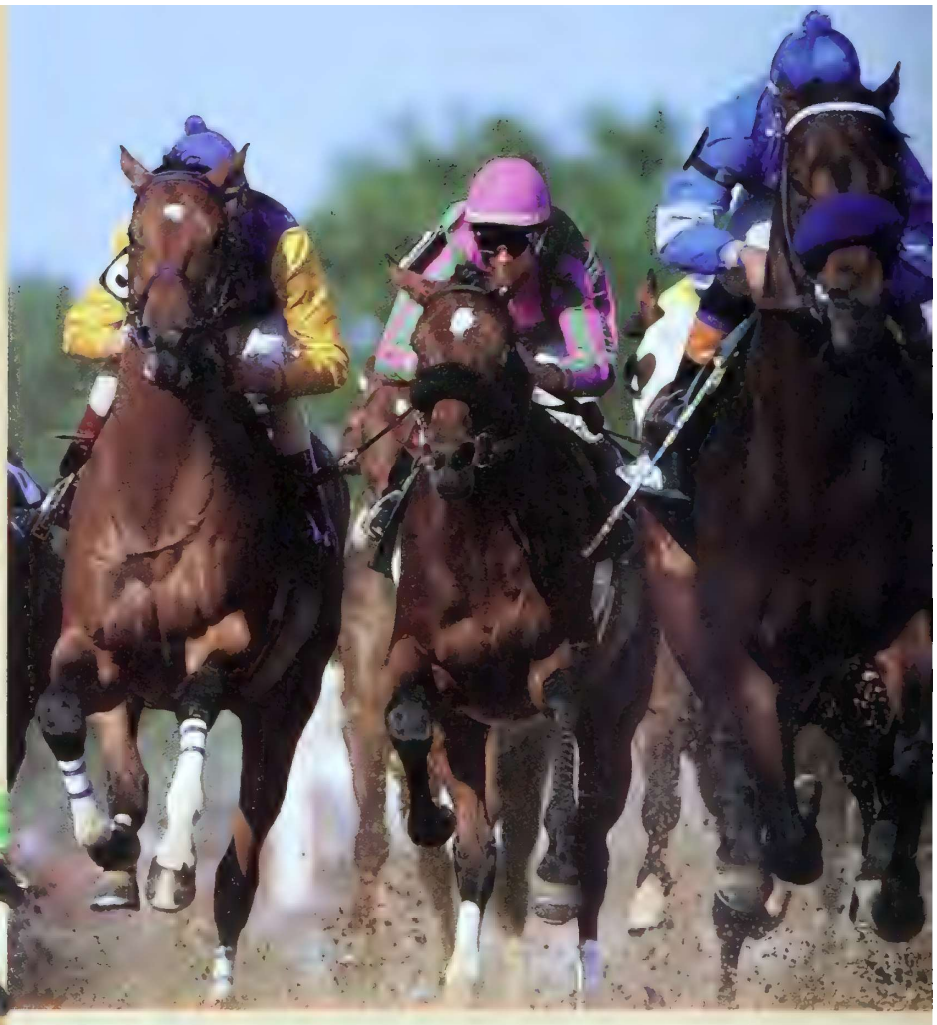
CHAPTER 9

Introduction to Genetics





There are few things as graceful and magnificent as a running horse. A good combination of many inherited traits—fine-boned legs, swiftness, and stamina, for example—helps thoroughbred race horses compete at Churchill Downs in the Kentucky Derby.

Inheritance is something that we are all familiar with; each of us has a biological inheritance. As a child you may have been told that you "inherited" your eyes from your grandfather, your hair from your grandmother, your intelligence from your mother, and your artistic talents from your father. Everyday experience shows us that offspring resemble their parents.

But why do we take after our parents and grandparents? Why do people expect great things from a newborn foal if his father won the Kentucky Derby? Why do the kittens born of a yellow tabby and a black cat have fur colored somewhere between yellow and black? In this chapter you will discover the answers to these questions as you explore the nature of biological inheritance.

CHAPTER OUTLINE

9-1 The Work of Gregor Mendel
- Early Ideas About Heredity
- Gregor Mendel
- Genes and Dominance
- Segregation
- Independent Assortment
- A Summary of Mendel's Work

9-2 Applying Mendel's Principles
- Genetics and Probability
- Using the Punnett Square

9-3 Meiosis
- Chromosome Number
- The Phases of Meiosis
- Meiosis and Genetics
- Gamete Formation
- Comparing Mitosis and Meiosis

9-1 The Work of Gregor Mendel

Section Objectives

- Discuss Mendel's experiments.
- Describe dominance, segregation, and independent assortment.

Biological inheritance, or **heredity**, is the key to differences between species. Cats give birth to kittens, dogs produce puppies, and oak trees produce acorns from which, as the saying goes, mighty oaks may grow. Heredity, however, is much more than the way in which a few superficial characteristics are passed from one generation to another. Heredity is at the very center of what makes each species unique, as well as what makes us human. The branch of biology that studies heredity is called **genetics**.

Early Ideas About Heredity

Until the nineteenth century, the most common explanation for the resemblances between parent and offspring was the theory of blending inheritance. People reasoned that because both a male and a female were involved in producing offspring, each parent contributed factors that determined inheritance—factors that were blended in their offspring. The nature of these factors was unknown.

At first, the theory of blending inheritance seemed a reasonable explanation. It is common to see a little bit of both parents in a child. So it seemed fair to say that the characteristics of the mother and father have blended in making the new life. But in the last century biologists began to look at the details of heredity. When they did, they began to develop a very different



Figure 9–1 *Why don't the two baby guinea pigs look like each other? Why are they different from their mother? The science of genetics helps us answer questions such as these.*

view. The work of the Austrian monk Gregor Mendel was particularly important in changing people's views about how characteristics are passed from one generation to the next.

Gregor Mendel

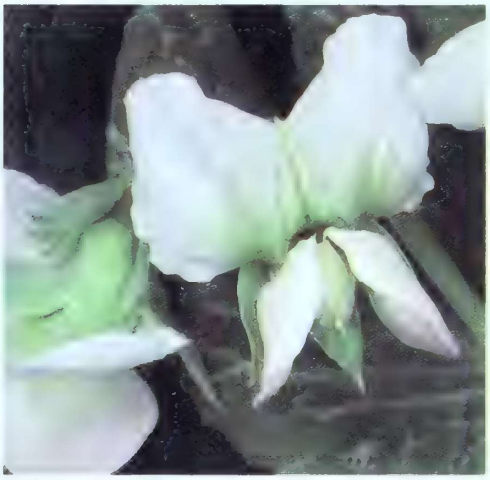
Gregor Mendel was born in 1822 to peasant parents in what is now Czechoslovakia. He did very well in school and entered a monastery in the town of Brno at the age of 21. Four years later he was ordained a priest. The monastery was a center of scientific learning. In 1851, Mendel was sent to the University of Vienna to study science and mathematics. He returned two years later and spent the next fourteen years working in the monastery and teaching at the high school in Brno.

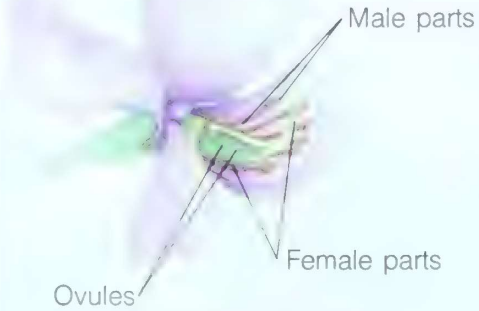
In addition to his teaching duties, Mendel had charge of the monastery garden. It was in this ordinary garden that he was to do the work that revolutionized biological science.

From his studies in biology, Mendel had gained an understanding of the sexual mechanisms of the pea plant. Pea flowers have both male and female parts. Normally, pollen from the male part of the pea flower fertilizes the female egg cells of the very same flower. Because the pollen produced by the plant fertilizes the egg cells of that very same plant, peas are said to produce seeds by **self-pollination**. Seeds produced by self-pollination inherit all of their characteristics from the single plant that bore them.

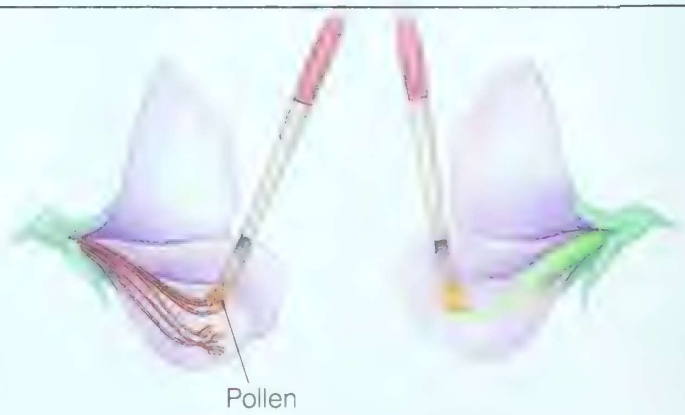
Mendel learned that self-pollination could be prevented. He carefully cut the male parts off all the flowers of one plant and the female parts off all the flowers of another plant. He then pollinated the two plants by dusting the pollen from one plant onto the flowers of the other plant. The fertilization of a plant's egg cells by the pollen of another plant is known as **cross-pollination**. Cross-pollination produces seeds that are the offspring of two different plants. With this technique, Mendel was able to cross plants with different characteristics.

Figure 9–2 Mendel used the garden pea in his experiments on heredity. Garden peas usually reproduce by self-pollination because the male and female reproductive parts are tightly enclosed within the flower's petals (left) One method Mendel used to cross-pollinate his pea plants was to cut off the male parts of a flower (thus preventing self-pollination) and then dust the pollen from another plant onto that flower (right).





Structure of a Pea Flower



Cross-pollination

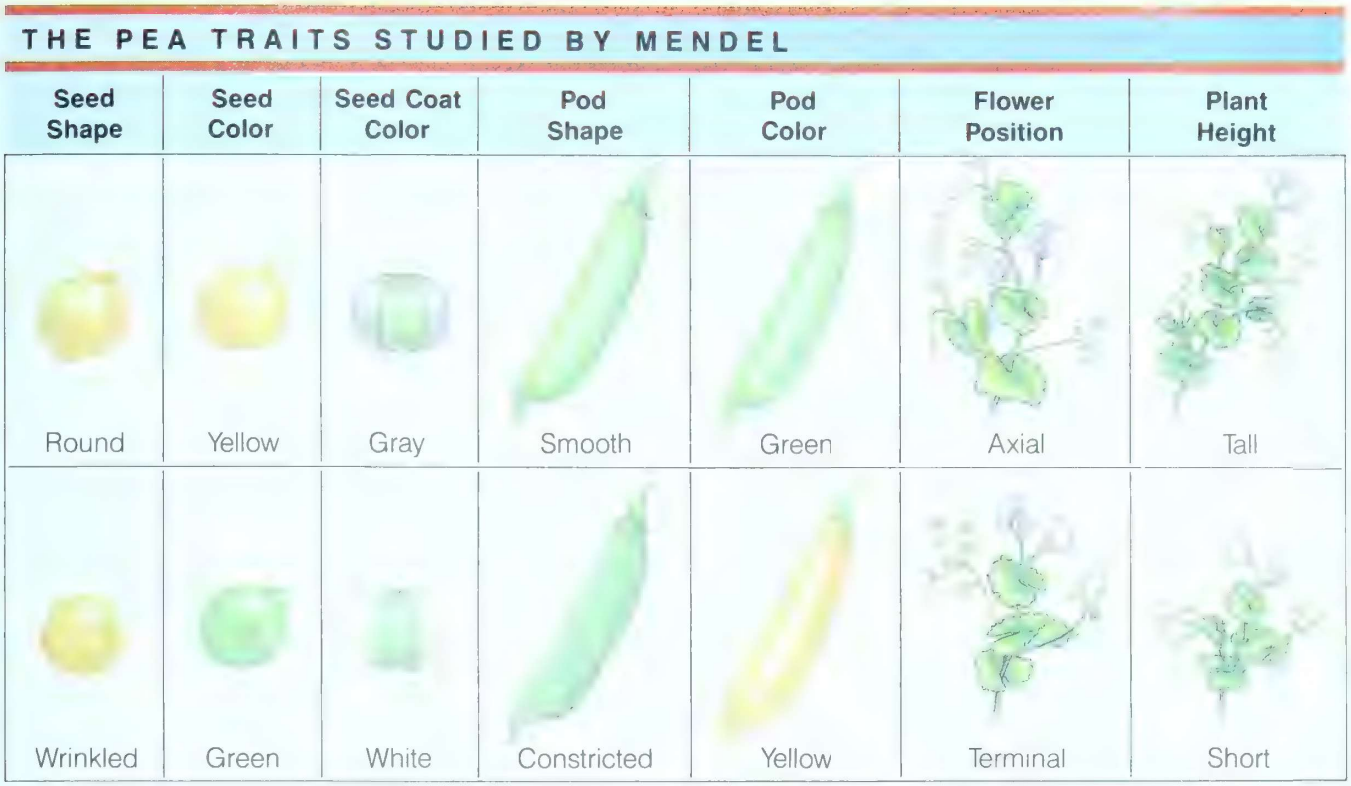


Figure 9–3 *The seven pea traits studied by Mendel are seed shape, seed color, seed coat color, pod shape, pod color, flower position, and plant height. As you can see, each of these traits has two contrasting characters, or forms.*

One of the gifts that Mendel received when he took charge of the monastery garden was a stock of peas developed by earlier gardeners. These peas were **purebred**. This means that if they were allowed to self-pollinate, the purebred peas would produce offspring that were identical to themselves. One line of plants would produce only tall plants, another only short plants. One line would produce only green seeds, another only yellow seeds. These purebred plants were the basis of Mendel's experiments.

In many respects, the most important decision Mendel made was to study just a few isolated **traits**, or characteristics, that could easily be observed. In the case of the peas, one trait was the size of the plant, another the shape of the pod, another the color of the seed. Figure 9–3 shows the seven traits that Mendel studied. By deciding to restrict his observations to just a few such traits, Mendel made his job of measuring the effects of heredity much easier.

Genes and Dominance

What would you do if you were interested in heredity, had several kinds of purebred peas, and also knew how to cause cross-pollination? No, pea soup is not a good answer.

Mendel decided to see what would happen if he crossed pea plants with different characters for the same trait. A character is a form of a trait. For example, the flower-position trait has two characters: axial and terminal. Mendel crossed the tall

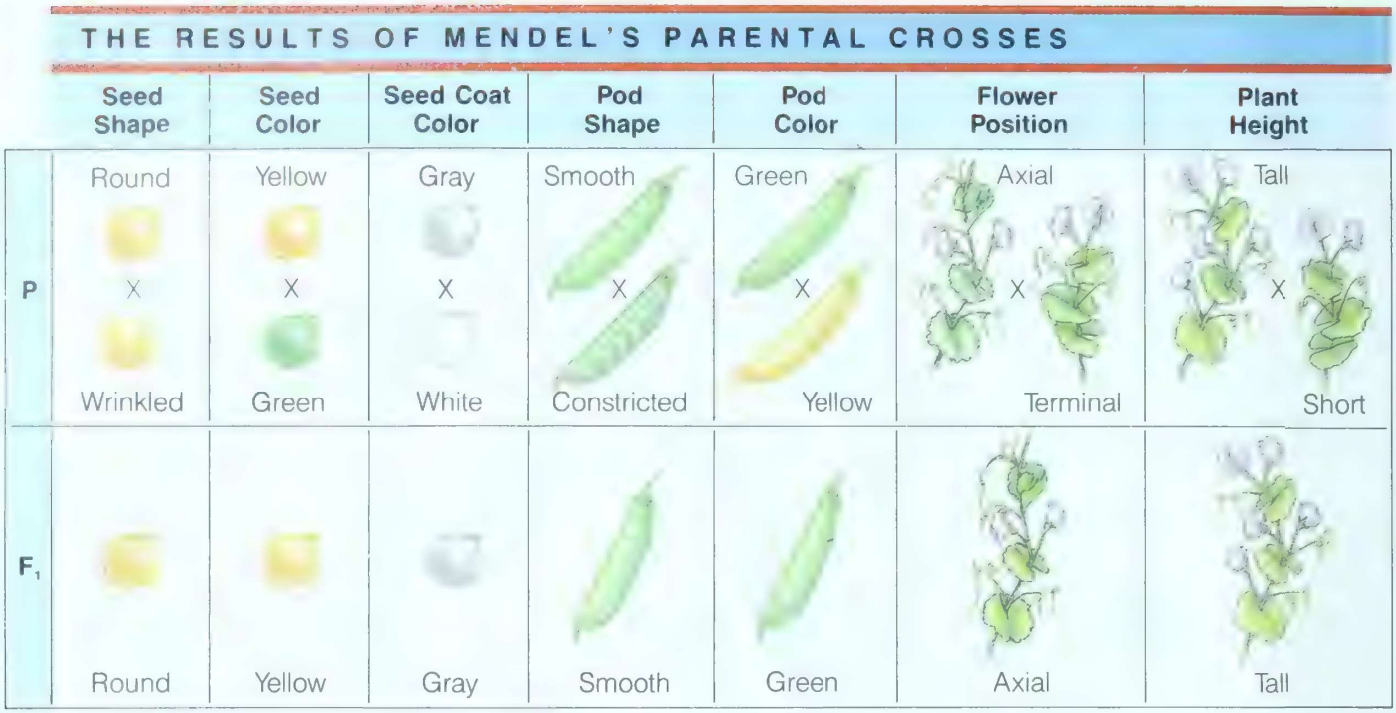


Figure 9–4 *When Mendel crossed plants with contrasting characters for the same trait, the resulting offspring had only one of the characters. From the results of these experiments, Mendel concluded that factors that do not blend control the inheritance of traits and that some of these factors are dominant, whereas others are recessive.*

plants with the short ones; the plants with yellow seeds with those with green seeds; and so on. From the crosses in his pea plants, Mendel obtained seeds that he then grew into plants. These plants were **hybrids**, or organisms produced by crossing parents with differing characters.

What were those hybrid plants like? Did the characters of the parent plants blend in the offspring? To Mendel's surprise, the plants were not half tall, nor were the seeds they produced half yellow. Instead, all of the offspring had the character of only one of the parents. The plants resulting from his crosses were all tall or produced only yellow seeds. The other character had apparently disappeared.

From this set of experiments, Mendel was able to draw two conclusions. The first is that individual factors, which do not blend with one another, control each trait of a living thing. Mendel used the word *Merkmal* to refer to these factors. *Merkmal* means character in German. Today the factors that control traits are called **genes**. Each of the traits Mendel studied was controlled by one gene that occurred in two contrasting forms. These contrasting forms produced the different characters of each trait. For example, the gene for plant height occurs in a tall form and a short form. The different forms of a gene are now called **alleles** (uh-LEELZ).

The second of Mendel's conclusions is often called the principle of **dominance**: Some factors (alleles) are **dominant**, whereas others are **recessive**. The effects of a dominant allele are seen even if it is present with a contrasting recessive allele. The effects of a recessive allele are not observed when the dominant allele is present. In Mendel's experiments, the tall

and yellow alleles were dominant, whereas the short and green alleles were recessive. Although dominance is seen in the inheritance of many traits, it does not apply to all genes.

Segregation

Mendel was not content to stop his experimentation at this point. He wanted the answer to another question: What happened to the recessive characters? To answer this question, he allowed all seven kinds of hybrid plants to reproduce by self-pollination.

To keep the different groups of seeds and plants clear in his mind, Mendel gave them different names. He referred to the purebred parental plants as the P generation (P for parental). To the first generation of plants produced by cross-pollination, he gave the name F_1, which stood for first filial generation (from the Latin word *filius*, which means son). If the F_1 plants were crossed among themselves, he called the offspring F_2, for second filial generation, and so forth.

THE F_1 CROSS The results of the F_1 cross were remarkable. The recessive characters had not disappeared! Some of the F_2 plants produced by each of the F_1 crosses showed the recessive trait. This proved to Mendel that the alleles responsible for the recessive characters had not disappeared. But why did the recessive alleles disappear in the F_1 generation and reappear in the F_2? To answer this question, let's take a closer look at one of Mendel's crosses. Keep in mind that the concepts that apply to the crosses involving the trait of plant height also apply to the crosses for the other six traits.

EXPLAINING THE F_1 CROSS To begin with, Mendel assumed that the presence of the dominant tall allele had masked

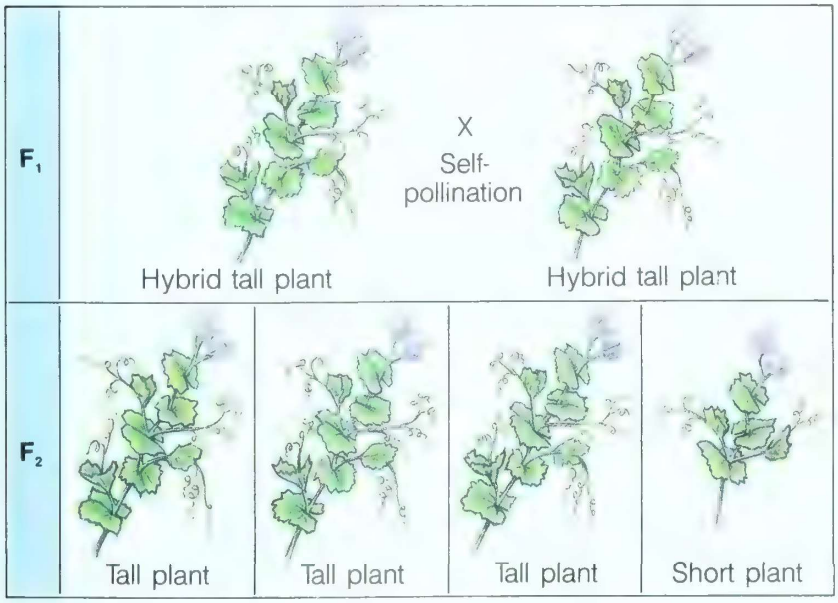


Figure 9–5 *When the F_1 hybrid plants were allowed to reproduce by self-pollination, some of the resulting F_2 offspring had the recessive character.*

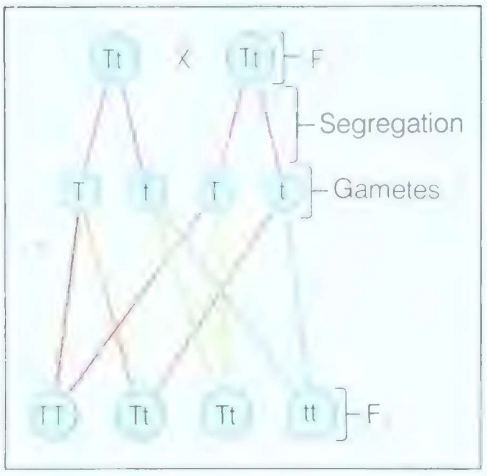


Figure 9–6 *Segregation of alleles occurs during gamete formation. The alleles are paired up again when gametes fuse during the process of fertilization.*

the recessive short allele in the F_1 generation. But the fact that the recessive allele was not masked in some of the F_2 plants indicated that the short allele had managed to get away from the tall allele. But how did this separation, or **segregation**, of alleles occur? Mendel suggested that during the formation of the reproductive cells (pollen and eggs), the tall and short alleles in the F_1 plants were segregated, or separated, from each other. Did that suggestion make sense?

Perhaps Mendel thought as follows: Let's assume that the F_1 plants have one tall factor from one parent and one short factor from the other parent. (Remember that Mendel did not know about genes and alleles.) Suppose such a plant forms flowers and the two factors are segregated from each other when reproductive cells are made. Each F_1 plant will produce two types of reproductive cells: one that has the tall factor and one that has the short factor. What should be the result when two F_1 plants are crossed?

If segregation occurs the way Mendel thought it did, then the possible gene combinations in the offspring that result from a cross can be determined by drawing a diagram known as a **Punnett square**. Biologists represent a particular gene by using a symbol. The dominant allele is represented by a capital letter. The recessive allele is represented by the corresponding lowercase letter. In this case, *T* represents the dominant tall allele and *t* represents the recessive short allele.

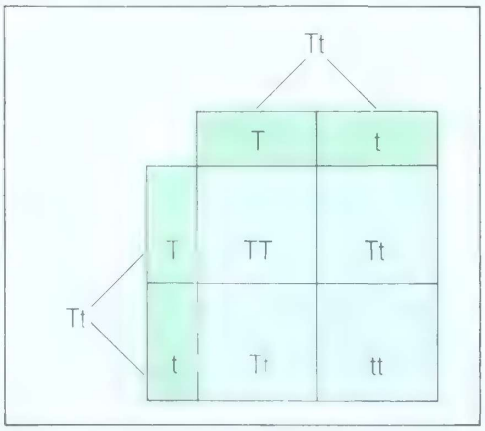
The Punnett square in Figure 9–7 shows the types of reproductive cells, or **gametes** (GAM-eets), produced by each F_1 parent along the top and left-hand side of the square. It also shows each possible gene combination for the F_2 offspring in the four boxes that make up the square.

You can see the probable results of the cross of two F_1 plants from the Punnett square: 1/4 of the F_2 plants have two tall alleles (*TT*); 2/4, or 1/2, of the F_2 plants have one tall allele and one short allele (*Tt*), and 1/4 of the F_2 plants have two short alleles (*tt*). Because tall is dominant over short, 3/4 of the F_2 plants should be tall and 1/4 of the F_2 plants should be short. These numbers are often expressed as ratios. For example, there are 3 tall plants for every 1 short plant in the F_2 generation. Thus the ratio of tall plants to short plants is 3:1. If, of course, Mendel's model of segregation is correct.

Did the data from Mendel's experiments fit his model? Yes. The predicted ratio—3 dominant to 1 recessive—showed up consistently, indicating that Mendel's assumptions about segregation had been correct. For each of his seven crosses, about 3/4 of the plants showed the dominant trait and about 1/4 showed the recessive trait. Segregation did indeed occur according to Mendel's model.

Look again at the Punnett square. You will see that three of the possible combinations result in tall plants. Because all these plants appear tall, we can say that they have the same **phenotype**, or physical characteristics. They do not, however,

Figure 9–7 *This Punnett square shows a cross between two hybrid tall* (Tt) *pea plants.*



have the same **genotype**, or genetic makeup. The genotype of 1/3 of the tall plants is *TT*, whereas the genotype of 2/3 of the tall plants is *Tt*.

Organisms that have two identical alleles for a particular trait (*TT* or *tt* in our example) are said to be **homozygous** (hoh-moh-ZIGH-guhs) (*homo-* means same; *-zygous* refers to alleles). Organisms that have two different alleles for the same trait are **heterozygous** (heht-er-oh-ZIGH-guhs)(*hetero-* means different). In other words, homozygous organisms are purebred for a particular trait and heterozygous organisms are hybrid for a particular trait.



Figure 9–8 *Although these plants have different genotypes* (TT *and* Tt), *they have the same phenotype (tall).*

Independent Assortment

After establishing that genes segregate during the formation of gametes (reproductive cells), Mendel began to explore the question of whether they do so independently. In other words, does the gene that controls one trait have anything to do with the gene that controls a different trait? For example, does the gene that determines whether a seed is round or wrinkled in shape have anything to do with the gene for seed color? Must a round seed also be yellow? To answer these questions, Mendel first crossed purebred plants that produced round yellow seeds with purebred plants that produced wrinkled green seeds.

THE TWO-FACTOR CROSS: F_1 In this cross, the two kinds of plants would be symbolized like this:

Round yellow seeds *RRYY*

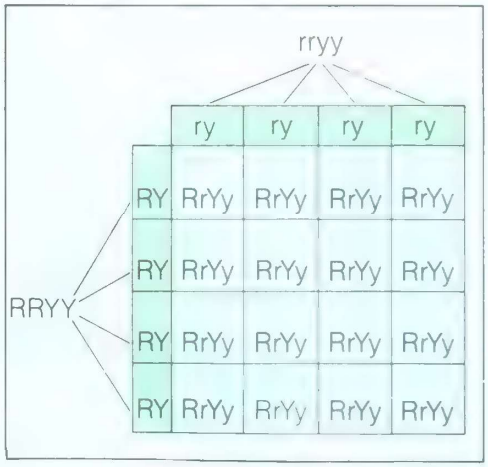
Wrinkled green seeds *rryy*

Because two traits are involved in this experiment, it is called a two-factor cross. As you examine this cross, keep in mind that you are looking at the kind of seeds the plant produces. (These seeds are not necessarily the same as the seeds from which the plants grew!)

The plant that bears round yellow seeds produces gametes that contain the alleles *R* and *Y*, or *RY* gametes. The plant that bears wrinkled green seeds produces *ry* gametes. An *RY* gamete and an *ry* gamete combine to form a fertilized egg with the genotype *RrYy*. Thus only one kind of plant will show up in the F_1 generation—plants that are heterozygous, or hybrid, for both traits. What is the phenotype of the F_1 plants? That is, what will the seeds produced by the F_1 plants look like? Because we know that round and yellow are dominant traits, we can conclude that the F_1 plants will produce seeds that are round and yellow. Remember that the concept of dominance tells us that the dominant traits will show up in a hybrid, whereas the recessive traits will seem to disappear.

This cross does not indicate whether genes assort, or segregate, independently. However, it provides the hybrid plants

Figure 9–9 *When an individual that is homozygous dominant for two traits is crossed with an individual that is recessive for the same two traits, all of the offspring are heterozygous dominant for those two traits.*



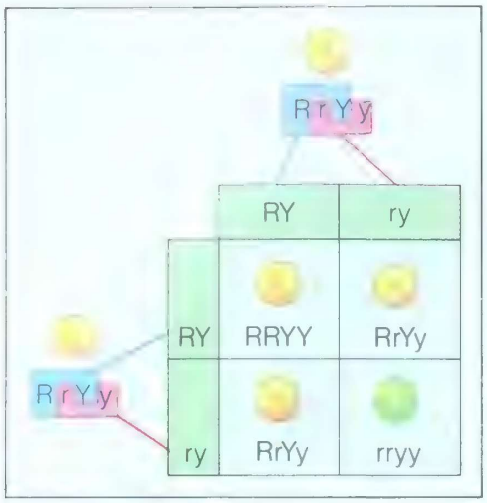


Figure 9–10 *If the genes for two traits are connected in some way, only two combinations of the traits are possible in the offspring.*

needed for the next cross—the cross of F_1 plants to produce the F_2 generation. The seeds from the F_2 plants will show whether the genes for seed shape and seed color have anything to do with one another. Now for the real experiment.

THE TWO-FACTOR CROSS: F_2 What will happen when F_1 plants are crossed with each other? If the genes for seed shape and color are connected in some way, then the dominant *R* and *Y* alleles (which came from one parent) and the recessive *r* and *y* alleles (which came from the other parent) will be segregated as matched sets into the gametes. Thus, the gametes could only contain one of two possible gene combinations: *RY* or *ry*. As you can see in Figure 9–10, all round seeds will be yellow and all wrinkled seeds will be green.

If the genes are not connected, then they should segregate independently, or undergo **independent assortment**. This produces four possible types of gametes: *RY*, *Ry*, *rY*, and *ry*. In addition, if the genes assort independently, some of the seeds produced by the F_2 plants will have new combinations of traits —they may be wrinkled and yellow, or round and green.

This two-factor cross is examined in the Punnett square in Figure 9–11. Now that we have four possible gamete types (and sixteen possible offspring) the square is especially useful. If the genes for seed shape and seed color are inherited independently, then the seeds produced by the offspring should be exactly as predicted by the Punnett square:

9/16	**yellow round seeds**	**(315)**
3/16	**yellow wrinkled seeds**	**(101)**
3/16	**green round seeds**	**(108)**
1/16	**green wrinkled seeds**	**(32)**

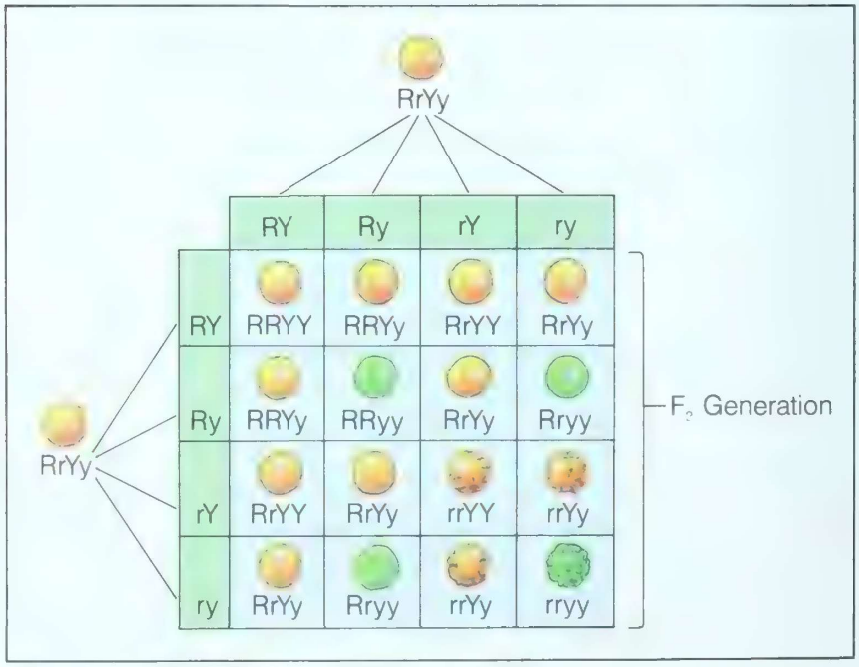


Figure 9–11 *If the genes for two traits are not linked, then they will undergo independent assortment. This results in new combinations of the traits. The phenotypic ratio of the offspring that results from crossing individuals that are hybrid for two traits is 9:3:3:1.*

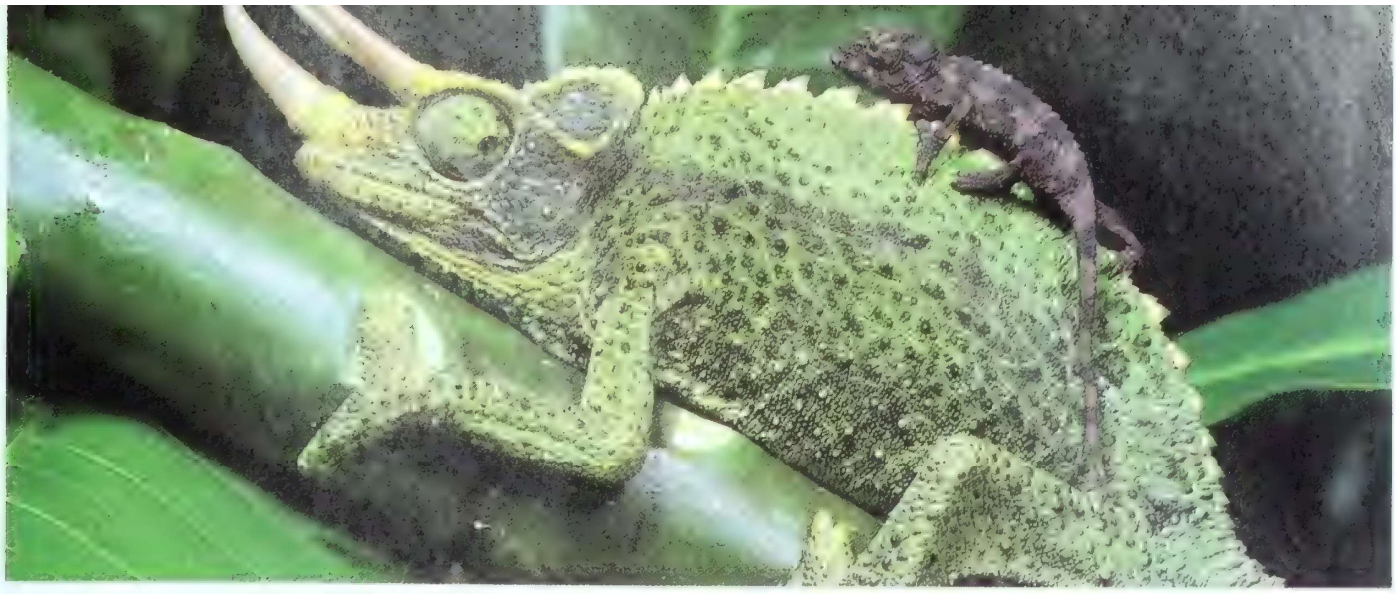


Figure 9–12 *This young chameleon has obtained half of its genes—and a piggyback ride—from its parent.*

Mendel actually carried out this exact experiment, and his results, shown in parentheses, were very close to the 9:3:3:1 ratio that the Punnett square predicts. From these results, Mendel concluded that genes could segregate independently during the formation of gametes. In other words, genes could undergo independent assortment. As we shall see later, there is an important exception to independent assortment. Genes located on the same chromosome are linked and may not undergo independent assortment.

A Summary of Mendel's Work

Mendel's work on the genetics of peas can be summarized in four basic statements:

- **The factors that control heredity are individual units known as genes. In organisms that reproduce sexually, genes are inherited from each parent.**
- **In cases in which an organism possesses two forms of the gene for a single trait, some forms of the gene may be dominant and others may be recessive.**
- **The two forms of each gene are segregated during the formation of reproductive cells.**
- **The genes for different traits may assort independently of one other.**

9–1 SECTION REVIEW

1. What is dominance? Segregation?
2. What is independent assortment?
3. Define the terms genotype and phenotype. To which term does heterozygous refer?
4. Why were purebred peas important for Mendel's experiments?

Section Objectives

- Relate probability to genetics.
- Solve genetics problems using a Punnett square.

9–2 Applying Mendel's Principles

Mendel's careful record keeping and his knowledge of mathematics enabled him to see the patterns of heredity. His paper describing his experiments and conclusions was published in 1866 in the *Proceedings of the Brno Society of Natural Science*. Unfortunately, Mendel's ideas about heredity and his applications of mathematics and statistics to biology were far ahead of their time. Mendel's fellow scientists failed to understand and recognize the importance of his work. In fact, a prominent botanist encouraged Mendel to start working with a different kind of plant and to give up on the hybrid peas. Mendel's pioneering work in genetics remained unappreciated during his lifetime.

In the early 1900s, several scientists working independently rediscovered Mendel's paper. They realized that it correctly described the basic principles of genetics. More than twenty years after his death, Mendel's experiments and conclusions were recognized as important breakthroughs in biology.

Genetics and Probability

One of the most innovative things Mendel did was to apply the mathematical concept of **probability** to biology. **Probability is the likelihood that a particular event will occur.** Probability is determined by the following formula.

$$\text{Probability} = \frac{\text{The number of times a particular event occurs}}{\text{The number of opportunities for the event to occur (the number of trials)}}$$

Consider, for example, the flipping of a coin. When a coin is flipped, one of two possible events can occur: The coin can land heads up or it can land tails up. The probability of the coin coming up heads is 1/2, or 1:1. In other words, you will probably get heads (the particular event) one time out of every two times you flip the coin (the trials). And you will probably get tails one time out of every two times you flip the coin. Therefore, if you were to flip the coin 10 times, the most likely outcome would be 5 heads and 5 tails. However, there is a chance that you would wind up with a different outcome—perhaps 4 heads and 6 tails, or 10 heads and 0 tails.

These different outcomes reveal an important rule of probability: You only get the expected ratio for large numbers of trials. The larger the number of trials, the closer you get to the expected ratios. If you were to flip the coin hundreds of times, your final results would be much closer to 1:1. If you were to flip the coin thousands of times, your final results would be even closer to 1:1. With this in mind, why do you think Mendel worked with thousands of pea plants?

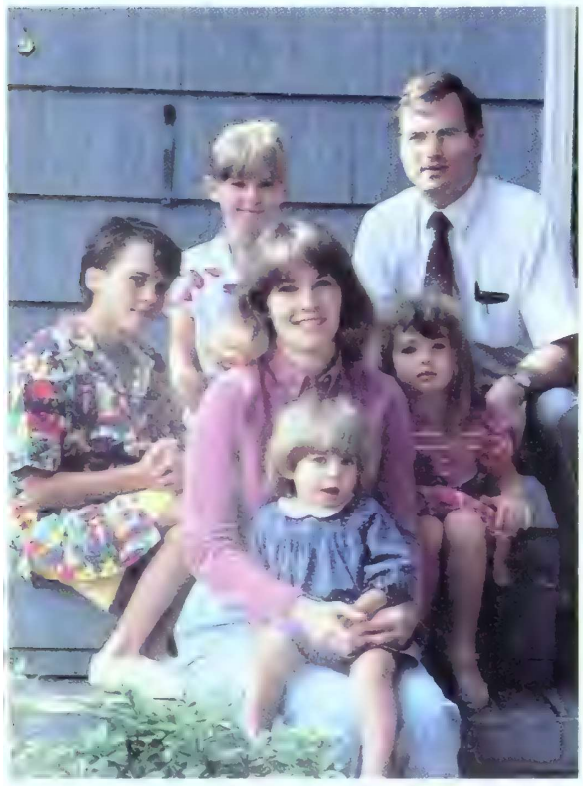


Figure 9–13 *The mathematical concept of probability allows us to calculate the likelihood that a particular event will occur. What is the probability that the next child in this family will be another girl?*

Suppose you flipped a coin and it came up heads ten times in a row. What are the chances of getting heads again on your next flip? Because of all the times the coin came up heads, you might think it is more likely that the coin will now come up tails rather than heads. But this is not the case. There is another important rule of probability: Previous events do not affect future outcomes. Each flip of the coin is a separate, independent event. For each flip of the coin, the probability of getting heads is always 1/2, or 1:1. It does not matter what happened on previous flips of the coin.

The rules of probability apply to genetics as well as to flipping a coin. Expected genetic ratios may not show up when only a few pea plants (or other organisms) are considered. The larger the number of organisms examined, the closer the numbers will get to the expected values. In addition, genetic ratios do not indicate what the outcome of a single event will be. Because previous events do not affect future outcomes, it cannot be assumed that a particular event will occur because it seems overdue. Despite such limitations, genetic ratios are still very useful because they make it possible to predict the most likely outcome for a large number of events.

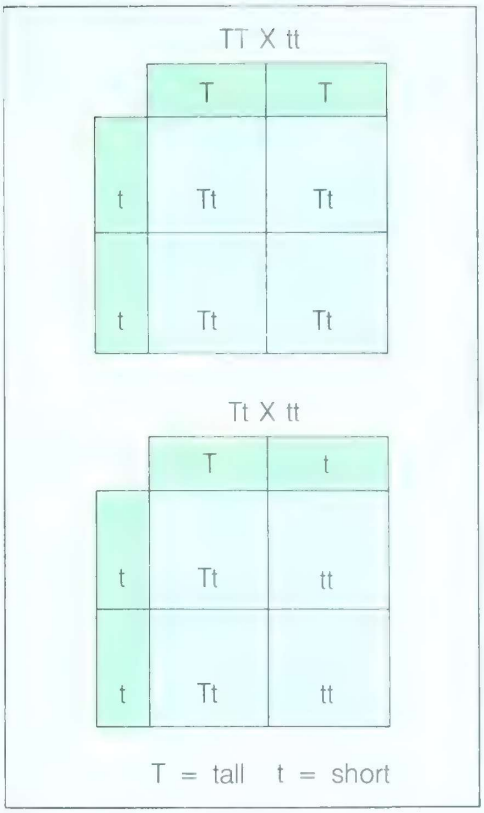


Figure 9–14 *A test cross is used to determine the genotype of an individual showing a dominant trait. If any of the offspring resulting from a test cross has the recessive phenotype, then the unknown parent is heterozygous.*

Using the Punnett Square

The Punnett square is a handy device for analyzing the results of an experimental cross, and it's a good idea to become familiar with its use. Practice using the Punnett square in the one-factor and two-factor genetics problems that follow.

ONE-FACTOR CROSS In pea plants, tall (*T*) is dominant over short (*t*). You have a tall plant. Design a cross to see if this plant is homozygous (*TT*) or heterozygous (*Tt*).
Solution:

Cross your tall plant with a short plant. The cross of an organism of unknown genotype and a homozygous recessive individual is called a **test cross**. Figure 9–14 shows how a test cross works.

As you can see in the Punnett squares, if any of the offspring resulting from a test cross shows the recessive phenotype, then the unknown parent must be heterozygous.

TWO-FACTOR CROSS In pea plants, green pods (*G*) are dominant over yellow pods (*g*), and smooth pods (*N*) are dominant over constricted pods (*n*). A plant heterozygous for both traits (*GgNn*) is crossed with a plant that has yellow constricted pods (*ggnn*). What are the probable genotypic and phenotypic ratios for this cross?
Solution:

Genotypic ratio = 4*GgNn*:4*Ggnn*:4*ggNn*:4*ggnn* = 4:4:4:4 = 1:1:1:1
Phenotypic ratio = 4 green smooth:4 green constricted:4 yellow smooth:4 yellow constricted = 4:4:4:4 = 1:1:1:1

Figure 9–15 *This Punnett square illustrates a cross between a pea plant that has the genotype* GgNn *and one that has the genotype* ggnn.

GgNn X ggnn

	GN	Gn	gN	gn
gn	GgNn	Ggnn	ggNn	ggnn
gn	GgNn	Ggnn	ggNn	ggnn
gn	GgNn	Ggnn	ggNn	ggnn
gn	GgNn	Ggnn	ggNn	ggnn

G = green g = yellow
N = smooth n = constricted

SCIENCE, TECHNOLOGY, AND SOCIETY **APPLICATION**

Creating a New Breed of Cat

Siamese and Persian cats are two of the most popular kinds of purebred cats. They are also two of the most ancient breeds, with histories that go back several centuries. Siamese cats are slender, with light-colored bodies and dark markings on the face, legs, and tail. Persian cats are stocky and have long luxurious fur. A third breed of cat, the Himalayan, has the distinctive markings of the Siamese and the stocky build and long fur of the Persian. Unlike Siamese and Persian cats, Himalayans have been around for a relatively short time—less than 60 years. And unlike most breeds of cats, the Himalayan is an artificial breed.

The first Himalayan was born in 1935, the product of five years of genetics experiments at Harvard Medical School. The researchers were trying to determine how certain cat traits, such as long fur and Siamese markings, are inherited.

The scientists first crossed Siamese cats with gray, black, or striped Persian cats. The offspring of these crosses all had short hair and were gray, black, or striped in color. When two of the short-haired cats were mated, one of the female offspring had long black fur. This female, when mated to her male parent, produced a long-haired kitten with Siamese markings—the first Himalayan cat.

From their crosses, the scientists determined that short hair was dominant over long hair and that solid or striped colors were dominant over Siamese markings. Although the scientists had created a new type of cat, their role in the new Himalayan breed was over. After all, they had discovered what they had set out to find. Cat breeders in the United States and Britain took over where the scientists had left off. These breeders focused their attention, however, on the effects of other genes, such as those for general body type. By the early 1960s, more than 25 years after the birth of the first Himalayan, the breed was officially recognized by all of the major cat associations in the United States and Britain.



The Himalayan is an artificial breed of cat. It was created during the course of genetics experiments.

9-2 SECTION REVIEW

1. What is probability?
2. What is a test cross?
3. What kind of cross produces a 9:3:3:1 ratio of offspring?
4. A cross of F_1 plants heterozygous for height should produce a ratio of tall to short plants of 3:1. Three seeds from such a cross have been grown and they have produced three tall plants. What are the chances that a fourth seed will produce a short plant?

9–3 Meiosis

Section Objectives

- Describe the process of meiosis.
- Compare meiosis and mitosis.

The principles of genetics described by Mendel require that organisms inherit a single copy of each gene from each of their parents. These two copies are then segregated from each other during the formation of gametes. An obvious way to test Mendel's ideas would be to see if something similar to segregation takes place during the formation of gametes.

But how are gametes formed? In Chapter 8 you learned about mitosis, a process that involves the separation of chromosomes and the formation of new cells. Could gametes be formed by mitosis?

The answer to this question is no. If gametes were formed by mitosis in the common fruit fly, *Drosophila melanogaster*, each gamete would contain 8 chromosomes—as do the other cells of the fly. When sperm and egg fused in the process of fertilization, the first cell of the offspring would contain 16 (or 8 + 8) chromosomes. This is twice the number of chromosomes in the cells of the parents. If the number of chromosomes doubled in each generation, before long the cells would contain an unwieldy number of chromosomes.

Chromosome Number

The 8 chromosomes in a *Drosophila* cell can be divided into two sets: One set contains 4 chromosomes from the male parent and the other set contains 4 chromosomes from the female parent. Each chromosome in the male set has a corresponding chromosome in the female set. These corresponding chromosomes are said to be **homologous**. (The chromosomes themselves are called homologs.) A cell that contains both sets of homologous chromosomes (one set from each parent) is said to be **diploid**.

The diploid number is sometimes represented by the symbol 2N. Thus for *Drosophila* 2N=8. A diploid cell contains two complete sets of chromosomes and two complete sets of genes.

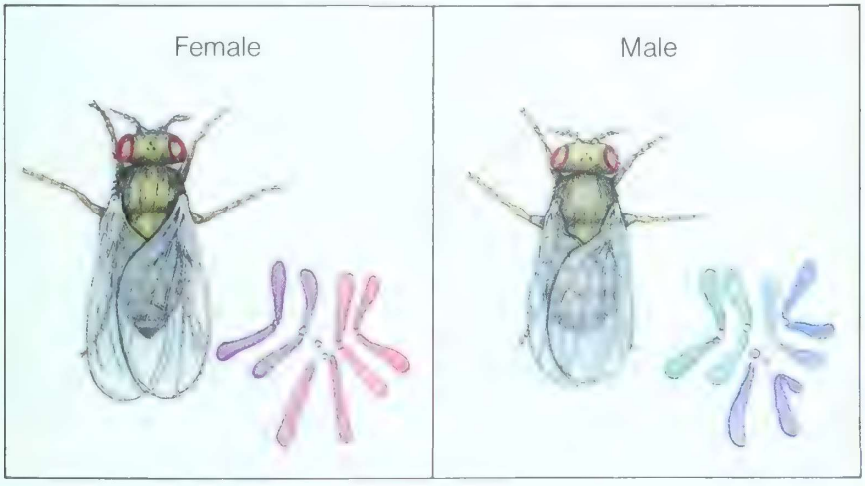




Figure 9–16 *Each body cell in a fruit fly contains 8 chromosomes—4 from the male parent and 4 from the female parent (left). This photograph shows the 4 pairs of giant chromosomes of the fruit fly* Drosophila *(right). These giant chromosomes consist of many chromatids attached in parallel.*

This agrees with Mendel's idea that all of an organism's cells (except the gametes) contain two alleles for a given trait. Mendel's model of segregation implies that gametes, unlike other cells, should contain only a single set of genes because alleles are separated during the process of gamete formation. This is exactly the case. The gametes of organisms that reproduce sexually contain a single set of chromosomes (and genes). Cells that contain a single set of chromosomes are said to be **haploid** and are represented by the symbol N. For *Drosophila*, N=4. In order for gametes to be produced, there must be a process that divides the diploid number of chromosomes in half.

The Phases of Meiosis

Haploid gametes are produced from diploid cells by the process of **meiosis** (migh-OH-sihs). Meiosis is a process of reduction division in which the number of chromosomes per cell is cut in half and the homologous chromosomes that exist in a diploid cell are separated.

In most organisms, meiosis takes place in two stages, known as the first and second meiotic divisions. Do not be confused because the phases of meiosis have the same names as the phases of mitosis. The phases of meiosis are actually very different from the phases of mitosis. We will examine meiosis in an organism with a diploid number of 8 (2N=8). Refer to Figure 9–17 as the process of meiosis is described.

MEIOSIS I In the first stage of meiosis, meiosis I, special cells in the reproductive organs undergo a round of DNA replication. The cells then enter a process of cell division that looks deceptively like mitosis. But it's not.

Recall that in mitosis the 8 chromosomes line up in the center of the cell. At this time, each chromosome contains 2 chromatids, which separate from each other as anaphase begins. But in prophase I of meiosis, each chromosome seeks out its corresponding homologous chromosome to form a special structure called a tetrad. The word tetrad comes from the Greek word *tetra*, which means four. And as you can see in

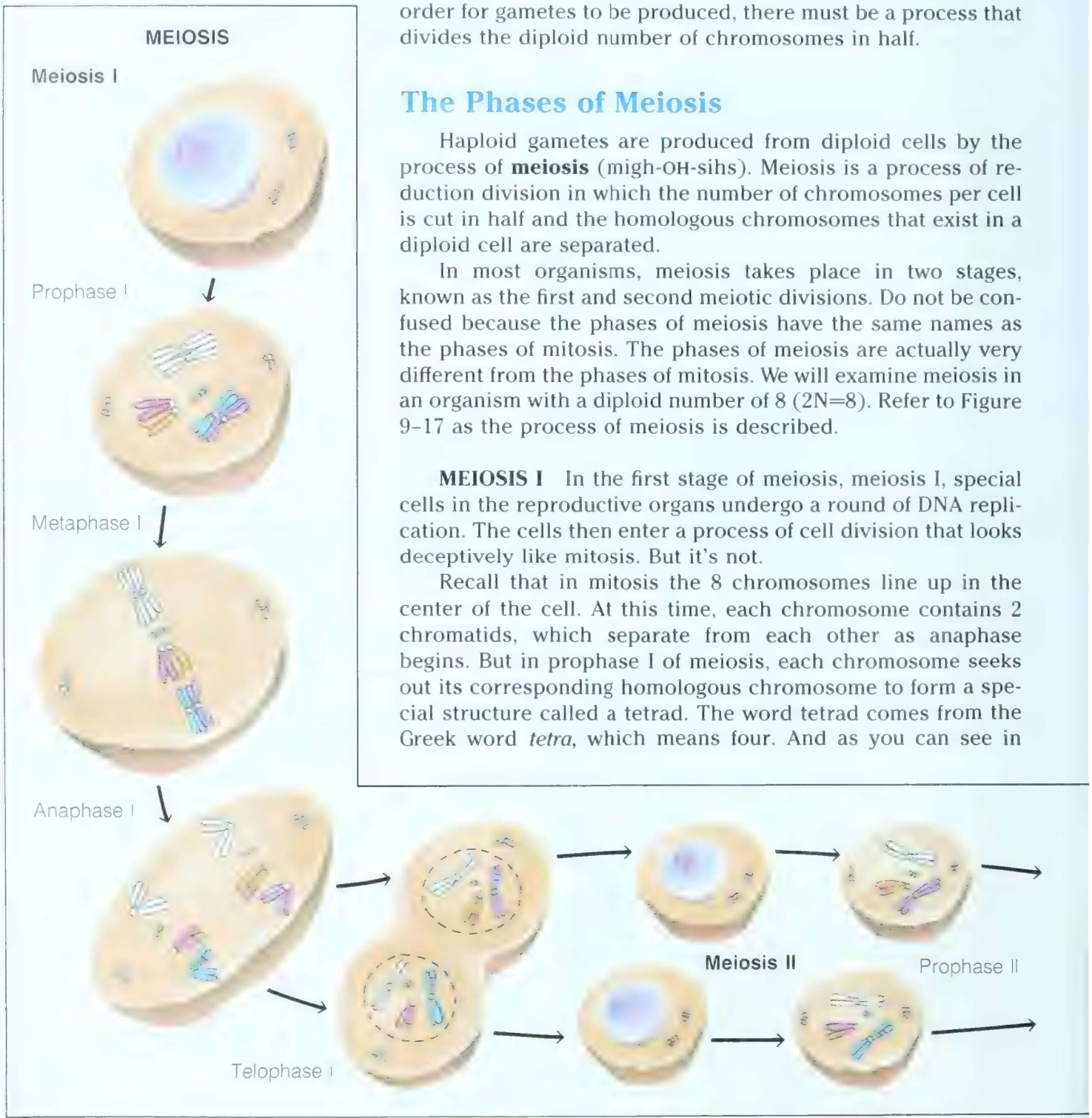


Figure 9–17 *In the process of meiosis, the number of chromosomes per cell is cut in half and homologous chromosomes are separated. Meiosis produces four haploid gamete cells that are genetically different from one another and from the original diploid parent cell.*

Figure 9–17, there are 4 chromatids in a tetrad. Tetrads, rather than individual chromosomes, line up in the center of the cell during metaphase I of meiosis.

As the homologous chromosomes pair up and form tetrads in meiosis I, they may exchange portions of their chromatids in a process called **crossing-over**. Crossing-over results in the exchange of genes between homologous chromosomes and produces new combinations of genes.

What happens next? The homologous chromosomes separate and two new cells are formed. Although each cell now has 8 chromatids (just as it would after normal mitosis) something is different. Look at Figure 9–17 closely. The two cells no longer have two complete sets of the 4 chromosomes. Instead, the maternal and paternal chromosomes have been shuffled like a deck of cards. The two cells produced by meiosis I have sets of chromosomes (and genes) that are different from each other. These sets are also different from the set in the cell that began the division.

MEIOSIS II The two cells produced by meiosis I now enter meiosis II. Unlike a cell undergoing a second mitotic division, neither cell goes through a round of DNA replication before entering the second meiotic division. Thus each of the cells' chromosomes contains 2 chromatids. During metaphase II of meiosis, 4 chromosomes line up in the center of each cell. In anaphase II, the paired chromatids separate. Each of the four daughter cells produced in meiosis II receives 4 chromatids. The four daughter cells contain the haploid number (N)—4 chromosomes each. The amount of genetic material has been reduced. In addition, the combinations of chromosomes in each gamete have been made at random.

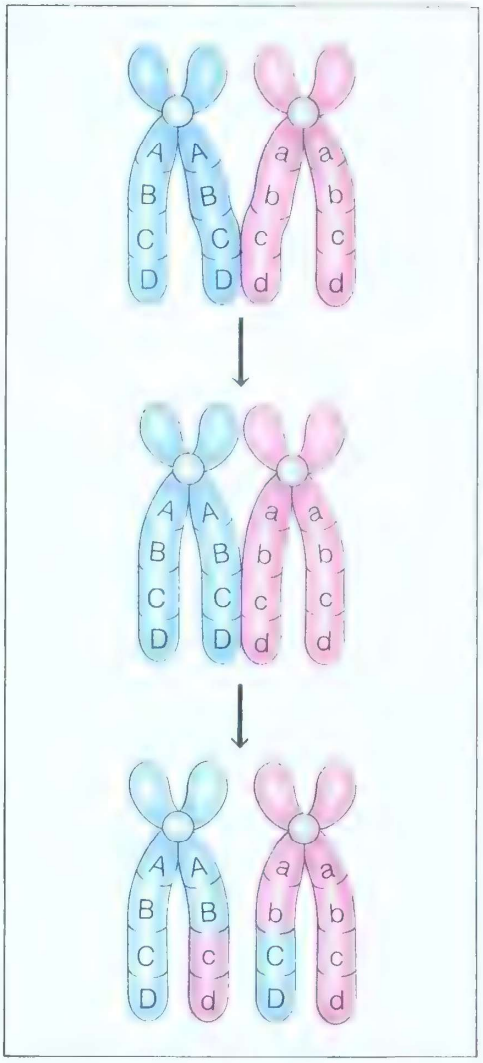
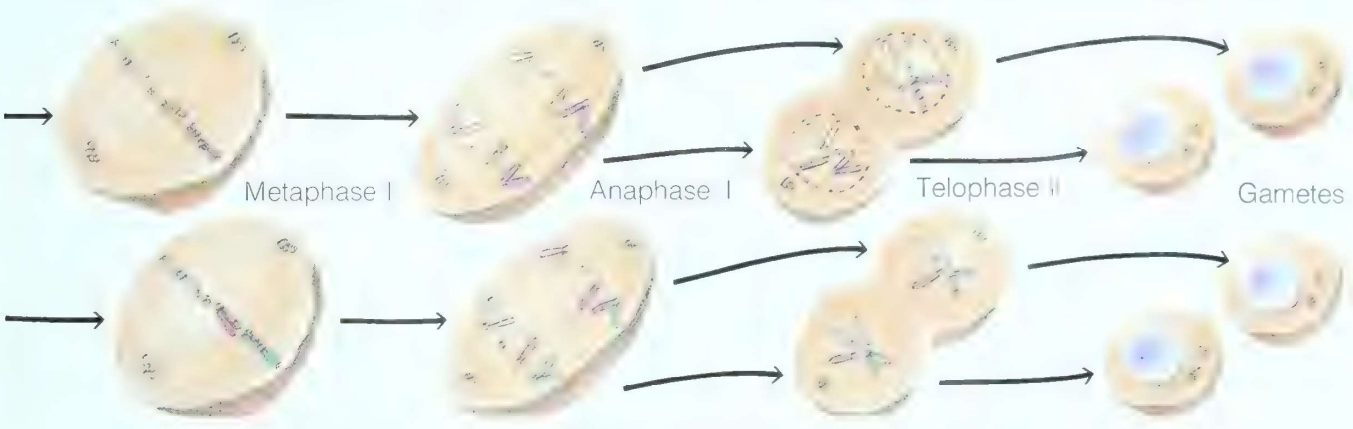


Figure 9–18 *During prophase I of meiosis, homologous chromosomes may exchange portions of their chromatids in a process called crossing-over.*

Meiosis and Genetics

As they pass through meiosis, the chromosomes do all the things that Mendel's ideas predicted structures that carry genes would do. Meiosis I results in segregation and independent assortment. During anaphase I of meiosis, the homologous chromosomes separate and are segregated to



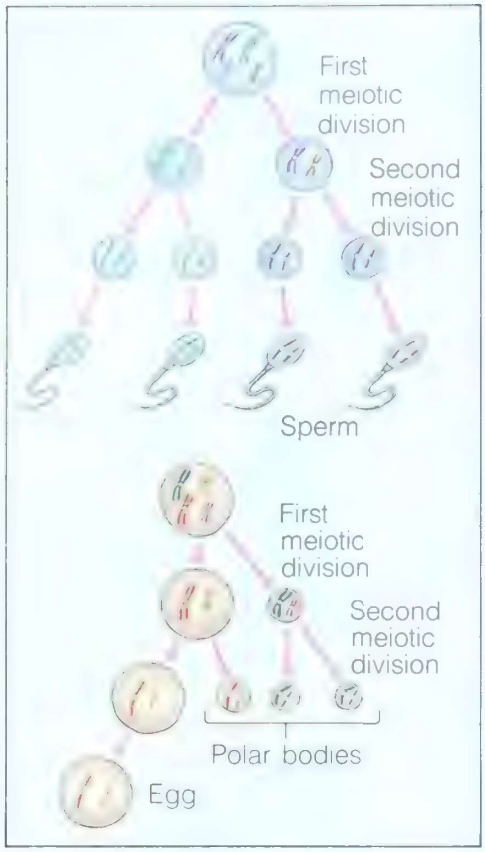


Figure 9–19 *In males, meiosis results in four gametes that are the same size as one another. In females, the four cells produced in meiosis are different sizes—three are small and one is large. The large cell is usually the only one of the four female cells that participates in reproduction.*

different cells. This also segregates the homologous forms of a gene, or alleles, that are located on these chromosomes. This agrees with Mendel's principles. The chromosomes themselves assort independently during meiosis I. The separation of chromosomes during the first meiotic division is completely random. Which cell receives the maternal copy of a chromosome and which cell receives the paternal copy is strictly a matter of chance.

Gamete Formation

In male animals, the haploid gametes produced by meiosis are called sperm. In higher plants, pollen grains contain haploid sperm cells. In female animals, generally only one of the cells produced by meiosis is used for reproduction. This female gamete is called an egg (animals) or ovule (higher plants). In female animals, the cell divisions at the end of meiosis I and meiosis II are uneven, so that the egg or ovule receives most of the cytoplasm. The other three cells produced in the female during meiosis are known as polar bodies and usually do not participate in reproduction.

Comparing Mitosis and Meiosis

In a way, it's too bad that the words mitosis and meiosis sound so similar and have the same names for their phases because the two processes are very different. Mitosis results in the production of two genetically identical cells. A diploid cell that divides by mitosis gives rise to two diploid daughter cells. The daughter cells have sets of chromosomes (and genes) identical to each other and to the original parent cell.

Meiosis, on the other hand, begins with a diploid cell but produces four haploid cells. These cells are genetically different from the diploid cell and from one another. This is because homologous chromosomes are separated during the first meiotic division and because crossing-over results in the production of new gene combinations on the chromosomes.

9–3 SECTION REVIEW

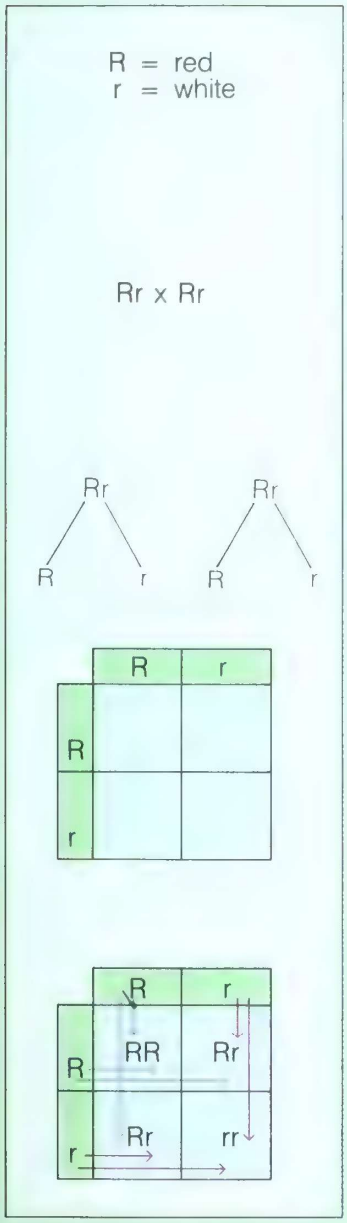
1. What is meiosis?
2. Define diploid and haploid.
3. In which meiotic division does segregation occur?
4. What are the principal differences between mitosis and meiosis?
5. In human cells, 2N=46. How many chromosomes would you expect to find in a sperm cell? In an egg cell? In a white blood cell? Explain your answers.

SOLVING GENETICS PROBLEMS

One-Factor Crosses: Sample Problem

In pea plants, red flowers are dominant over white flowers. A heterozygous red flower is allowed to self-pollinate. What are the probable genotypic and phenotypic ratios in the offspring of this plant?

SOLUTION



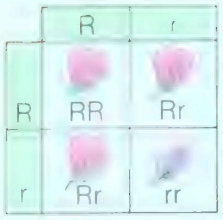
Step 1 **Choose a letter to represent the genes in the cross.**
Use a letter whose capital form does not look too similar to its lowercase form. This will make it easier for you to read your finished Punnett square. Except for that requirement, it is not important which letter you select. In this case, let's use *R* for the dominant red allele and *r* for the recessive white allele.

Step 2 **Write the genotypes of the parents.**
This step is often written as an abbreviation of the cross being studied. The X between the parents' genotypes is read "is crossed with." In this case, *Rr* X *Rr* is read "*Rr* is crossed with *Rr*." Although only one parent is involved in this problem, you must still write it as a cross in which you account for a male parent and a female parent.

Step 3 **Determine the possible gametes (reproductive cells) that the parents can produce.**
Remember that alleles are segregated during the formation of gametes. Each gamete has 1/2 the number of alleles in the parent.

Step 4 **Enter the possible gametes at the top and side of the Punnett square.**

Step 5 **Complete the Punnett square by writing the alleles from the gametes in the appropriate boxes.**
This step represents the process of fertilization. The allele from the gamete above the box and the allele from the gamete to the side of the box are combined inside each of the four boxes. If there is a combination of capital letter and lowercase letter in a box, write the capital letter first. The letters inside the boxes represent the probable genotypes of the offspring resulting from the cross. In this example, 1/4 of the offspring are genotype *RR*, 1/2 are *Rr*, and 1/4 are *rr*.



Genotypic ratio = 1:2:1
Phenotypic ratio = 3:1

Step 6 **Determine the phenotypes of the offspring.**
Remember that phenotype refers to the physical appearance of an organism. The principle of dominance makes it possible to determine the phenotype that corresponds to each genotype inside the Punnett square. In this example, 3/4 of the offspring have red flowers and 1/4 of the offspring have white flowers.

Step 7 **Using the results of Steps 5 and 6, answer the problem.**
Usually you will be asked to summarize the results of the cross by providing genotypic and phenotypic ratios. When writing such ratios, the numbers for the dominant genotype(s) or phenotype(s) come first. In this example, 1/4 of the offspring are genotype *RR*, 1/2 (or 2/4) are *Rr*, and 1/4 are *rr*. The genotypic ratio is therefore 1/4:2/4:1/4, or 1:2:1. Three fourths of the offspring have red flowers and 1/4 have white flowers. The phenotypic ratio is therefore 3/4:1/4, or 3:1.

Two-Factor Crosses: Sample Problem

In the fruit fly *Drosophila melanogaster*, wings (*A*) are dominant over a lack of wings (*a*) and red eyes (*E*) are dominant over sepia (brownish) eyes (*e*). A wingless fly that is heterozygous for eye color is crossed with a fly that is heterozygous for both eye color and presence of wings. What are the genotypic and phenotypic ratios for this cross? What fraction of the offspring from this cross will be wingless and have sepia eyes? What fraction will have the genotype *AaEe*?

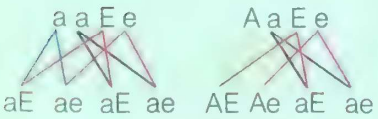
SOLUTION

A = wings
a = wingless
E = red
e = sepia

Step 1 **Choose letters to represent the genes in the cross.**
In this particular problem, the letters to use are given to you. In the event that they are not, follow the same suggestions for choosing letters stated in Step 1 of the One-Factor Cross.

aaEe x AaEe

Step 2 **Write the genotypes of the parents.**



Step 3 **Determine the possible gametes that the parents can produce.**

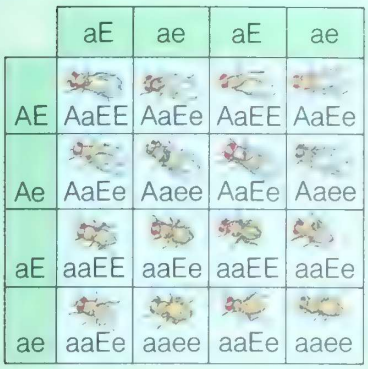
Step 4 **Enter the possible gametes at the top and side of the Punnett square.**

	aE	ae	aE	ae
AE				
Ae				
aE				
ae				

	aE	ae	aE	ae
AE	AaEE	AaEe	AaEE	AaEe
Ae	AaEe	Aaee	AaEe	Aaee
aE	aaEE	aaEe	aaEE	aaEe
ae	aaEe	aaee	aaEe	aaee

Step 5 **Complete the Punnett square by writing the alleles from the gametes in the appropriate boxes.**

The alleles from the gamete above the box and the alleles from the gamete to the side of the box are combined inside each of the boxes. Write the capital letter first for each pair of alleles. The letters inside each box represent the probable genotypes of the offspring resulting from the cross. In this example, 2/16 of the offspring are *AaEE*, 4/16 are *AaEe*, 2/16 are *Aaee*, 2/16 are *aaEE*, 4/16 are *aaEe*, 2/16 are *aaee*.



Step 6 **Determine the phenotypes of the offspring.**

In this example, 6/16 are winged and red-eyed, 2/16 are winged and sepia-eyed, 6/16 are wingless and red-eyed, 2/16 are wingless and sepia-eyed.

Step 7 **Using the results of Steps 5 and 6, answer the problem.**

Note that in this example, as in many of the genetics problems you will encounter, you are asked for more than just the ratios resulting from the cross. This is one reason why it is important to read genetics problems carefully. In this example, the genotypic ratio is 2/16:4/16:2/16:2/16:4/16:2/16 = 2:4:2:2:4:2 = 1:2:1:1:2:1. The phenotypic ratio is 6/16:2/16:6/16:2/16 = 6:2:6:2 = 3:1:3:1. And 4/16, or 1/4, of the offspring have the genotype *AaEe*.

One-Factor Crosses: Practice Problems

1. Pollen from a pea plant with white flowers is used to fertilize the ovules (female gametes) of a heterozygous plant. What are the possible phenotypes in the offspring from this cross?
2. You have a pea plant with red flowers. Design a cross to determine if this plant is homozygous or heterozygous. Use a Punnett square to show all possible crosses.

Two-Factor Crosses: Practice Problems

1. A purebred wingless red-eyed fruit fly is crossed with a purebred winged sepia-eyed fruit fly to produce F_1 flies. The F_1 flies are crossed to produce F_2 flies. What is the phenotypic ratio of the F_2 flies?
2. You have a winged red-eyed fruit fly. Design a cross to determine whether the fly is heterozygous for either or both traits. Use a Punnett square to show all possible crosses.

LABORATORY INVESTIGATION

SIMULATING A ONE-FACTOR CROSS

PROBLEM

How is probability applied to genetics?

MATERIALS *(per student)*

2 labeled game markers
paper cup

PROCEDURE

1. On a separate sheet of paper, prepare a completed data table similar to the one below.
2. In pea plants, yellow seeds (*A*) are dominant over green seeds (*a*). Using a Punnett square, determine the probable color of the seeds produced by pea plants whose parents are heterozygous (*Aa*) for the seed-color trait. Record the expected genotypic and phenotypic ratios in the appropriate places in your data table.
3. Each labeled marker represents the alleles in the heterozygous plant. Tossing the labeled markers together represents the crossing of heterozygous plants.
4. Put the 2 labeled markers into the cup. Holding one hand over the mouth of the cup, shake the cup to toss the markers. Empty the cup onto your desk or laboratory table. Record the results of each of 10 tosses by making a tally mark in the appropriate box in your data table.
5. Toss the markers 100 times and record the results in your data table.
6. One student in the class will compile the data for 100 tosses by 10 students and report the results. Record this information.
7. Count the tally marks for each genotype in each series of tosses (10, 100, 1000). Record these totals in the appropriate box.
8. Determine the total number of seeds with the yellow phenotype for each series of tosses.
9. Using the data, calculate the genotypic and phenotypic ratios for each series of tosses. This is done by dividing each number in the ratio by the ratio's smallest number and rounding off to the nearest tenth's place. For example, suppose you obtained 23 *AA*, 51 *Aa*, and 26 *aa* for a series of 100 tosses. This gives you the ratio 1:2.2:1.1 (23/23 = 1, 51/23 = 2.2, 26/23 = 1.1)

OBSERVATIONS

1. Which genotype was obtained most often?
2. What were your expected genotypic and phenotypic ratios?
3. What were your genotypic and phenotypic ratios for a series of 10 tosses? 100 tosses? 1000 tosses?

ANALYSIS AND CONCLUSIONS

1. How do the experimental ratios compare with the expected ratios?
2. Which series of tosses produced the experimental ratios that were closest to the expected ratios? Explain your results.
3. How does probability apply to the results of your experiment? How does probability apply to the study of genetics?

Offspring Phenotype	Yellow				Green		Total Number of Yellow Seeds (*AA* + *Aa*)	Expected Genotypic Ratio	Expected Phenotypic Ratio	Experimental Genotypic Ratio	Experimental Phenotypic Ratio
Offspring Genotype	*AA*		*Aa*		*aa*						
	Tally	Total	Tally	Total	Tally	Total					
10 Tosses											
100 Tosses											
1000 Tosses											

SUMMARIZING THE CONCEPTS

The key concepts in each section of this chapter are listed below to help you review the chapter content. Make sure you understand each concept and its relationship to other concepts and to the theme of this chapter.

9–1 The Work of Gregor Mendel

- Mendel's genetic experiments involved the mathematical analysis of the offspring resulting from crosses between pea plants.
- Genes are individual factors that control heredity.
- The different forms of a gene are called alleles. Some alleles are dominant; others are recessive.
- Because of dominance, the effects of the recessive gene are not observed when the dominant gene is present.
- Alleles for the same trait are separated during the process of segregation.
- The genes for different traits may undergo independent assortment.
- An organism's physical characteristics, which reflect its genetic makeup, are its phenotype. An organism's genetic makeup is its genotype.
- Organisms that have two identical alleles for a particular trait are said to be homozygous, or purebred, for that trait. Organisms that have two different alleles for the same trait are said to be heterozygous, or hybrid, for that trait.

9–2 Applying Mendel's Principles

- Probability is the likelihood that a particular event will occur. The rules of probability apply to genetics.
- Genetics problems can be solved by using a Punnett square.

9–3 Meiosis

- A cell that contains both sets of homologous chromosomes is said to be diploid (2N). A cell that contains a single set of chromosomes is said to be haploid (N).
- Meiosis is a form of cell division that results in the formation of haploid gametes. The cells formed in meiosis have different sets of chromosomes from one another and from the diploid mother cell.

REVIEWING KEY TERMS

Vocabulary terms are important to your understanding of biology. The key terms listed below are those you should be especially familiar with. Review these terms and their meanings. Then use each term in a complete sentence. If you are not sure of a term's meaning, return to the appropriate section and review its definition.

9–1 The Work of Gregor Mendel
heredity
genetics
self-pollination
cross-pollination
purebred
trait
hybrid
gene
allele
dominance
dominant
recessive
segregation
Punnett square
gamete
phenotype
genotype
homozygous
heterozygous
independent assortment

9–2 Applying Mendel's Principles
probability
test cross

9–3 Meiosis
homologous
diploid
haploid
meiosis
crossing-over

CHAPTER REVIEW

CONTENT REVIEW

Multiple Choice

Choose the letter of the answer that best completes each statement.

1. Alleles for the same trait are separated from each other during the process of
   a. mitosis. c. cross-pollination.
   b. meiosis II. d. segregation.
2. Organisms that have two identical genes for a particular trait are said to be
   a. haploid. c. heterozygous.
   b. homozygous. d. diploid.
3. Pea plants usually produce seeds through
   a. self-pollination. c. mitosis.
   b. cross-pollination. d. meiosis.
4. Because body cells contain two sets of chromosomes, they are
   a. homozygous. c. haploid.
   b. heterozygous. d. diploid.
5. An organism's physical appearance is its
   a. genotype. c. heredity.
   b. phenotype. d. homolog.
6. What is the exchange of genes between homologous chromosomes called?
   a. tetrad c. independent assortment
   b. segregation d. crossing-over
7. The phenotypic ratio in the offspring resulting from the cross $Tt \times Tt$ is
   a. 1:2:1. c. 1:1.
   b. 3:1. d. 9:3:3:1.
8. Some F_2 individuals show the recessive character because of
   a. dominance. c. crossing-over.
   b. segregation. d. independent assortment.

True or False

Determine whether each statement is true or false. If it is true, write "true." If it is false, change the underlined word or words to make the statement true.

1. The fertilization of a plant's ovules (egg cells) by the pollen of another plant is called <u>self-pollination</u>.
2. If allowed to self-pollinate, <u>hybrid</u> peas will produce offspring exactly like themselves.
3. Meiosis results in <u>haploid</u> cells.
4. The effects of a <u>recessive</u> allele are seen in a heterozygous organism.
5. The offspring produced by crossing F_1 plants are known as the <u>P generation</u>.
6. Reproductive cells are also called <u>gametes</u>.
7. Homologous chromosomes pair up during the first stage of <u>mitosis</u>.
8. Expected genetic ratios show up only when <u>small</u> numbers of offspring are considered.

Word Relationships

An analogy is a relationship between two pairs of words or phrases generally written in the following manner: a:b::c:d. The symbol : is read "is to," and the symbol :: is read "as." For example, cat:animal::rose:plant is read "cat is to animal as rose is to plant."

In the analogies that follow, a word or phrase is missing. Complete each analogy by providing the missing word or phrase.

1. mitosis:2N::meiosis: _____
2. allele:gene::green seeds:_____
3. purebred:hybrid::homozygous:_____
4. white fur:*ff*::phenotype:_____
5. egg:ovule::sperm:_____
6. *A*:dominant::*a*:_____

CONCEPT MASTERY

Use your understanding of the concepts developed in the chapter to answer each of the following in a brief paragraph.

1. Why is Gregor Mendel sometimes called the "father of genetics"?
2. Describe the process of meiosis.
3. List the four basic principles of genetics that Mendel discovered in his experiments. Briefly describe each of these principles.
4. What is probability? How does probability relate to genetics?
5. How do the cellular events in meiosis account for Mendel's observations?

CRITICAL AND CREATIVE THINKING

Discuss each of the following in a brief paragraph.

1. **Applying concepts** In dogs, short hair is dominant over long hair. Two short-haired dogs are the parents of a litter of eight puppies. Six puppies have short hair and two have long hair. What are the genotypes of the parents?
2. **Applying concepts** Purebred tall plants with round seeds are crossed with purebred short plants with wrinkled seeds. Some of the offspring are then crossed with an unknown plant. The offspring from this second cross are 1/2 tall round and 1/2 tall wrinkled. What are the genotype and phenotype of the unknown plant?
3. **Making inferences** Explain why horse breeders will pay a lot of money to breed one of their horses to a horse that has won the Kentucky Derby.
4. **Making calculations** The probability of two independent events occurring simultaneously is the product of each of their probabilities. For example, if you flip two coins, the chance that both will come up heads is 1/4 (= 1/2 x 1/2). Suppose that you have ten Ping-Pong balls in a jar, each marked with a numeral from 0 to 9. If you mix them thoroughly and take out one, the chances are 1 in 10 (1/10) that you will get a particular numeral. Now suppose you have six such jars. What is your chance of drawing the number 531963?
5. **Making generalizations** In guinea pigs, a rough coat (*R*) is dominant over a smooth coat (*r*). A heterozygous guinea pig (*Rr*) and a homozygous recessive guinea pig (*rr*) have a total of nine offspring. Each has a smooth coat. Explain these results.

	R	r
	Rr	rr
r	Rr	rr

6. **Designing an experiment** In sheep, white wool (*A*) is dominant over black wool (*a*). How would you determine the genotype of a white ram, or male sheep?
7. **Using the writing process** In the 1950s, a television series presented an imaginary voyage back in time. Each week a famous person in history was visited. The show was designed to provide insight into the work of the person being interviewed and the time in which he or she lived. You are in charge of producing such a program for today's television viewers. The first person you will visit is Gregor Mendel. Write a script for this program.