Inquire: Laws of Inheritance

Overview

Mendel postulated that genes (characteristics) are inherited as pairs of alleles (traits) that behave in a dominant and recessive pattern. Alleles segregate into gametes such that each gamete is equally likely to receive either one of the two alleles present in a diploid individual. In addition, genes are assorted into gametes independently of one another. That is, alleles are generally not more likely to segregate into a gamete with a particular allele of another gene. A dihybrid cross demonstrates independent assortment when the genes in question are on different chromosomes or distant from each other on the same chromosome. For crosses involving more than two genes, you will learn how to use the forked line or probability methods to predict offspring genotypes and phenotypes rather than a Punnett square.

Big Question: How can a dihybrid cross be used to calculate the probability of genotypes and phenotypes from multiple gene crosses?

Watch: Independent Assortment

Have you ever seen someone with dark skin, dark hair, and brilliant blue or green eyes? In some countries, this is rare and in others, it is a more frequent occurrence than you might realize. While it is common to see people with dark hair and dark eyes, or light hair with blue eyes, these traits are not inherited together. Instead, these genes are independently inherited. This is called independent assortment, meaning there are many genes that are not connected to one another and, although they often show up together, they can be inherited separately from one another.
Through his experiments, Mendel observed that genes will only inherit once through plant breeding. For example, if a parent plant has the genotype for a wrinkly pea pod (which is recessive) and another parent plant has the genotype for a round pea pod (which is dominant) and both of these genotypes are homozygous — the same — then each resulting child pea plant will inherit exactly one half of the parents genes. Inheriting more than one half of a parent’s gene is very rare and results in serious genetic mutations. Inheriting one of each parent’s genes or passing on only one of each of your genes is known as the law of segregation.

Scientists have used the concepts of independent assortment and the law of segregation to predict the genotypes and phenotypes of a variety of species. They can do this by calculating the probability of each genotype based on the genotypes of the parents in the crosses. Scientists can not only predict and calculate the phenotypes of a species, they can predict multiple gene inheritance such as a pea plant’s color, texture, and size altogether. What do you think? Can you figure out the probability of a homozygous recessive plant for three different genes just by knowing the genotypes of the parent crosses?

Read: Laws of Inheritance

Overview

Mendel’s law of dominance states that in a heterozygote, one trait will conceal the presence of another trait for the same characteristic. Rather than both alleles contributing to a phenotype, the dominant allele will be expressed exclusively. The recessive allele will remain “latent” but will be transmitted to offspring by the same manner in which the dominant allele is transmitted. The recessive trait will only be expressed by offspring that have two copies of this allele, and these offspring will breed true when self-crossed.

Equal Segregation of Alleles

Observing that true-breeding pea plants with contrasting traits gave rise to F₁ generations that all expressed the dominant trait and F₂ generations that expressed the dominant and recessive traits in a 3:1 ratio, Mendel proposed the law of segregation. This law states that paired unit factors (genes) must segregate equally into gametes such that offspring have an equal likelihood of inheriting either factor. For the F₂ generation of a monohybrid cross, the following three possible combinations of genotypes could result: homozygous dominant, heterozygous, or homozygous recessive. Because heterozygotes could arise from two different pathways (receiving one dominant and one recessive allele from either parent), and because heterozygotes and homozygous dominant individuals are phenotypically identical, the law supports Mendel’s observed 3:1 phenotypic ratio. The equal segregation of alleles is the reason we can apply the Punnett square to accurately predict the offspring of parents with known genotypes. The physical basis of Mendel’s law of segregation is the first division of meiosis, in which the homologous chromosomes with their different versions of each gene are segregated into daughter nuclei. The role of the meiotic segregation of chromosomes in sexual reproduction was not understood by the scientific community during Mendel’s lifetime.

Independent Assortment

Mendel’s law of independent assortment states that genes do not influence each other with regard to the sorting of alleles into gametes, and every possible combination of alleles for every gene is equally likely to occur. The independent assortment of genes can be illustrated by the dihybrid cross, a cross between two true-breeding parents that express different traits for two characteristics.
The physical basis for the law of independent assortment also lies in meiosis I, in which the different homologous pairs line up in random orientations. Each gamete can contain any combination of paternal and maternal chromosomes (and therefore the genes on them) because the orientation of tetrads on the metaphase plane is random.

Forked-Line Method
What is the probability of phenotypes for a cross that has three different genes (color of pea, texture of pea, and size of pea plant)? We can create a forked-line diagram to understand the probability of genetics. To prepare a forked-line diagram for a cross between F₁ heterozygotes resulting from a cross between AABBCC and aabbcc parents, we first create rows equal to the number of genes being considered (3 rows — one for color, one for texture, and one for size), and then segregate the alleles in each row on forked lines according to the probabilities for individual monohybrid crosses (we created a Punnett square for each and determined 3 yellow and 1 green pea color would result, 3 round and 1 wrinkled pea texture would result, and 3 tall and 1 dwarf size would result). However, we want to understand the probability of the combinations of these different genes together. To do this, we then multiply the values along each forked path to obtain the F₂ offspring probabilities. Note that this process is a diagrammatic version of the product rule. The values along each forked pathway can be multiplied because each gene assorts independently. For a trihybrid cross, the F₂ phenotypic ratio is 27:9:9:9:3:3:3:1.

Probability Method
For a trihybrid cross between individuals that are heterozygotes for all four genes, and in which all four genes are sorting independently and in a dominant and recessive pattern, what proportion of the offspring will be expected to be homozygous recessive for all four alleles? Rather than writing out every possible genotype, we can use the probability method. We know that for each gene, the fraction of homozygous recessive offspring will be 1/4. Therefore, multiplying this fraction for each of the four genes, \((1/4) \times (1/4) \times (1/4) \times (1/4)\), we determine that 1/256 of the offspring will be quadruply homozygous recessive.

Rules for Multihybrid Fertilization
Predicting the genotypes and phenotypes of offspring from given crosses is the best way to test your knowledge of Mendelian genetics. Given a multihybrid cross that obeys independent assortment and follows a dominant and recessive pattern, several generalized rules exist. You can use these rules to check your results as you work through genetics calculations. To apply these rules, first you must determine \(n\), the number of heterozygous gene pairs (the number of genes segregating two alleles each).
For example, a cross between $AaBb$ and $AaBb$ heterozygotes has an $n$ of 2. In contrast, a cross between $AABb$ and $AABb$ has an $n$ of 1 because $A$ is not heterozygous.

General Rules for Multihybrid Crosses

<table>
<thead>
<tr>
<th>General Rule</th>
<th>Number of Heterozygous Gene Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of different $F_1$ gametes</td>
<td>$2n$</td>
</tr>
<tr>
<td>Number of different $F_2$ genotypes</td>
<td>$3n$</td>
</tr>
<tr>
<td>Given dominant and recessive inheritance, the number of different $F_2$ phenotypes</td>
<td>$2n$</td>
</tr>
</tbody>
</table>

Reflect Poll: Determining Offspring Probabilities

The independent assortment of genes can be illustrated by the dihybrid cross, the fork-line method and the probability method. If you were determining offspring probabilities for $F_1$, $F_2$ generations, which method would be best to use?

- dihybrid cross
- fork-line method
- probability method

Expand: Probability Method

Earlier, we examined the phenotypic proportions for a trihybrid cross using the forked-line method. Now we will use the probability method to examine the genotypic proportions for a cross with even more genes.

So why did Mendel repeatedly obtain 3:1 ratios in his crosses? To understand how Mendel deduced the basic mechanisms of inheritance that lead to such ratios, we must first review the laws of probability.

Probability Basics

Probabilities are mathematical measures of likelihood. The empirical probability of an event is calculated by dividing the number of times the event occurs by the total number of opportunities for the event to occur. It is also possible to calculate theoretical probabilities by dividing the number of times that an event is expected to occur by the number of times that it could occur. Empirical probabilities come from observations, like those of Mendel. Theoretical probabilities, on the other hand, come from knowing how the events are produced and assuming that the probabilities of individual outcomes are equal. A probability of one for some event indicates that it is guaranteed to occur, whereas a probability of zero indicates that it is guaranteed not to occur. An example of a genetic event is a round seed produced by a pea plant.

In one experiment, Mendel demonstrated that the probability of the event “round seed” occurring was one in the $F_1$ offspring of true-breeding parents, one of which has round seeds and one of which has wrinkled seeds. When the $F_1$ plants were subsequently self-crossed, the probability of any given $F_2$ offspring having round seeds was now three out of four. In other words, in a large population of $F_2$ offspring chosen at random, 75 percent were expected to have round seeds, whereas 25 percent were expected to have...
wrinkled seeds. Using large numbers of crosses, Mendel was able to calculate probabilities and use these to predict the outcomes of other crosses.

The Product Rule and Sum Rule

Mendel demonstrated that pea plants transmit characteristics as discrete units from parent to offspring. Mendel also determined that different characteristics, like seed color and seed texture, were transmitted independently of one another and could be considered in separate probability analyses. For instance, performing a cross between a plant with green, wrinkled seeds and a plant with yellow, round seeds still produced offspring that had a 3:1 ratio of green:yellow seeds (ignoring seed texture) and a 3:1 ratio of round:wrinkled seeds (ignoring seed color). The characteristics of color and texture did not influence each other.

The **product rule** of probability can be applied to this phenomenon of the independent transmission of characteristics. The product rule states that the probability of two independent events occurring together can be calculated by multiplying the individual probabilities of each event occurring alone.

On the other hand, the **sum rule** of probability is applied when considering two mutually exclusive outcomes that can come about by more than one pathway. The sum rule states that the probability of the occurrence of one event or the other event, of two mutually exclusive events, is the sum of their individual probabilities. Notice the word “or” in the description of the probability. The “or” indicates that you should apply the sum rule. The sum rule can be applied to show the probability of having just one dominant trait in the F\textsubscript{2} generation of a dihybrid cross.

To use probability laws in practice, we must work with large sample sizes because small sample sizes are prone to deviations caused by chance. The large quantities of pea plants that Mendel examined allowed him calculate the probabilities of the traits appearing in his F\textsubscript{2} generation. As you will learn, this discovery meant that when parental traits were known, the offspring’s traits could be predicted accurately even before fertilization.

For a trihybrid cross, writing out the forked-line method is tedious, albeit not as tedious as using the Punnett-square method. To fully demonstrate the power of the probability method, however, we can consider specific genetic calculations. For instance, for a tetrahybrid cross between individuals that are heterozygotes for all four genes, and in which all four genes are sorting independently and in a dominant and recessive pattern, what proportion of the offspring will be expected to be homozygous recessive for all four alleles? Rather than writing out every possible genotype, we can use the probability method. We know that for each gene, the fraction of homozygous recessive offspring will be 1/4. Therefore, multiplying this fraction for each of the four genes, \((1/4) \times (1/4) \times (1/4) \times (1/4)\), we determine that 1/256 of the offspring will be quadruply homozygous recessive.

For the same tetrahybrid cross, what is the expected proportion of offspring that have the dominant phenotype for all four genes? We can answer this question using phenotypic proportions, but let’s do it the hard way—using genotypic proportions. The question asks for the proportion of offspring that are 1) homozygous dominant at A or heterozygous at A, and 2) homozygous at B or heterozygous at B, and so on. Noting the “or” and “and” in each circumstance makes clear where to apply the sum and product rules. The probability of a homozygous dominant at A is 1/4 and the probability of a heterozygote at A is 1/2. The probability of the homozygote or the heterozygote is 1/4 + 1/2 = 3/4 using the sum rule. The same probability can be obtained in the same way for each of the other genes, so that the probability of a dominant phenotype at A and B and C and D is, using the product rule, equal to \(3/4 \times 3/4 \times 3/4 \times 3/4\), or
27/64. If you are ever unsure about how to combine probabilities, returning to the forked-line method should make it clear.

Lesson Toolbox

Additional Resources and Readings

An Amoeba Sisters video explaining dihybrid crosses
   - Link to resource: https://www.youtube.com/watch?v=qIGXTJLrLf8&t=7s

A video showing dihybrid crosses, test crosses, epistasis, polygenic traits, and how to calculate probabilities
   - Link to resource: https://www.youtube.com/watch?v=sRq_uB35jww

A video explaining the independent assortment of genes
   - Link to resource: https://www.youtube.com/watch?v=X-Zj8irYZ3o

A short video explaining the law of segregation
   - Link to resource: https://www.youtube.com/watch?v=V2Vz6LTqifk

Lesson Glossary

dihybrid: result of a cross between two true-breeding parents that express different traits for two characteristics
law of dominance: in a heterozygote, one trait will conceal the presence of another trait for the same characteristic
law of independent assortment: genes do not influence each other with regard to sorting of alleles into gametes; every possible combination of alleles is equally likely to occur
law of segregation: paired unit factors (i.e., genes) segregate equally into gametes such that offspring have an equal likelihood of inheriting any combination of factors
product rule: probability of two independent events occurring simultaneously can be calculated by multiplying the individual probabilities of each event occurring alone
sum rule: probability of the occurrence of at least one of two mutually exclusive events is the sum of their individual probabilities

Check Your Knowledge

1. The __________ rule states that the probability of two independent events occurring together can be calculated by multiplying the individual probabilities of each event occurring alone.
   a. test cross
   b. product rule
   c. monohybrid rule
   d. sum rule

2. While studying meiosis, you observe that gametes receive one copy of each pair of homologous chromosomes and one copy of the sex chromosomes. This observation is the physical explanation of Mendel's law of...
   a. dominance.
   b. independent assortment.
   c. random distribution of traits.
   d. segregation.
3. People with trisomy 21 develop Down’s syndrome. What law of Mendelian inheritance is violated in this disease? What is the most likely way this occurs?
   a. the law of probability
   b. the law of segregation
   c. the law of dominance
   d. the law of independent assortment

Answer Key:

Citations

Lesson Content:
Authored and curated by Jill Carson, Cat Jackson, M. Ed. for The TEL Library. CC BY NC SA 4.0

Adapted Content:
Title: Biology – 12.3 Laws of Inheritance – Pairs of Unit Factors, or Genes: Rice University, OpenStax CNX. License: CC BY 4.0.
Link to resource: https://cnx.org/contents/jVCgr5SL@8.17:8Zft46As@3/Laws-of-Inheritance

Title: Biology – 12.3 Laws of Inheritance – Pairs of Unit Factors, or Genes: Rice University, OpenStax CNX. License: CC BY 4.0.
Link to resource: https://cnx.org/contents/bDIuMp-w@7.1:xAaCmxuG@6/Laws-of-Inheritance

Attributions

“Punnett square (PSF)” By Pearson Scott Foresman is licensed under public domain.
Link to resource: https://commons.wikimedia.org/wiki/File:Punnett_square_(PSF).png

“Figure 3.” By OpenStax is licensed under CC BY 4.0
Link to resource: https://cnx.org/contents/GFy_h8cu@11.5:cUeevuaC@3/Laws-of-Inheritance