

13

Mendelian Genetics and Probability

Learning Objectives

In this chapter, you will learn:

- Mendelian Genetics
- Probability in Genetics Problems

Overview

The study of genetics started with Mendelian genetics. This chapter reviews the laws of Mendelian genetics and the laws of probability that relate to them.

Mendelian Genetics

The transfer of genetic information is a key process in living organisms. Information is transferred within an organism from the nucleus to the ribosome during the synthesis of proteins (which will be reviewed in [Chapter 16](#)). Information is transferred from generation to generation through inherited units of chemical information called genes. Information can be transferred between members of the same generation through the processes of conjugation, transformation, or transduction (all of which will be discussed in [Chapter 17](#)). In all cases, the carriers of this genetic information are DNA and RNA.

DNA, RNA, and ribosomes are found in all forms of life. DNA and RNA use a genetic code that is shared by all living organisms. This provides

powerful evidence to support the common ancestry of all living organisms on Earth.

Mendel's laws of segregation and independent assortment explain how genetic information can be transferred from one generation to the next.

It is important to note that Mendel's laws of segregation and independent assortment only apply to traits coded for by genes that are located on separate chromosomes. As discussed in [Chapter 12](#), genes that are close together on the same chromosome are linked and tend to be inherited together more often. Mendel's laws of segregation and independent assortment do not apply to linked genes.

Mendel's law of segregation states that an organism carries two variations of every trait (called alleles), one from each parent, and these alleles segregate, or separate, independently into gametes. This segregation occurs during anaphase of meiosis. When homologous chromosomes separate during anaphase I, the alleles on those chromosomes will segregate into separate gametes. One variation (or allele) for a trait ends up in each gamete. When two gametes join during fertilization, the resulting offspring then again has two alleles for the trait.

Mendel's law of independent assortment states that genes for different traits segregate independently of one another. This independent assortment occurs during metaphase I of meiosis. For example, in pea plants, inheriting the allele for purple flower color is an independent event from inheriting the allele for wrinkled peas. This is because the gene for flower color in peas is on a separate chromosome than the gene for pea shape. These chromosomes assort independently in metaphase I of meiosis.

A **pedigree** is a chart that illustrates the inheritance of a trait through several generations. Horizontal lines between two individuals in a pedigree show that those individuals have had offspring together. Offspring of these individuals are indicated by vertical lines. Circles typically represent females, and squares represent males. Circles or squares that are shaded usually represent individuals who possess the trait shown in the pedigree.

Examining the pattern of inheritance of a trait shown in a pedigree can give clues to the trait's possible mode of inheritance. Dominant traits tend to be expressed in at least one parent and their offspring because only one

allele for the trait is required for it to be expressed. Recessive traits often will be expressed in offspring, but not in either parent, because the parents are heterozygous carriers of the trait. Sex-linked recessive traits usually appear more often in males than in females. [Chapter 14](#) will discuss the patterns of inheritance seen in non-Mendelian traits.

Before practicing some genetics problems, review the following terms:

- **Genotype**—the genetic makeup or alleles for the trait in an organism (i.e., AA or Aa or aa)
- **Phenotype**—the physical expression of the genotype in an organism (i.e., purple flowers or white flowers)
- **Homozygous**—having two copies of the same allele for a trait (i.e., AA or aa)
- **Heterozygous**—having two different alleles for a trait (i.e., Aa); Mendel referred to this as “hybrid”
- **Dominant**—requires only one copy of the allele for the trait to be expressed in the phenotype; dominant traits are those that are expressed in organisms that are heterozygous
- **Recessive**—requires two copies of the allele for the trait to be expressed in the phenotype; recessive traits are not expressed in organisms that are heterozygous

Probability in Genetics Problems

Problems that Involve a Monohybrid Cross

One of the simplest types of crosses is called a monohybrid cross. In a **monohybrid cross**, both parents are heterozygous (have two different alleles) for the trait. For example, purple flowers are dominant to white flowers in pea plants. Two heterozygous purple flowers are crossed. The results are shown in [Figure 13.1](#).

TIP

Math is your friend when answering genetics problems! Using simple fractions and the laws of probability will help you solve genetics problems more accurately and efficiently.

	<i>P</i>	<i>p</i>
<i>P</i>	<i>PP</i>	<i>Pp</i>
<i>p</i>	<i>Pp</i>	<i>pp</i>

Figure 13.1 Cross Between Two Pea Plants that Are Heterozygous for Flower Color

There are three possible genotypes that could result from this cross: *PP*, *Pp*, or *pp*. The probabilities of each are $\frac{1}{4} PP$, $\frac{1}{2} Pp$, and $\frac{1}{4} pp$.

There are two possible phenotypes that could result from this cross: purple flowers or white flowers. Since both the *PP* and *Pp* genotypes would result in the purple flower phenotype, the probabilities of each phenotype are $\frac{3}{4}$ purple flowers and $\frac{1}{4}$ white flowers.

Consider another example. Two pea plants that are heterozygous for plant height are crossed. In pea plants, tall is dominant to short. The results of the cross are shown in [Figure 13.2](#).

	<i>T</i>	<i>t</i>
<i>T</i>	<i>TT</i>	<i>Tt</i>
<i>t</i>	<i>Tt</i>	<i>tt</i>

Figure 13.2 Cross Between Two Pea Plants that Are Heterozygous for Plant Height

There are three possible genotypes that could result from this cross: *TT*, *Tt*, or *tt*. The probabilities of each are $\frac{1}{4}$ *TT*, $\frac{1}{2}$ *Tt*, and $\frac{1}{4}$ *tt*.

There are two possible phenotypes that could result from this cross: tall plants or short plants. Since both the *TT* and *Tt* genotypes would result in the tall phenotype, the probabilities of each phenotype are $\frac{3}{4}$ tall plants and $\frac{1}{4}$ short plants.

For the AP Biology exam, it is not necessary to memorize which specific traits are dominant or recessive. Information about which traits are dominant will either be given to you directly in the problem or you will be able to infer that information from the text or data given to you in the problem.

Problems that Involve a Dihybrid Cross

A **dihybrid cross** looks at the result when two organisms (that are both heterozygous for the same two traits) are crossed. When solving dihybrid crosses, math is your friend! Treat each trait separately, find the probabilities of each outcome for each trait, and use the laws of probability to solve the problem.

Refer to the [Appendix](#) of this book for the relevant probability equations (and those same equations will be supplied to you on test day). The probability of two independent events occurring simultaneously is the product of their individual probabilities:

$$P(A \text{ and } B) = P(A) \times P(B)$$

Try the following example. Two pea plants that are both heterozygous for purple flower color and plant height are crossed. The genotypes of the parents are $PpTt \times PpTt$.

Recall from the monohybrid cross of $Pp \times Pp$ (Figure 13.1) that the probability of offspring with purple flowers is $\frac{3}{4}$ and the probability of offspring with white flowers is $\frac{1}{4}$.

Also recall from the monohybrid cross of $Tt \times Tt$ (Figure 13.2) that the probability of tall offspring is $\frac{3}{4}$ and the probability of short offspring is $\frac{1}{4}$.

So the probability of this cross producing a plant that is tall and has purple flowers is the product of the probability of producing a tall plant $\left(\frac{3}{4}\right)$ times the probability of producing a plant with purple flowers $\left(\frac{3}{4}\right)$. The result is $\frac{9}{16}$.

Using the same process, the probability of this cross producing a tall plant with white flowers is the product of the probability of producing a tall plant $\left(\frac{3}{4}\right)$ times the probability of producing a plant with white flowers $\left(\frac{1}{4}\right)$. The result is $\frac{3}{16}$.

Similarly, the probability of this cross producing a short plant with purple flowers is the product of the probability of producing a short plant $\left(\frac{1}{4}\right)$ times the probability of producing a plant with purple flowers $\left(\frac{3}{4}\right)$. The result is $\frac{3}{16}$.

Finally, the probability of this cross producing a short plant with white flowers is the product of the probability of producing a short plant $\left(\frac{1}{4}\right)$ times the probability of producing a plant with white flowers $\left(\frac{1}{4}\right)$. The result is $\frac{1}{16}$.

This same problem-solving process can be used for other types of crosses as well. Try this example. Imagine that there's a cross between a pea plant that is $PpTt$ and a pea plant that is $Pppt$.

First, find the probabilities of each possible outcome for the plant height trait, as shown in Figure 13.3.

	<i>T</i>	<i>t</i>
<i>t</i>	<i>Tt</i>	<i>tt</i>
<i>t</i>	<i>Tt</i>	<i>tt</i>

Figure 13.3 Results of a $Tt \times tt$ Cross

The probability of producing a tall offspring (Tt) is $\frac{1}{2}$. The probability of producing a short offspring (tt) is also $\frac{1}{2}$.

Now, find the probabilities of each possible outcome for the flower color trait, as shown in [Figure 13.4](#).

	<i>P</i>	<i>p</i>
<i>P</i>	<i>PP</i>	<i>Pp</i>
<i>p</i>	<i>Pp</i>	<i>pp</i>

Figure 13.4 Results of a $Pp \times Pp$ Cross

The probability of producing an offspring with purple flowers (PP or Pp) is $\frac{3}{4}$. The probability of producing an offspring with white flowers (pp) is $\frac{1}{4}$.

Now, using the laws of probability, solve for the following outcomes:

$$\text{Offspring that are tall and have purple flowers} = \frac{1}{2} \times \frac{3}{4} = \frac{3}{8}$$

$$\text{Offspring that are tall and have white flowers} = \frac{1}{2} \times \frac{1}{4} = \frac{1}{8}$$

$$\text{Offspring that are short and have purple flowers} = \frac{1}{2} \times \frac{3}{4} = \frac{3}{8}$$

$$\text{Offspring that are short and have white flowers} = \frac{1}{2} \times \frac{1}{4} = \frac{1}{8}$$

Problems that Involve a Test Cross

An organism that displays the dominant phenotype may have either the homozygous dominant genotype or the heterozygous genotype. One way to determine which genotype the organism has is by using a test cross. A **test cross** is a cross between an organism with a dominant phenotype (whose genotype is unknown) and an organism with the recessive phenotype. If the organism with the dominant phenotype is homozygous, all of the offspring of the test cross will show the dominant phenotype. If the organism with the dominant phenotype is heterozygous, $\frac{1}{2}$ of the offspring of the test cross will show the dominant phenotype and $\frac{1}{2}$ of the offspring of the test cross will show the recessive phenotype, as shown in [Figure 13.5](#).

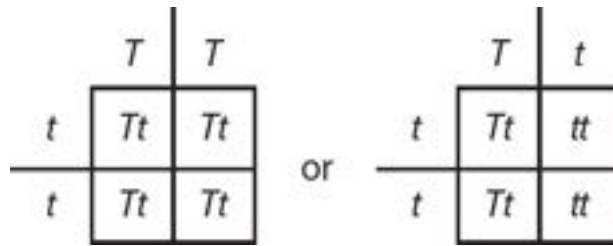


Figure 13.5 Possible Outcomes of a Test Cross

Practice Questions

Multiple-Choice

1. Mendel's law of independent assortment is a result of
 - (A) the random nature of fertilization of ova by sperm.
 - (B) the random way homologous chromosomes undergo genetic recombination in meiosis.
 - (C) the random way homologous chromosomes line up in metaphase I of meiosis.
 - (D) the random nature of molecular movement at high temperatures.
2. The term *hybrid* can also mean _____.
 - (A) homozygous
 - (B) heterozygous
 - (C) haploid
 - (D) diploid
3. In peas, round (*R*) peas are dominant and wrinkled (*r*) peas are recessive. A plant with an unknown genotype for this trait has round peas. Which of the following results of a test cross would support the hypothesis that the genotype of the plant with the round peas is heterozygous?
 - (A) 100% round offspring
 - (B) 75% round offspring and 25% wrinkled offspring
 - (C) 50% round offspring and 50% wrinkled offspring
 - (D) 100% wrinkled offspring
4. In pea plants, smooth (*S*) pods are dominant and constricted (*s*) pods are recessive. Which of the following is a correct statement?
 - (A) A genotype of *SS* would result in the constricted pod phenotype.
 - (B) A genotype of *Ss* would result in the constricted pod phenotype.

- (C) Constricted pods would always be homozygous.
- (D) Smooth pods would always be homozygous.
5. Round peas are dominant to wrinkled peas. Smooth pea pods are dominant to constricted pea pods. Two pea plants that are heterozygous for both traits are crossed, and 800 offspring are produced. How many of the offspring are expected to have round peas and constricted pods?
- (A) 450
- (B) 150
- (C) 50
- (D) 0
6. A pea plant that is heterozygous for round peas and heterozygous for smooth pods is crossed with a pea plant that is heterozygous for round peas and has constricted pods. What fraction of the offspring are expected to have round peas and constricted pods? (Remember that round peas are dominant to wrinkled peas, and smooth pods are dominant to constricted pods.)
- (A) $\frac{3}{4}$
- (B) $\frac{3}{8}$
- (C) $\frac{1}{4}$
- (D) $\frac{1}{8}$
7. In humans, the gene for polydactyly (extra fingers or toes) is dominant over the gene for the typical number of fingers and toes. If a person who is heterozygous for polydactyly has children with a person with the typical number of fingers and toes, what is the probability that their first child will have polydactyly?
- (A) 100%
- (B) 50%
- (C) 25%

(D) 0%

8. In the cross $AaBbCc \times AaBbCc$, what is the probability of producing an offspring with the $AABBCc$ genotype?

(A) $\frac{1}{4}$

(B) $\frac{1}{8}$

(C) $\frac{1}{16}$

(D) $\frac{1}{32}$

Questions 9 and 10

Rh positive (R) is a trait that is dominant over Rh negative (r). A woman, who is Rh positive, has a son, who is Rh negative.

9. Which of the following is a true statement about the mother?

(A) She must have the rr genotype.

(B) She must have the RR genotype.

(C) She must be heterozygous for the trait.

(D) She must have the same genotype as her son.

10. Which of the following is a true statement about the father of the woman's son?

(A) He must have the RR genotype.

(B) He must have the Rr genotype.

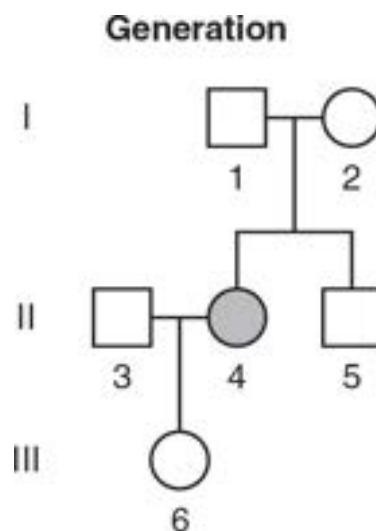
(C) He must have the rr genotype.

(D) He may have either the Rr or the rr genotype.

Short Free-Response

11. Sickle cell disease is an autosomal recessive disorder. Homozygous recessive individuals have red blood cells that can assume a sickle

shape when oxygen levels are low. These sickled blood cells can cause blockages in blood vessels, leading to pain and possibly fatal complications. Heterozygous individuals do not suffer the pain or complications from sickle cell disease and are more resistant to malaria than individuals with two nonsickle alleles. The following figure shows the pattern of inheritance of sickle cell disease through three generations of a family. Squares indicate males, circles indicate females, and shaded shapes indicate individuals who have sickle cell disease.



- (a) **Describe** the genotype of individual I-2. **Justify** your answer with evidence from the pedigree.
- (b) What is the genotype of individual III-6? **Explain** how you know her genotype.
- (c) Create a Punnett square that **represents** the possible genotypes of the offspring of individuals 1 and 2 from generation I.
- (d) **Explain** which genotype from this pedigree would provide an advantage in San Francisco (where the mosquito that carries malaria does not live) and which genotype would be most advantageous to survival in Haiti (where the mosquito that carries malaria is found).

12. Fur color in hamsters is determined by a single gene, with yellow fur color being dominant to white fur color. Inheriting two copies of the allele for yellow fur color is fatal, so all individuals with yellow fur are heterozygous.
- Determine** the probability that the offspring of two hamsters with yellow fur would also have yellow fur.
 - Construct** a Punnett square that represents the two hamster parents from part (a), and use the Punnett square to **explain** your answer to part (a).
 - A hamster population lives in an area covered with yellow-goldenrod-colored grasses. An unusually cold winter results in the death of all the yellow-goldenrod-colored grasses, so in the spring the area is covered only in white sand. **Predict** what would happen to the frequency of the allele for yellow fur color over time.
 - Justify** your prediction from part (c).

Long Free-Response

13. In pea plants, tall plant height is dominant over short. A new type of plant food (Supersize Food) is advertised to increase plant height. Two pea plants that are heterozygous for plant height are crossed, and the seeds that are produced are harvested. Half of the seeds are planted and grown in the presence of Supersize Food, and the other half of the seeds are planted and grown without Supersize Food. When the plants reach full maturity, the number of tall and short plants are recorded. The data are shown in the table.

Number of Tall and Short Pea Plants Grown in the Absence or Presence of Supersize Food

Height of Plant	Plants Grown Without Supersize Food	Plants Grown with Supersize Food
Tall	1,290	1,265
Short	1,290	1,265

Short	430	455
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- (a) **Describe** the proportions of tall and short plants that were expected to result from the cross. Use a Punnett square to support your answer.
- (b) **Identify** the independent variable and the dependent variable in this experiment. **Identify** one possible appropriate experimental constant.
- (c) A student makes the claim that “there is no statistically significant difference between the plants grown in the presence or absence of Supersize Food.” Use the chi-square equation to **analyze** the data and **evaluate** this claim. Use a p -value of 0.05 for your analysis.
- (d) A tall plant with an unknown genotype is crossed with a short plant. **Predict** the expected proportions of tall and short offspring if the tall plant is heterozygous. **Justify** your prediction.

Answer Explanations

Multiple-Choice

1. **(C)** Each pair of chromosomes lines up independently in metaphase I of meiosis, leading to the independent assortment of the traits on those chromosomes. Choices (A) and (B) are incorrect because they do not lead to independent assortment (but they do contribute to increased genetic diversity). Choice (D) is incorrect because temperature does not affect independent assortment.
2. **(B)** *Hybrid* refers to heterozygous genotypes. Choice (A) is the opposite of the correct answer. Choices (C) and (D) are both incorrect because haploid and diploid are terms that refer to the number of chromosomes in a cell, not genotypes.
3. **(C)** If the plant with round peas is heterozygous, its genotype is Rr . The definition of a test cross is to cross an individual with the dominant phenotype (but an unknown genotype) with a homozygous recessive individual. Thus, if the Rr plant was crossed with an rr plant, 50% of the offspring would be expected to be round and 50% would be expected to be wrinkled. Choice (A) is incorrect because it describes the expected results if the original round plant was homozygous dominant (RR). Choice (B) is incorrect because in order to produce that proportion of offspring, both parent plants would have to be heterozygous (Rr), but the plant used to do the test cross must be rr . In order to produce 100% wrinkled offspring, both parent plants would have to be homozygous recessive (rr), so choice (D) is incorrect.
4. **(C)** A genotype of ss would result in the constricted pod phenotype. Choices (A) and (B) are incorrect because both SS and Ss would result in the smooth phenotype. Choice (D) is incorrect because smooth pods would not always have the SS genotype; smooth pods could also have the Ss genotype.
5. **(B)** The chances of this cross producing a plant with round peas is $\frac{3}{4}$. The chances of this cross producing a plant with constricted pods is $\frac{1}{4}$.

So the chances of producing a plant with both round peas and constricted pods is the product of their individual probabilities: $\frac{3}{4} \times \frac{1}{4} = \frac{3}{16}$. Given a total number of 800 offspring, $800 \times \frac{3}{16} = 150$. Choice (A) is incorrect because it is the expected number of offspring with round peas and smooth pods. Choice (C) is incorrect because it is the expected number of offspring with wrinkled peas and constricted pods. Choice (D) is incorrect because $\frac{3}{4}$ of the offspring are expected to be round and $\frac{1}{4}$ are expected to be constricted, so some of the offspring must be both round and constricted and thus the answer cannot be 0.

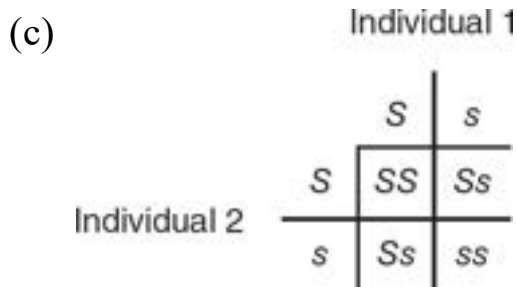
6. **(B)** The genotypes of the plants described in the problem are $RrSs$ and $Rrss$. First, calculate the probability for each trait separately. The probability of two plants that are heterozygous for round peas producing an offspring with round peas is $\frac{1}{2}$. The probability of a plant with heterozygous smooth pods crossed with a plant with constricted pods producing an offspring with constricted pods is $\frac{1}{2}$. Multiplying the two probabilities together gives the probability of a plant with both round peas and constricted pods: $\frac{3}{4} \times \frac{1}{2} = \frac{3}{8}$.
7. **(B)** A person who is heterozygous for polydactyly would have the Ff genotype. A person with the typical number of fingers and toes would have the ff genotype, so the chances their first child will have polydactyly is 50%. (Whether this is their first child, second child, etc., is irrelevant because each is an independent event.)
8. **(D)** Remember to break this down one trait at a time, find the probability of the outcomes for each trait, and then multiply the probabilities together. $Aa \times Aa$ would produce AA $\frac{1}{4}$ of the time. Similarly, $Bb \times Bb$ would produce BB $\frac{1}{4}$ of the time. $Cc \times Cc$ would produce Cc $\frac{1}{2}$ of the time. Multiply all three probabilities together: $\frac{1}{4} \times \frac{1}{4} \times \frac{1}{2} = \frac{1}{32}$.
9. **(C)** Since the mother is Rh positive, she must have at least one dominant R allele. Since she has a child who is Rh negative, she must have an r allele. Therefore, the mother must be heterozygous Rr . Choice (A) is incorrect because if the mother was rr , she would not be Rh positive.

Choice (B) is incorrect because an RR mother could not produce an Rh negative child. Choice (D) is incorrect because since the mother is Rh positive and her son is Rh negative, they cannot have the same genotype.

10. (D) Since the son is Rh negative, his genotype must be rr . He must have inherited one r allele from each parent. So the father (whose Rh phenotype is unknown) could be either Rr or rr . Choice (A) is incorrect because an RR father would not be able to pass on an r allele to his offspring. Choices (B) and (C) are incorrect because while both are possible genotypes for the father, it is not possible to say with certainty which genotype the father has without knowing the father's phenotype.

Short Free-Response

11. (a) Individual I-2 is heterozygous for sickle cell. This is true because she does not have sickle cell disease (so she cannot have the ss genotype), but she has a child who has sickle cell disease. So individual I-2 must be a carrier of the allele (Ss).
- (b) Individual III-6 must be heterozygous. This is true because she does not have sickle cell disease, so she must have at least one S allele, and since one of her parents (individual II-4) does have sickle cell disease, she must have inherited a copy of the s allele from that parent.



- (d) Since there is no malaria in San Francisco, the SS genotype would be most advantageous because those individuals would not have sickle cell disease. In Haiti, due to the presence of malaria, the heterozygous genotype (Ss) would be the most advantageous because

individuals with that genotype would not have sickle cell disease but would also be resistant to malaria.

12. (a) The probability of producing a hamster offspring with yellow fur would be $\frac{2}{3}$.
- (b) As shown in the following Punnett square, both parents must be heterozygous, so the possible genotypes are YY , Yy , or yy . However, since YY is always fatal as per the information stated in the question, there are only two possible outcomes for live offspring: Yy or yy . So $\frac{2}{3}$ would be heterozygous for yellow fur, and $\frac{1}{3}$ would have white fur.

	Y	y
Y	YY	Yy
y	Yy	yy

- (c) The frequency of the yellow allele would probably decrease over time.
- (d) Hamsters with white fur color would be better able to blend in with the white sand environment and more likely to hide from potential predators than hamsters with yellow fur. Thus, the frequency of the yellow allele would likely decrease over time.

Long Free-Response

13. (a) If both of the parental plants in the cross are heterozygous, one would expect $\frac{3}{4}$ of the progeny to be tall and $\frac{1}{4}$ of the progeny to be short. TT and Tt plants would be tall, and tt plants would be short.

	T	t
T	TT	Tt
t	Tt	tt

- (b) The independent variable is the presence or absence of Supersize Food. The dependent variable is the number of plants that are tall or short. One appropriate constant might be the amount of light the plants were exposed to. Other appropriate constants include the amount of water the plants were given or the type of soil the plants were grown in.
- (c) Using the chi-square equation:

$$\chi^2 = \frac{(1,265 - 1,290)^2}{1,290} + \frac{(455 - 430)^2}{430} = \frac{625}{1,290} + \frac{625}{430} = 1.94$$

There are two possible outcomes in the experiment (tall or short), so there is one degree of freedom (df = number of possible outcomes – 1). Using a *p*-value of 0.05 and the chi-square table, the critical value is 3.84. The calculated chi-square value of 1.94 is less than the critical value. So it fails to reject the null hypothesis, and thus the student's claim is supported.

- (d) A test cross is when an organism with the dominant trait (but an unknown genotype) is crossed with an organism with the recessive phenotype. If the tall plant is heterozygous and is crossed with a short plant (the recessive phenotype), half of the offspring would be tall and half would be short, as shown in this Punnett square.

	T	t
t	Tt	tt
t	Tt	tt