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Simulating Genetic Drift and Natural Selection

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The concepts associated with evolutionary processes can be challenging for students, especially without a way to conduct hands-on experiments about processes that occur in evolutionary time frames. Laboratory simulations make it possible to allow the manipulation of variables that could not otherwise be investigated. This experiment includes two simulations; one to investigate the impact of population size on the degree of genetic drift in a population, and a second simulation to demonstrate the effect of a selective pressure on the evolution of a population. The comparison of results from each simulation allows the processes of genetic drift and natural selection to be clearly delineated from each other.

Keywords: evolution, natural selection, genetic drift, simulation

Introduction

A strong understanding of evolutionary processes is fundamental to understanding biology at all levels, from subcellular physiology to community ecology. For this reason, the incorporation of evolution into the content of introductory biology courses is essential and remains one of the core concepts of biological literacy (AAAS, 2011). There can be multiple challenges to overcome while determining the best way to teach evolution in an introductory biology laboratory course. One challenge is that evolutionary processes, such as natural selection, can be difficult to demonstrate in real time. Another obstacle is the misconceptions about evolution that students may bring to the classroom (Gregory, 2009). The laboratory experiment presented here addresses both of these challenges in two easy, and even fun, simulations of evolutionary processes.

The time required for natural selection to effect a change in the characteristics of a population presents a challenge to teaching this concept in a laboratory course. Students benefit most from directly experiencing and manipulating biological processes in a laboratory experiment and this is challenging when the biological process in question occurs on an evolutionary time scale. The use of simulations to mimic evolutionary processes addresses this issue and provide students with practice in applying model systems to investigate biological processes (AAAS, 2011).

Introductory biology students often have misconceptions about evolution, and especially about the process of natural selection (Kalinowski, et al., 2013; Gregory, 2009). One of the most common misconceptions is that natural selection acts at the level of the individual, rather than at the population level (Gregory, 2009). The laboratory activities presented here can help to dispel this confusion. The natural selection simulation uses the very common example of the evolution of cryptic coloring in the peppered moth, *Biston betularia*, during the industrial revolution [first described by Tutt (1891); later extensively studied by Kettlewell (1955)]. Prior to conducting the simulation students often believe that the population of peppered moths changed from predominantly showing the wild-type light coloring to the dark coloring because the soot and air pollution produced in the industrial revolution landed on the moths. This confusion is resolved when students realize that the change to the moth population did not occur by painting the light moths to a dark color and returning them to the population during the simulation.

There are many positive aspects to this laboratory experiment. Students can experience, in a hands-on manner, a very clear demonstration of the process of natural selection. Comparing the results from the two simulations facilitates a discussion of the differences between evolutionary change from genetic drift and from natural selection. Students can improve their understanding of the nature of science by applying the simulation results to test the hypotheses given in the experiment. And as a bonus, students enjoy the game-like nature of the natural selection simulation.

Student Outline

Objectives

- Use a simulation to evaluate the effect of population size on genetic drift
- Use a simulation to evaluate the effect of a selective pressure on the evolution of a population
- Compare the impact of genetic drift to that of a selective pressure on the evolution of a population

Introduction

In today's exercise, you will explore the evolutionary effects of processes that can influence an individual's survival and reproduction within a population. **Natural selection** is a nonrandom process that favors adaptive traits (traits that increase survival and reproduction). If these adaptive traits have a genetic basis, natural selection can result in evolution—a change in the frequency of a heritable trait as it passes from one generation to the next.

In contrast, two random processes, the bottleneck effect and the founder effect, cause genetic drift, random changes in the genetic status of a population. The **bottleneck effect** is a reduction in the size of a population as a result of mortality that is not due to the quality of an individual's traits but is simply a result of bad luck. A natural disaster, such as a flood or a hurricane, is an example of a bottleneck that could severely reduce the number of individuals in a population. The **founder effect** is the separation of a few individuals into a new population by a random process that is also not due to the quality of their traits. The migration of a small number of birds from a mainland to establish a new population on a remote island is an example of a founder effect. Notice that although these effects are not due to the influence of a particular trait on survival or migration, they can change the frequency of important traits. If genetic drift as a result of the bottleneck or the founder effect persists from one generation to the next, evolution has occurred.

The size of a population determines the influence of random events, such as bottleneck or founder effects. For example, if you flip a coin twice, the frequency of "heads" could easily range from 0/2 (0%) to 2/2 (100%); however, if you flipped the coin 100 times, the frequency of "heads" would be much more likely to stay near 50%. To put this same process into a biological context, individual random events determining the assignment of chromosomes to gametes, the combination of gametes at fertilization, or the survival of individuals, have a stronger influence on small populations. As a result, genetic drift is much stronger in small populations than in large populations.

In today's activities, you will be observing the evolutionary impacts of genetic drift and natural selection. Evolutionary change occurs between generations, so you will have to observe each population over a number of generations. Because it is simply not practical to conduct these experiments with living organisms in a single laboratory session, you will manipulate a model system to simulate genetic drift and natural selection. These simulations will involve counts of beans that will be used to represent light and dark moths. In the first activity, you will simulate genetic drift; in the second activity, you will simulate natural selection.

Simulation of Genetic Drift

In this simulation, you will use black and white beans to represent dark-colored and light-colored moths (Fig. 1). You will randomly determine which individual moths survive to produce the next generation. In some generations, many individuals will survive to produce the next generation; in other generations, only a few individuals will be lucky enough to survive and contribute to the next generation. This will allow you to contrast the effect of genetic drift on small and large populations.

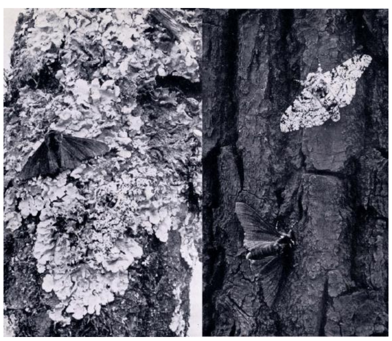

Figure 1. Black and white beans will be used to represent dark and light moths, *Biston betularia*. Photo credit: Wikimedia Commons.

Each group of four students will share their results with the entire class. When you compare the evolutionary results (changes in the frequencies of dark moths between generations) between groups, you will be able to determine if genetic drift affects all populations the same way, or if it varies between groups.

HYPOTHESIS: Following a random event that changes the size of a population, the rate of survival influences the degree of genetic drift.

You first will simulate three rounds of genetic drift associated with survival and reproduction of a large random sample (50 individuals) of the population. You will then simulate three rounds of genetic drift associated with survival and reproduction of a small random sample (5 individuals) of the population. In the space below write a statement of what you predict will be the results of this simulation.

PREDICTED RESULTS OF GENETIC DRIFT SIMULATION:

Methods of the Genetic Drift Simulation

l. Begin with 50 light and 50 dark moths and set them in a mixed pile on the table, the composition of Generation One (50 light moths and 50 dark moths) has already been recorded in Table 1.

Table l. Group results, numbers of light and dark moths in genetic drift simulation.

GENERATION	NUMBER OF MOTHS AT THE BEGINNING OF THE GENERATION (Out of 100)		NUMBER OF SURVIVING MOTHS (Out of sample of 5 or 50)	
	LIGHT	DARK	LIGHT	DARK
One (50)	50	50		
Two (50)				
(50)				
Four (5)				
Five (5)				
Six (5)				
Seven				

2. Simulate the first round of genetic drift by closing your eyes and randomly picking 50 moths from the pile of 100 on the table. These 50 selected moths are the ones that have survived a bottleneck effect during Generation One. Record the numbers of surviving light and dark moths in Table 1.
3. Build the population back up to 100, assuming these 50 parents produced offspring similar to themselves. For example, Table 2 contains sample data in which a group of students selected 27 light moths and 23 dark moths as the survivors of the

bottleneck event. To determine the composition of the population for the beginning of the second generation, they calculated the new ratio of light moths in the population by dividing 27 by 50 and multiplying by 100. They found that the second generation will consist of 46% light moths. Since the total population size is 100, Generation Two will begin with 46 light moths. They then calculated the new ratio of dark moths for Generation Two in the same way (dividing 23 by 50 and multiplying by 100) and started the second generation with 54 dark moths. After you complete the calculations for your own data, set up Generation Two with a total of 100 moths using the new ratio of light to dark moths.

Table 2. Sample data for the genetic drift simulation.

GENERATION	PROPORTION OF MOTHS AT THE BEGINNING OF THE GENERATION (OUT OF 100)		NUMBER OF SURVIVING MOTHS (OUT OF SAMPLE OF 5 OR 50)	
	LIGHT	DARK	LIGHT	DARK
One (50)	50	50	23	27
Two (50)	46	54		

4. Starting with this second generation of moths, repeat steps 2 and 3 to determine which moths survived Generation Two and started Generation Three. Repeat steps 2 and 3 again to determine who survived Generation Three and entered Generation Four.
5. Now you are ready to implement genetic drift using a small sample size. Repeat steps 2 and 3 for the last three generations, except in these simulations, only allow five individuals to survive each bottleneck. Still start each population with 100 individuals.
6. Record your group's numbers of dark moths at the beginning of each of the six generations in a table that your instructor will draw on the board. Record each group's data into Table 3.

Table 3. Class results from the genetic drift simulation.

GENERATION	NUMBER OF DARK MOTHS AT THE BEGINNING OF EACH GENERATION					
	GROUP I	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
One						
Two						
Three						
Four						
Five						
Six						
Seven						

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Simulation of Natural Selection

In this simulation, you will investigate the evolutionary effects of differences in survival that are associated with a genetically based trait. In other words, you will study evolution in response to natural selection. You will then contrast the pattern of evolution generated by natural selection with the pattern of evolution generated by genetic drift.

Many animals, including insects, reptiles, and mammals, have evolved cryptic color patterns (Fig. 2). Cryptic color patterns are types of natural camouflage that allow individuals to blend into their habitat. Crypsis is adaptive because it reduces predation—if they can't see you, they can't eat you.

Figure 2. An example of crypsis. Photo credit:Wikimedia Commons.

One of the most well-known examples of rapid evolution is the evolution of industrial melanism in the moth, *Biston betularia*. In the daytime, moths rest on tree trunks where they risk being eaten by birds. Prior to the industrial revolution, light-colored moths were well hidden in the light lichen growing on tree trunks. In contrast, dark forms of the moth that contain more of the pigment melanin were easier to see and were eaten more often by avian predators. As a result, light moths were common, and dark moths were rare.

The light-colored lichen growing on the tree trunks died as a result of air pollution during the industrial revolution. The bark returned to its natural dark brown color and the selective values of the moth color were reversed. The dark moths were well hidden from birds, while the moths rested on the darkened tree trunks, but the light moths were now more visible to birds (Fig. 3). As a result, the dark moths survived more often and produced more offspring. Since the color differences of the moths are genetically based traits, this natural selection resulted in a dramatic increase in the frequency of the dark moths. In 1850, dark *Biston betularia* were sought after by collectors and approximately 4% of their collections were composed of dark moths. After 50 years, which equals 50 generations of the moth, 95% of the collections were made up of dark moths. The color of *Biston betularia* had evolved in response to natural selection.

Figure 3. Light and dark Biston betularia moths on dark bark. Image credit: Modified from Khaydock, Wikimedia Commons https://commons.wikimedia.org/wiki/File:Peppered_moths_c2.jpg

HYPOTHESIS: Under a selective pressure, the phenotypes of an organism allow for differential survival of members of a population.

Methods of the Natural Selection Simulation

In this activity, you will simulate predation on light and dark moths against a dark background. Dark gravel in a tub will represent trees that have been darkened by pollution; black and white beans will represent black and white moths—and you will imitate the predator, a bird. Along with your lab partners (fellow birds) you will simulate six 10-second meals or feeding trials. At the end of this first experiment, you will describe the effects of this selection pressure on the phenotypic frequencies of the moths. Before beginning the simulation, use the space below to write a statement of what you predict will be the results of this simulation.

PREDICTED RESULTS OF NATURAL SELECTION SIMULATION:

l. Begin with 50 light and 50 dark moths. The composition of Generation One has already been recorded for you in Table 5.
2. The dark tree trunk is represented by the dark aquarium gravel in the bottom of the tub. Mix the 100 dark and light moths, and then scatter them onto the tree trunk (in the tub).
3. Your group will now simulate bird predation. Your instructor will time the 10-second feeding trials. Your group will act like birds and will be referred to as birds in the rest of the methods. When the timer says "GO!", the flock of birds will begin to feed on the moths. Each of the birds will do this by picking up one moth at a time and placing it into the cup; once it is dropped into the cup, the bird may grab another moth The bird that can eat the most moths in a 10-second foraging bout is the King or Queen of the flock and will receive all sorts of avian benefits.
4. Record in Table 5 the number of moths of each phenotype that your group has eaten during Generation One.
5. Use subtraction to determine the number of light and dark moths that you have not eaten; record these values as surviving light and dark moths in Table 5. Add the surviving light and dark moths together to calculate the total number of surviving moths.

Table 4 contains an example of data for this simulation. During the first feeding trial a group of students (birds) removed (ate) 11 light moths and 8 dark moths. They then calculated that there were 39 light moths (calculated by subtracting 11 from 50) remaining on the tree. They also calculated that there were 42 dark moths (50 minus 8) remaining on the tree. The total moths remaining on the tree after the first feeding trial was 81 (39 plus 42).

Table 4. Sample data for the natural selection simulation.

GENERATION	BEGINNING PROPORTION		NUMBERS EATEN		NUMBERS SURVIVING			PERCENT OF SURVIVING		NUMBERS ADDED DURING	
	LIGHT	DARK	LIGHT	DARK	LIGHT	DARK	TOTAL	LIGHT	DARK	LIGHT	DARK
One	50	50	11	8	39	42	81	48	52	9	10
Two	48	52									

6. Build the population back up to 100, assuming these surviving moths produced offspring similar to themselves.
   a. First calculate the percent of the surviving moths that are light and the percent of the surviving moths that are dark. Record the percent of each type in Table 5 (as an integer, between 0 and 100, not as a decimal between 0 and l). Notice in the sample data (Table 4) that the total number of surviving moths was 81 (39 plus 42). Therefore, the percent of light moths surviving after the first feeding trial was 48% (39 surviving light moths divided by 81 total surviving moths multiplied by 100). The percent of dark moths surviving the first feeding trial was 52% (42 divided by 81 multiplied by 100).
   b. Subtract the number of surviving light moths from the percent of surviving light moths to determine the number of light moths that you must add during reproduction. Do the same calculation with the dark moths. Record the number you have added of each type in Table 5. The sample data (Table 4) shows that the ratio of light and dark moths surviving the first feeding trial was 48% light and 52% dark moths. These are the proportions of light and dark moths that begin Generation Two. Since 39 light moths remain on the tree after the first feeding trial, the students only had to add 9 light moths (48 minus 39) to set up Generation Two. There were still 42 dark moths on the tree, so the students added 10 more to reach the 52 dark moths needed for Generation Two.

To check that you have done the calculation correctly, add the total number surviving moths (this is 81 in Table 4) to the numbers added during reproduction (9 light and 10 dark moths in the sample data), and make sure it equals 100.

7. Repeat steps 3 through 6 until you have simulated natural selection and recorded the results for generations three through seven. Record the data in Table 5.

Table 5. Group data for the number of moths during the simulations of natural selection.

GENERATION	BEGINNING NUMBERS		NUMBERS EATEN		NUMBERS SURVIVING			PERCENT OF SURVIVING MOTHS		NUMBERS ADDED DURING REPRODUCTION	
	LIGHT	DARK	LIGHT	DARK	LIGHT	DARK	TOTAL	LIGHT	DARK	LIGHT	DARK
One	50	50									
Two											
Three											
Four											
Five											
Six											
Seven											

8. Record your group's proportion of dark moths at the beginning of each of the seven generations in a table that your instructor will draw on the board. Record each group's data into Table 6.

Table 6. Class results from natural selection simulation.

GENERATION	PROPORTION OF DARK MOTHS AT THE BEGINNING OF EACH GENERATION					
	GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6
One						
Two						
Three						
Four						
Five						
Six						
Seven						

Data Analysis

Your results from both the Genetic Drift Simulation and the Natural Selection Simulation can easily be compared. Use Figure 4 to show the effect of the survival rate following a genetic drift event influences the degree of genetic drift experienced by the population. Be sure to label the X-axis and Y-axis appropriately. The graph should contain all of the class data from Table 3. Likewise, use Figure 5 to graph all the class data from Table 6, demonstrating the effect of a selection pressure on the phenotypic ratio within the population.

Complete your data analysis by answering the following questions.

1. Describe the results of the genetic drift simulations seen in Figure 4. Did all the simulations from the different lab groups show the same results? Why or why not?

2. What evidence is seen in Figure 4 that either supports or refutes the hypothesis of the genetic drift simulation?

3. Describe the results of the natural selection simulations as seen in Figure 5. Did all the simulations from the different lab groups show the same results? Why or why not?

4. What evidence is seen in Figure 5 that either supports or refutes the hypothesis of the natural selection simulation?

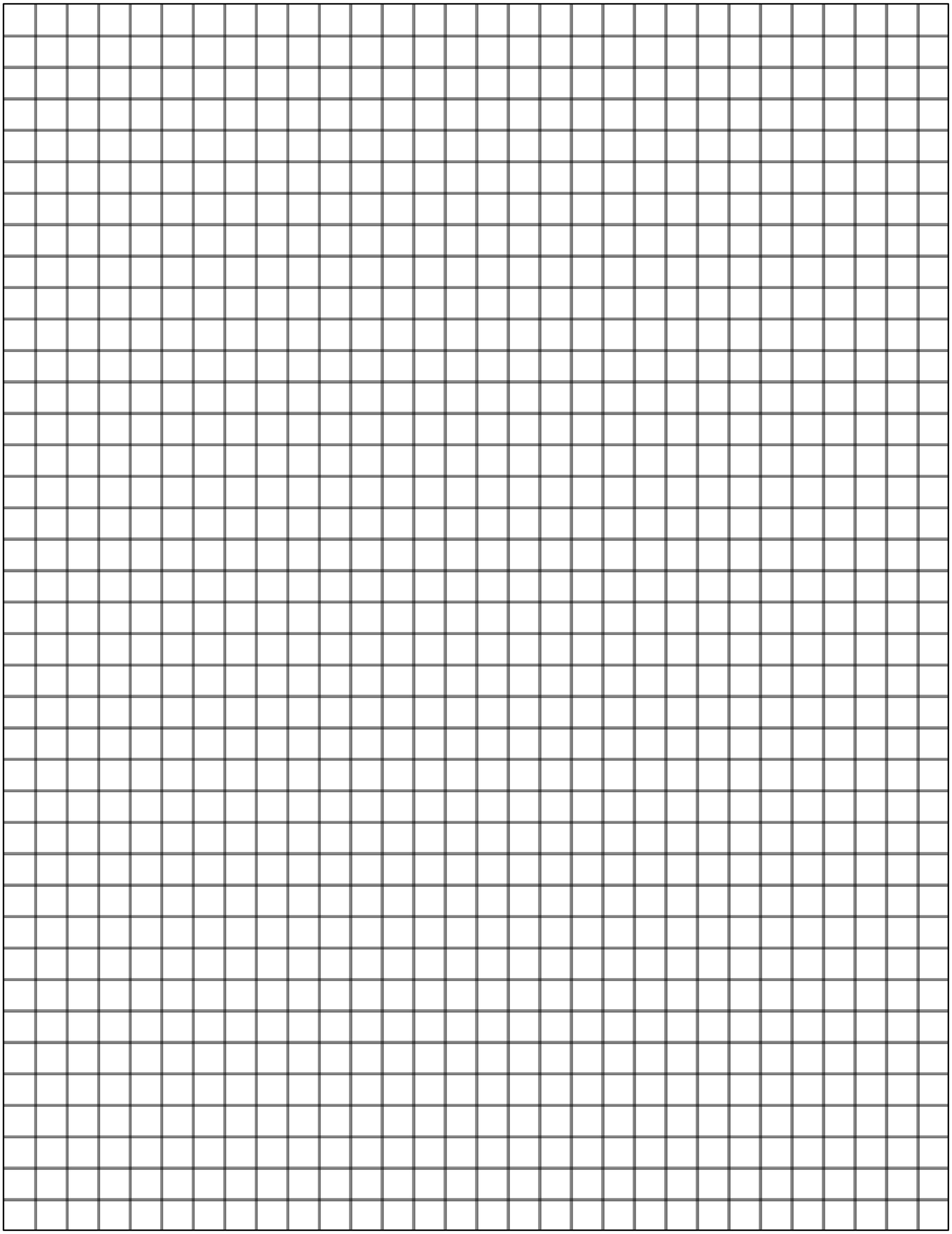

Figure 4. Simulation Effect of population size on genetic drift.

Figure 5. Simulation effect of selective pressure on the evolution of *Biston betularia*.

Materials

Large plastic tubs are used to represent the “tree trunks” during the natural selection simulation. The tubs should be approximately 5” deep by 17” wide and 25” in length. One tub is required for each group of up to four students. The tubs should be filled with 0.5 – 1.0” (~2cm) of black aquarium gravel. It is important that the gravel have a matte finish rather than a glossy finish. The black beans will become too visible against a glossy gravel background. The light moths and dark moths for both simulations are represented by beans. Any light and dark beans can be used, such as navy beans and black beans. The most important aspect of choosing the beans is that both colors of beans should be the same size. Beans of different sizes may inadvertently influence which color bean is selected during either simulation. Each student should also have a small cup (paper cup or 50mL plastic beaker) for collecting their beans during the natural selection simulation.

Notes for the Instructor

The greatest challenge when teaching this exercise is to stimulate students to consider how a simulation represents natural processes; how to consider the significance of manipulation of abstract models. Tying natural selection and genetic drift to explicit examples is an important aspect of introducing this experiment. As they use the models to study the dynamics of drift and selection, and if they keep track of the phenomena represented by different components in the simulation, they will begin to see how interactions between the environment and individuals determine the evolutionary trajectory of the population. The results of the simulations provide a striking comparison between the evolutionary consequences to genetic drift and natural selection. The drift simulations also illustrate the effects of sample size on the strength of genetic drift.

During the genetic drift simulation, the main source of confusion is reproduction, the need to create a new generation with the same phenotypic frequencies as the moths that were selected by genetic drift. During the natural selection simulation, the same confusion can arise with respect to the reproduction of the population between generations. During both simulations it is often necessary to take the class through the calculations for creating the next generation of the population. For the natural selection simulation, it is often easier if the instructor acts as the timer (saying “Go!” and “Stop!”) so that all groups of students conduct the simulation simultaneously. This allows all groups to also simultaneously complete the calculations (Tables 1 and 5) for setting up the next generation. The instructor can project a blank data table on a whiteboard and then walk the entire class through the necessary calculations, rather than working with each group of students separately. Examples of the necessary calculations have been provided in Tables 2 and 4.

Students generally enjoy the natural selection simulation at the level of a game. It is important to encourage the friendly competition, to encourage students to attempt to pick the most moths (one moth at a time) so that they don’t bias their behavior by considering the purpose of the experiment as they pick moths. Also, students must clean the remaining beans out of the tub before they leave, so the next group of students does not have additional beans (usually black ones) in their tub.

The lab report for this lab exercise consists of reporting the observed results and evaluating the hypothesis for each simulation. Appendix A includes the grading rubric for this assignment. The Results section of the lab report requires that students use Excel to graph the data from all the groups (Tables 3 and 6). If students are inexperienced with graphing in Excel, or are not clear about what the data demonstrates, they can create an incorrect graph without realizing that it does not accurately represent the data. To prevent this, I recommend ending the lab period with a graphing exercise. Each group can add their data to a graph on the board (Figures 4 and 5). This not only shows students what the graph should look like, but also facilitates discussion about the results and conclusion of the experiment.

Analyzing the results of these experiments requires the ability to critically examine subtle aspects of graphs; instructors tend to assume that students see the same things they do when they inspect the graphs, but this is often not the case. Students will need to consider the slopes, rather than magnitudes, of individual lines, compare slopes across lines within a graph, and lastly compare slopes of sets of lines between graphs.

Within a single group’s results of six generations of genetic drift, the results illustrate how sample size affects the evolutionary response to drift. The slopes of these lines usually change noticeably after the survival rate drops from 50% to 5% in the simulation. The comparison between data from different student groups illustrates the random nature of genetic drift. It is important that students see the difference between the random nature of genetic drift and the directionality of the natural selection data. The comparison between the lines generated in the natural selection simulation will show that they are close to parallel and all have a positive slope (Fig. 5), in sharp contrast to the comparison between groups randomly picking moths in the genetic drift simulation (Fig. 4); this provides an interesting contrast of genetic drift and natural selection.

In more advanced courses, students can be assigned to read and analyze a paper by Bouzat et al (1998) to help them appreciate the effects of genetic drift on the genetic diversity of at-risk populations. This paper evaluates the effects of genetic drift on a population of

Greater Prairie Chickens by comparing its genetic diversity to that of other populations that have not experienced genetic drift and by comparing it to museum specimens collected before a bottleneck. After a little help with the terminology, beginning students can understand the introduction, and the results and discussion sections of this paper reasonably well; I suggest they skip the methods and materials section.

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About the Authors

Amy Marion has been the Biology Laboratory Coordinator at New Mexico State University since 2001, where she coordinates three introductory laboratory courses and occasionally teaches the associated lecture courses.

Appendix A: Genetic Drift & Natural Selection Lab Report Grading Rubric

Category	earned points	potential points
Results Describe the results of the genetic drift simulation by providing: - a graph (computer generated) of the data in Table 3. - a written summary of the results shown in this graph. Describe the results of the natural selection simulation by providing: - a graph (computer generated) of the data in Table 6. - a written summary of the results shown in this graph. Be sure that each graph accurately represents the data from the table. The graph must be in the correct format with proper axes labels and an appropriate title. For the written descriptions of the results, do NOT simply repeat the numbers from the tables. Instead, summarize the trends you see in the data. Pay attention to the slopes of the lines. For the genetic drift simulation, notice any differences in the effect of the genetic drift simulation on large or small populations. For the natural selection simulation, notice whether any of the populations reached fixation.		1.0 pts 0.5 pts 1.0 pts 0.5 pts
Discussion Write a Discussion for the genetic drift simulation containing: - a statement of the hypothesis *in your own words* and cite the source - a comparison of the predicted results to the observed results - a statement which evaluates the hypothesis of the experiment, indicating whether the hypothesis is supported by the class data or not - You must use your observed results to convince your reader that your conclusion is accurate. Write a Discussion for the natural selection simulation containing: - a statement of the hypothesis *in your own words* and cite the source - a comparison of the predicted results to the observed results - a statement which evaluates the hypothesis of the experiment, indicating whether the hypothesis is supported by the class data or whether the class data does not support the hypothesis - You must use your observed results to convince your reader that your conclusion is accurate. Discuss the implication of these simulations by considering how they relate to something beyond this lab exercise. For example, you might consider the following ideas as you write the implications: -How do these simulations relate to the restoration of endangered species? -If you were studying the evolutionary history of a particular trait, discuss how you might determine if the evolution of the trait had been driven primarily by genetic drift or primarily by natural selection?		0.5 pts 0.5 pts 1.0 pt 1.0 pt 0.5 pts 0.5 pts 1.0 pt 1.0 pt 1.0 pt
Format The report must be typed, double-spaced, in paragraph format. The Results and Discussion sections of the report should be separated by subheadings. In-text citations and the list of References must be in the proper format.		TA discretion
Total		10.0 pts

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