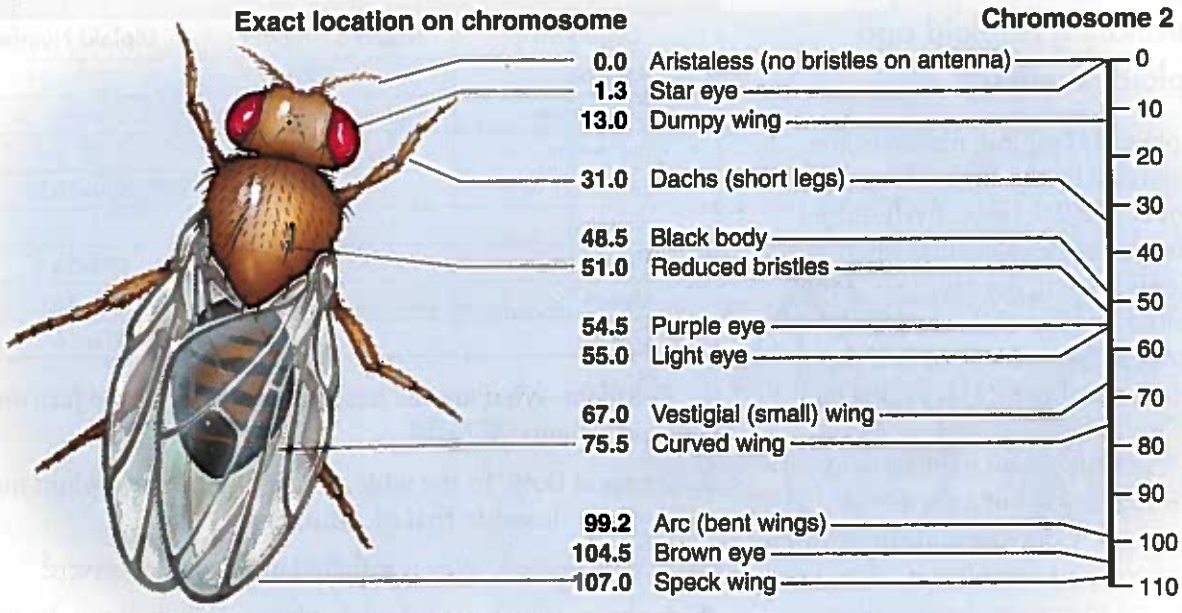


FIGURE 11–18 Gene Map This gene map shows the location of a variety of genes on chromosome 2 of the fruit fly. The genes are named after the problems that abnormal alleles cause, *not* after the normal structures. **Interpret Graphics** ***Where on the chromosome is the "purple eye" gene located?***

Morgan's findings led to two remarkable conclusions. First, each chromosome is actually a group of linked genes. Second, Mendel's principle of independent assortment still holds true. It is the chromosomes, however, that assort independently, not individual genes.

Alleles of different genes tend to be inherited together from one generation to the next when those genes are located on the same chromosome.

How did Mendel manage to miss gene linkage? By luck, or by design, six of the seven genes he studied in pea plants are on different chromosomes. The two genes that are found on the same chromosome are so far apart that they also assort independently.

Gene Mapping In 1911, a Columbia University student was working part time in Morgan's lab. This student, Alfred Sturtevant, wondered if the frequency of crossing-over between genes during meiosis might be a clue to the genes' locations. Sturtevant reasoned that the farther apart two genes were on a chromosome, the more likely it would be that crossing-over would occur between them. If two genes are close together, then crossovers between them should be rare. If two genes are far apart, then crossovers between them should be more common. By this reasoning, he could use the frequency of crossing-over between genes to determine their distances from each other.

Sturtevant gathered up several notebooks of lab data and took them back to his room. The next morning, he presented Morgan with a gene map showing the relative locations of each known gene on one of the *Drosophila* chromosomes. Sturtevant's method has been used to construct gene maps, like the one in **Figure 11–18,** ever since this discovery.

MYSTERY CLUE

White is the least common color found in parakeets. What does this fact suggest about the genotypes of both green parents?

11.4 Assessment

Review Key Concepts

1. **a. Review** Describe the main results of meiosis.
   b. Calculate In human cells, 2N = 46. How many chromosomes would you expect to find in a sperm cell? How many would you expect to find in an egg cell? MATH
2. **a. Review** Write a summary of each phase of meiosis.
   b. Use Analogies Compare the chromosomes of a diploid cell to a collection of shoes in a closet. How are they similar? What would make the shoe collection comparable to the chromosomes of a haploid cell?
3. **a. Review** What are the principle differences between mitosis and meiosis?
   b. Apply Concepts Is there any difference between sister chromatids and homologous pairs of chromosomes? Explain.
4. **a. Review** How does the principle of independent assortment apply to chromosomes?
   b. Infer If two genes are on the same chromosome but usually assort independently, what does that tell you about how close together they are?

Apply the Big idea

Information and Heredity

5. In asexual reproduction, mitosis occurs but meiosis does not occur. Which type of reproduction—sexual or asexual—results in offspring with greater genetic variation? Explain your answer.

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