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.

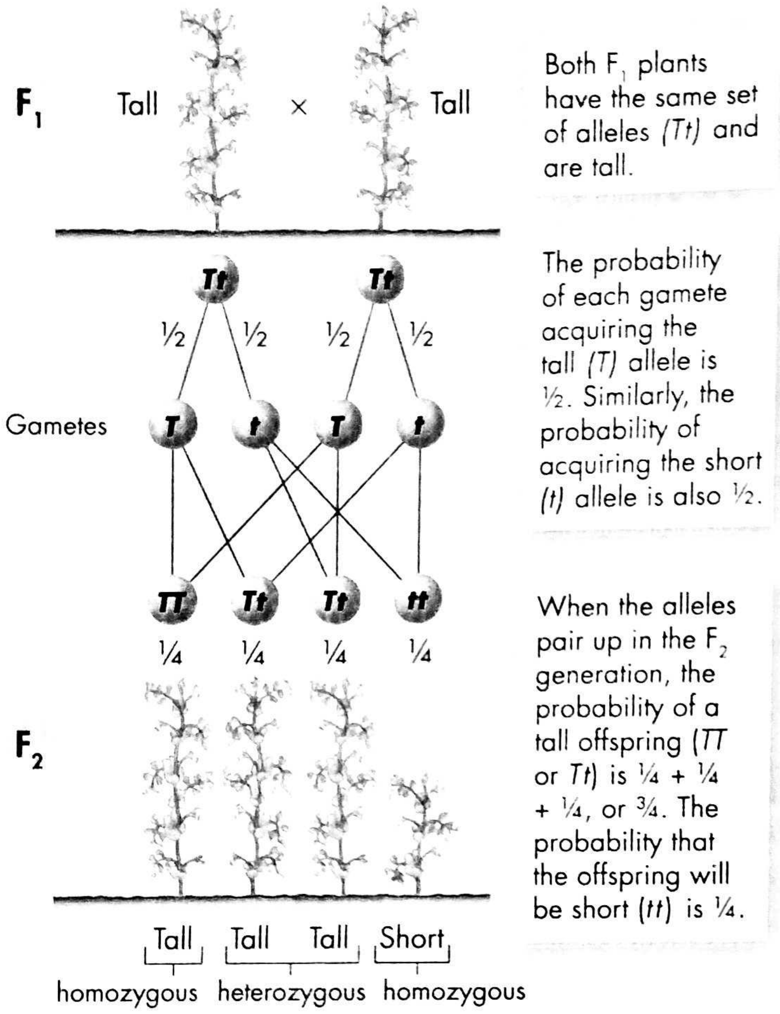

FIGURE 11-7 Segregation and Probability In this cross, the *TT* and *Tt* allele combinations produced three tall pea plants, while the *tt* allele combination produced one short plant. These quantities follow the laws of probability. **Predict** ***If you crossed a*** **TT** ***plant with a*** **Tt** ***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, and the phenotype is largely determined by the genotype. Two organisms may share the same phenotype but have different genotypes.

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."

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.

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).

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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

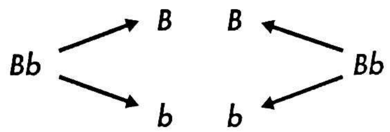
① Start With the Parents

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 hawk, 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.

	B	*b*
B		
b		

④ Write Out the New Genotypes

Fill in the table by combining the gametes' genotypes.

	B	*b*
B		*Bb*
b	*Bb*	

	B	*b*
B	*BB*	*Bb*
b	*Bb*	*bb*

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)*.

	B	*b*
B	*BB*	*Bb*
b	*Bb*	*bb*

Two-Factor Cross

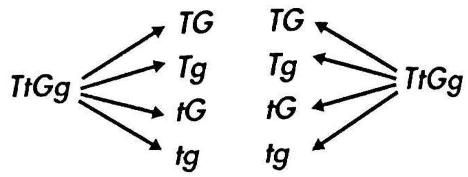
① Start With the Parents

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.

	TG	*tG*	*Tg*	*tg*
TG				
tG				
Tg				
tg				

④ Write Out the New Genotypes

Fill in the table by combining the gametes' genotypes.

	TG	*tG*	*Tg*	*tg*
TG				
tG			*TtGg*	
Tg				
tg		*ttGg*		

	TG	*tG*	*Tg*	*tg*
TG	*TTGG*	*TtGG*	*TTGg*	*TtGg*
tG	*TtGG*	*ttGG*	*TtGg*	*ttGg*
Tg	*TTGg*	*TtGg*	*TTgg*	*Ttgg*
tg	*TtGg*	*ttGg*	*Ttgg*	*ttgg*

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.

	TG	*tG*	*Tg*	*tg*
TG	*TTGG*	*TtGG*	*TTGg*	*TtGg*
tG	*TtGG*	*ttGG*	*TtGg*	*ttGg*
Tg	*TTGg*	*TtGg*	*TTgg*	*Ttgg*
tg	*TtGg*	*ttGg*	*Ttgg*	*ttgg*

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.

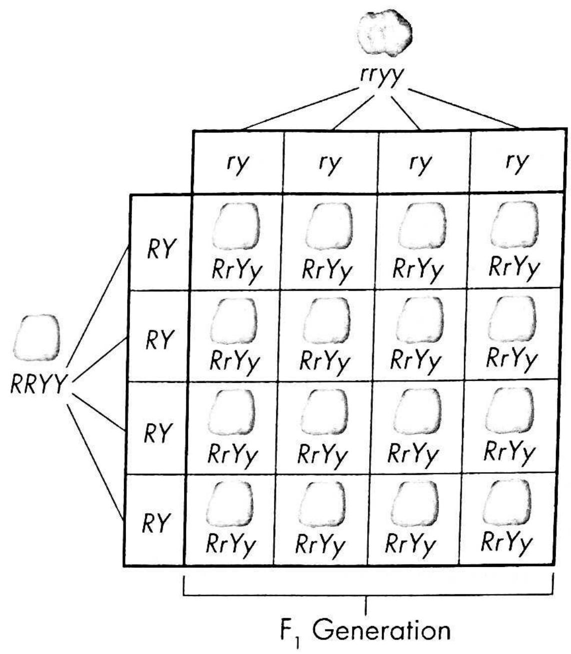


FIGURE 11–9 Two-Factor Cross: F_1 Mendel crossed plants that were homozygous dominant for round yellow peas with plants that were homozygous recessive for wrinkled green peas. All of the F_1 offspring were heterozygous dominant for round yellow peas. **Interpret Graphics** ***How is the genotype of the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

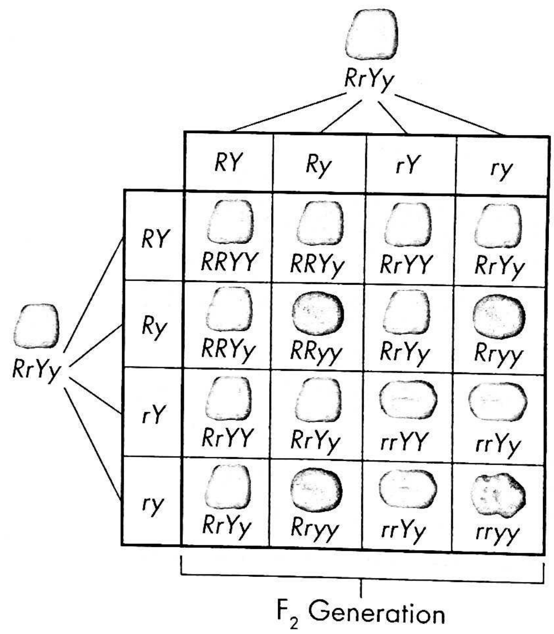


FIGURE 11–10 Two-Factor Cross: F_2 When Mendel crossed F_1 plants that were heterozygous dominant for round yellow peas, he found that the alleles segregated independently to produce the F_2 generation.

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 hundreds of young. 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.