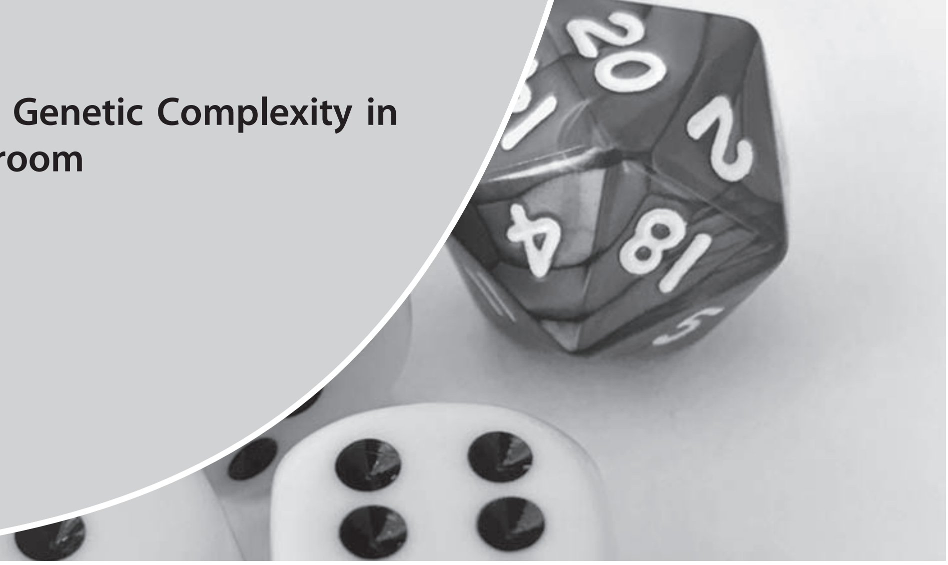
Modeling Genetic Complexity in the Classroom



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Abstract

This classroom exercise aims to help students understand the three Ps of genetic complexity: polymorphic, polygenic, and pleiotropic. Using coin flips and dice rolls, students are able to generate the genotype and phenotype of a random individual. From there, students find a mate for this individual and determine the phenotype of their offspring. The randomness generated by the coin and dice mechanics illustrates the principles of independent assortment and segregation, variable gene expression, and environmental effects.

Key Words: *polymorphisms; polygenes; pleiotropy.*

○ Introduction

Much opportunity exists for future careers in genetics-related fields, so it can be greatly beneficial to students to gain an early appreciation of these biological mechanisms. However, research suggests that students have a difficult time understanding the principles of genes, alleles, and inheritance. Not comprehending these processes leads to misconceptions such as unequal parental genetic contributions, often perceived as daughters inheriting information from their mothers and sons from their fathers (Lewis & Wood-Robinson, 2000; Williams et al., 2012). This activity walks students through the genetic "construction" of offspring and the determination of its phenotype for two different traits, blood type and skin color. By using dice to simulate genetic inheritance and expression, students can see that the processes are neither predetermined nor entirely random, which is one of the first steps toward appreciating the nuances of genetic complexity.

○ The Activity

What You Need

For this activity, students can work in small groups. Each group will receive (1) an instruction manual that describes the activity and leads them through the different stages of phenotype construction; (2) a packet of tables, or data "notebook," where they record their results; (3) a two-sided coin, such as a penny; (4) a six-sided die (henceforth referred to as a d6); and optionally, (5) a twenty-sided die (d20). The students can each take on a task: reader, recorder, coin flipper, and dice roller.

In addition to basic terminology such as the three Ps—polymorphic, polygenic, and pleiotropic—the introduction in the instruction manual lists the different loci of interest for this exercise. Examples are listed in Table 1. These loci are responsible for the expression of two different phenotypic traits, a single locus trait and a polygenic trait. Also listed for each locus are the number polymorphisms in the gene pool for that site. It is easiest to have six alleles so that a d6 can be used to randomize them; however, it is possible to demonstrate more complexity by introducing a different die such as a d20.

For the two phenotypic traits, I use the ABO blood system and skin color. The ABO blood system serves as an example of classical genetics and a starting point to which the polygenic trait can be compared. The use of skin color as the polygenic trait has two benefits: (1) to address why we often see blending of traits in the offspring of two phenotypically different parents, and (2) to set up skin phenotypes that can be acted upon by natural selection in different environments. The fact that dark skin protects from folate degradation in high-UV environments, and that light skin promotes vitamin D synthesis in low-UV environments, is not only an elegant example of natural selection in human evolution but also useful for understanding present-day diversity (Jablonski & Chaplin, 2003).

Getting Started

Students will use their dice to generate the genome of a hypothetical female from the population. This randomization process assures there will be variation in the exercise across the classroom, which is helpful for class discussion. For the ABO blood system, students will roll the d6, record their result, and then determine the allele based on the roll: 1 or 2 = A, 3 or 4 = B, and 5 or 6 = O. They will do this twice for the locus in order to generate both the maternal and paternal contributed alleles in this individual's genome. For the other loci, if the number of alleles is 6, then they will roll the

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Table 1. An example of five loci for the activity. Loci 2–5 all affect melanin production. For locus 5, I have 20 alleles to demonstrate that not each locus affects the trait in the same way.

Locus number	Alleles	Phenotypic affects
1	3	Blood type
2	6	Melanin production
3	6	Melanin production
4	6	Melanin production
5	20	Melanin production

Part A. Female Genotype

		Maternal Genome		Paternal Genome	
Locus #	Alleles	Result	Value	Result	Value
1	3	1	A	5	O
2	6	2	2	4	4
3	6	6	6	5	5
4	6	2	2	2	2
5	20	15	15	7	7

Part B. Female Phenotype

Rule	Result	Exp
Co-Dom	A,O	A
	Heads/Tails	
Random	H	2
Random	T	5
Random	H	2
Random	H	15

Total #2-5 ⟶ 24

Figure 1. Genotype to phenotype worksheet: Sample student worksheet for the genotype (part A) and phenotype (part B) associated with the five loci. For locus 1, the rule is that a roll of 1–2 is allele A, 3–4 is allele B, and 5–6 is allele O. In this example, a 1 was rolled for the maternal genome and a 5 for the paternal genome, resulting in a genotype of AO. For loci 2–5, the roll result is the same as the value, so the numbers are the same in both columns. For locus 5, a d20 was used, resulting in a 15 for the maternal genome and a 7 for the paternal genome. After completing part A, students move on to part B to determine phenotype. For locus 1, the alleles are tallied and the dominant alleles are listed in the last column (Exp = expressed). For loci 2–5, a coin is used to randomly determine which of the two alleles are expressed. The result column shows the result of the coin flip, and the Exp column records the corresponding allele, with heads indicating it came from the maternal genome, and tails from the paternal. Finally, the expressed values for loci 2–5 are totaled to determine phenotyping contribution.

d6, and the result equals the value to be recorded. Other variants include having only two alleles and using the coin, or having 20 alleles and using a d20. An example of a student worksheet appears in Figure 1.

Genotype to Phenotype

Now that students have the female's genome, they can begin to work toward determining her phenotype. For each locus, there is an expression rule. The ABO blood system is listed as "Co-Dom" because it follows the principle of classical codominance. For each locus associated with skin color, I made the expression rule "random," meaning that it is random whether the individual expresses the allele received from their mother or their father. For these loci, students will flip their coin to determine which is expressed: heads = mother, tails = father. Once students fill in the values for each skin color locus, they will add them up to determine the overall contributions of the genome to phenotypic expression of the trait (Figure 1). After they calculate this total, they can compare their number to a chart provided in the handout to determine their female's level of skin pigmentation (Figure 2).

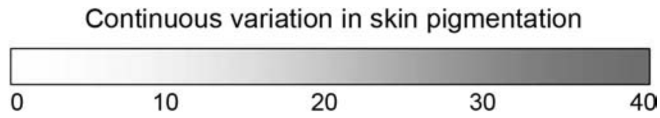

Figure 2. Skin phenotype. Student results can be compared to a gradient of continuous variation in order to assess their individual's skin color.

Table 2. Example haploid male gametes. Students are provided with the genetic makeup of six different sperm belonging to one male suitor with which their female will mate.

Sperm 1	Sperm 2	Sperm 3	Sperm 4	Sperm 5	Sperm 6
A	B	B	B	A	A
5	5	4	4	5	4
3	4	4	3	4	3
3	6	3	6	3	3
3	2	2	2	3	2

Sexual Reproduction

Students are now provided with the haploid genetic information of six male gametes of their female's suitor (Table 2). For each locus there can only be one of two different alleles, with each constrained by the number of alleles for that site. To generate this, I used my own coin and dice to generate their maternal and paternal alleles, and then mixed them up in different combinations for the six gametes.

Before they can proceed, students need to determine the genetic information coded in their female's gametes. For simplicity, it is assumed that these loci come from all across the genome, thus are considered to not demonstrate any chromosomal linkage in inheritance. Based on Mendel's principles of segregation and independent assortment, each locus has an equal chance of contributing one of its two alleles to the sex cell, and the result from one locus has no affect on the other. Therefore, students can flip a coin to determine whether the gamete receives the maternally inherited or paternally inherited part of the mother's genome. I have them do this twice to create two haploid eggs.

Offspring Genotype and Phenotype

Students will randomly determine which sperm fertilizes which egg by rolling a d6 and flipping a coin, respectively. Using that genetic information, they will generate the offspring's genotype and phenotype just as they did for their initial female.

Additional Effects

Lastly, students will investigate other factors affecting phenotype such as pleiotropic genes and environmental effects. I like to use the d20 for this portion, but expect this can be easily modified to continue using the d6.

Students will adjust the skin color phenotype based on two possible environmental factors: regular exposure to strong sunlight and effects of a diet rich with carotenoids. For each trait, a roll of the d20 determines an adjustment between –2 and +2: 1 to 4 = –2; 5 to 8 = –1; 9 to 12 = 0; 13 to 16 = +1; 17 to 20 = +2. There are no environmental factors for the ABO blood system since the phenotype is highly heritable.

Lastly, as an example of pleiotropy but also a deeper dive into probabilities, I have my students determine whether their individual suffers from phenylketonuria (PKU). This disorder, whereby a mutation causes the metabolism of the amino acid phenylalanine to be inhibited, affects many traits, most notably cognitive function, but also melanin synthesis. I use an estimated incidence of 1/8,000 for the disease. Students roll the d20, and whatever result they get, if they are able to roll that same number three more times in a row, the probability is the same as a random individual in the population inheriting PKU. If they happen to achieve this highly improbable series of rolls, I have them reduce their total melanin by 90 percent, which is an arbitrary adjustment, but generally reflective of the disease.

Once these effects are determined, and the total for skin color phenotype is adjusted, students can determine the level of skin pigmentation for the offspring, and compare it to their parents as well as to their classmates' results.

○ Class Discussion and Student Response

The groups of students are given discussion questions asking why offspring and mother phenotypes might differ, and asking in which environments these phenotypes may be best fit. I have seen that these discussions include a much more nuanced understanding of phenotypic variation than when the concepts of genetic complexity were only read in the text and lectured in class. I was never able to present how integrated these processes are without this activity. The first time I ran it, I had a single 12-page handout, and students got lost. By dividing it into an instruction manual and data packet, students are more likely to read the instructions before jumping to the tables. My handouts can be found online at http://www.entomoanthro.org/blog/gamers-dice-and-genetic-complexity. Of course, the activity can be modified to eliminate the use of the d20; however, I find its inclusion helpful to signify complexity since most students are unfamiliar with this type of die, and the novelty of it helps to keep them engaged.

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