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Modeling Evolution in the Classroom: An Interactive LEGO Simulation

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INQUIRY & INVESTIGATION

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Abstract

Evolutionary theory is critical for a comprehensive understanding of biology, yet students often fail to grasp its underlying principles. This results partially from ineffective teaching; however, the use of interactive activities could alleviate this problem. In this guided investigation of evolutionary mechanisms, students use LEGO bricks to simulate how mutation, migration, genetic drift, and natural selection can affect the evolution of a population. This exercise was undertaken and assessed with college introductory biology students, but is also appropriate for advanced high school students.

Key Words: *evolution; natural selection; mutation; simulation; interactive.*

○ Introduction

The importance of evolutionary theory to the field of biology as a whole is difficult to overstate. As Dobzhansky famously stated, "Nothing in biology makes sense except in the light of evolution" (1973). This statement is borne out today in the ever increasing applications of evolution to such divergent fields as medicine and conservation (Losos et al., 2013). Because of the wide-ranging implications for both ourselves and biological diversity, it is imperative that students have a clear understanding of evolutionary theory.

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Unfortunately, despite its continued importance, sociocultural factors can result in the minimization or exclusion of evolution in the high school biology classroom (Glaze & Goldstein, 2015; Goldston & Kyzer, 2009; Trani, 2004). Because any understanding of biology outside of the context of evolution is incomplete, it is reasonable to infer that these students are then less prepared to understand biology at the collegiate level. For example, it has been shown that students who were taught evolution (without creationism) in high school are significantly more likely to accept specific evolutionary claims as college students than those who were taught creationism, with or without evolution (Moore & Cotner, 2009). These students also have greater knowledge of the theory of evolution (Moore et al., 2009). Glaze and Goldston (2015) found that many factors can play a role in poor student understanding of evolution, such as the inclusion of creationism in the classroom, prior held beliefs of students, and ineffective teaching.

Both the inadequate training of high school teachers, who often have general rather than specialized science backgrounds, and their frequent reluctance to teach the subject have been documented in various studies (Berkman & Plutzer, 2011; Larkin & Perry-Ryder, 2015; Rutledge & Mitchell, 2002; Rutledge & Warden, 2000; Trani, 2004). Changing the personal beliefs of teachers could be difficult, but steps can be taken to better prepare them for the classroom. Specifically, providing easily accessible and interactive exercises would likely increase a teacher's comfort level and make them more willing to present the material. We have developed one such exercise in which students physically model the process of evolution using LEGO bricks. Educational research has consistently shown that active learning is crucial in the development of student cognitive skills (Antle, 2013; Freeman et al., 2014; Prince, 2004). The exercise described here is one way to help students understand evolution using manipulatives, group discussion, and a process-driven activity.

○ Student Objectives

After completion, students will be able to calculate frequencies of a phenotypic trait in a population and relate the change in frequencies to biological evolution. Students will also be able to identify mechanisms of evolution and understand how each mechanism can affect descent with modification.

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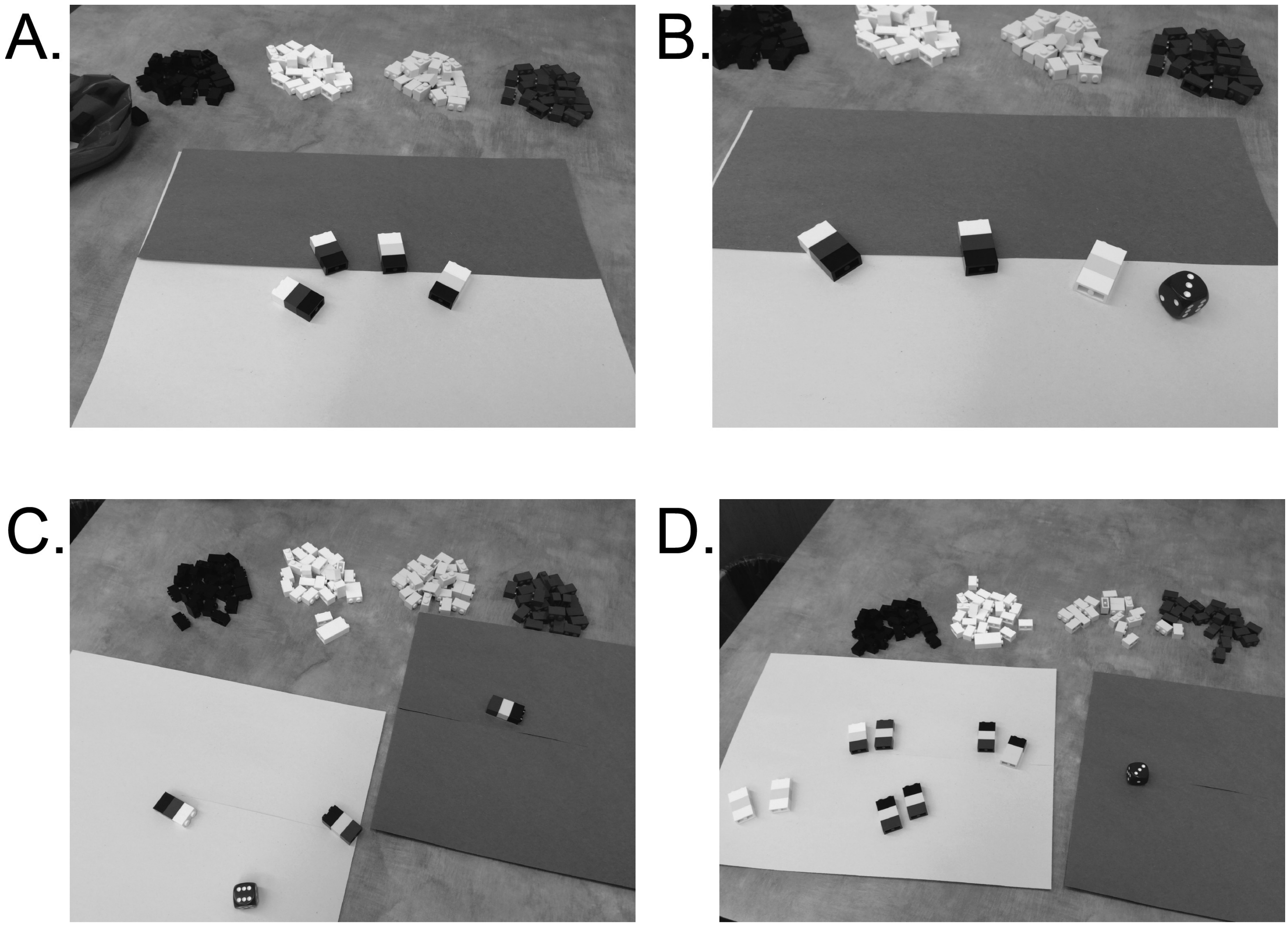

Figure 1. Example of progression of the exercise. **(A)** At the start of Part A, four LEGO organisms are built such that each has a single brick that matches their environment. In this case, the environment is two pieces of colored paper with a slit cut halfway through one axis. The papers fit together such that each represents half of the environment. **(B)** In this example, after reproduction and introduction of subsequent mutations, one of the offspring did not survive to reproduce. **(C)** In Part B, the population is divided by separating the pieces of paper. This increases selective pressure, since now the organisms must possess at least one brick of a single color (vs. one brick that matches one of two background colors). **(D)** In this picture, there are no surviving organisms on the dark piece of paper. Outcomes will vary in each group of students, not all transitional steps are shown in this figure.

○ Alignment of Exercise with Next Generation Science Standards (NGSS)

The described exercise aligns with several of the Next Generation Science Standards (NGSS). Specifically, several disciplinary core ideas (heredity, natural selection, adaptation), scientific and engineering practices (developing and using models, analyzing and interpreting data, constructing explanations), and crosscutting concepts (patterns; cause and effect; scale, proportion, and quantity; stability and change) are addressed.

○ Details of Exercise

Students are provided with some basic introductory information at the start of the activity (Supplementary Materials, Section I). This includes a definition of evolution and description of each of the four mechanisms that can cause evolution. Students then work in small groups and use LEGO bricks to build a population of organisms, make predictions, and simulate evolution.

The exercise has three parts. In Parts A and B, students model the mechanisms of evolution using specified parameters. Specifically, a small population of organisms is built from four different colors of LEGO bricks, where color is used as camouflage. The environment is represented by two pieces of colored paper (Figure 1). To survive, the LEGO organism must have at least one brick that matches either color of the environment. Organisms that match the environment better also have a reproductive advantage. Mutations in color are introduced into each generation by rolling dice. Students record the frequency of each color across several generations. These two parts of the exercise differ in the strength of selection. In Part A, the organisms have access to a more variable environment (i.e., two different colors) (Figure 1 A, B), whereas in Part B, the environment is a single color (Figure 1 C, D). Since the organism must at least partially match the environment to survive and to reproduce, natural selection is stronger in Part B. Finally, in Part C of the exercise, groups alter the simulation to test how changes in one of the mechanisms will affect the rate of evolution. This part is designed to facilitate development of critical thinking skills, but could be omitted for less advanced students. The instructions for the entire exercise are provided in the Appendix. Preprinted tables for data entry and discussion questions can be found in the supplementary materials (Section II).

○ Assessment

This exercise was assessed in multiple stages at the University of Nebraska–Kearney. It was first tested informally with a group of 10 students enrolled in "Evolution" (sophomore/junior majors), and then was piloted with a group of 19 students in Biology I (introductory biology for majors) in the spring semester of 2015. In both cases, students completed the lab exercise and then provided anonymous qualitative feedback. Specifically, all students were asked to answer two questions about the procedure (not shown) and two questions concerning their perceived learning (Table 1). Modifications to the exercise were made based on this feedback. After revision, all students (133) enrolled in Biology I in the fall semester of 2015 completed the exercise. A multiple-choice test was refined by an assessment specialist and, after modifications, was administered at the start of class and again immediately after completion of the exercise the same day. Each pre-test and post-test assessment associated with the lab included nine questions, and a total of 130 of the students completed both assessments (Supplementary Materials, Section III).

Improvement between the pretest and posttest results was statistically significant, as determined by a paired sample ttest ($t = 9.43$, $df = 129$, $p < .0001$) (Table 2). Correspondingly, the Cohen's d effect size associated with the difference between the pre-test and post-test scores was quite large at 0.959. For Cohen's d, a value of 0.2–0.3 is considered to represent a small effect size, a value of 0.4–0.7 is generally considered medium, and a value greater than 0.8 is considered to represent a large effect.

○ Conclusion

Our results show this activity is an effective means to assist students in understanding evolution. It was our objective to create an exercise that would assist teachers in accurately presenting evolutionary theory to students. Our results indicate a significant

Table 1. Questions used in qualitative assessment of perceived learning and selected student responses.

Did this lab help you better understand the four mechanisms of evolution? If so, which mechanisms do you think it helped explain the most?	Would you enjoy doing this exercise as an introductory biology lab?
Yes, this lab was very helpful in teaching and reinforcing the four mechanisms of evolution. I felt that this experiment helped to really explain the difference between natural selection and genetic drift and the lab really applied a good visual understanding.	Yes, it was a fun interactive experiment that made evolution fun and taught the subject in an interesting fashion.
Yes, it helped with both migration and selection. Visualizing that organisms cannot migrate and would die if they don't match their environment.	Yes! Visualization really helps.
Yes, it really helped with migration and selection.	Yes! A hands-on activity with a good explanation of how it works is very helpful when understanding a subject like this.
I understand migration and mutation more, not drift or selection.	Yes, it is better than just paper and it would keep you guessing on what happens next.
Yes, really showed how population size should be large in order for evolution to occur.	Yes
Yes, it was helpful to see it actually happen. The legos helped me understand the mutation effect.	Yes, it was one of the most fun evolution labs I have done so far.
Mutation was explained more to me however I'm still confused about migration/genetic drift.	Yes, I did but luck wasn't on our side.
Yes to some degree. It was best at showing how selection acts on mutation.	Yes, it had the unexpected result of showing the bottleneck effect and the random possibility of extinction.
Yes. It helped me understand more about mutations and genetic drift.	It was awesome!
Yes, helped with mutation the most, then migration.	Yes, it was a fun hands-on lab.

Table 2. Comparison of pre-test and post-test assessment.

Assessment	Mean Score[1]	Standard Deviation	Standard Error
Pre-test	5.05	1.22	0.107
Post-test	6.41	1.59	0.139

[1] Difference between mean pre-test and post-test scores was significantly different: $p < 0.0001$, $df = 129$, $t = 9.43$, Effect size = 0.959 (Cohen's d) Large effect size.

improvement in student learning, based on a pre-test/post-test assessment, which suggests that this objective was at least partially met. Specifically, based on both qualitative and quantitative assessment, random mutation and natural selection were clarified, but the effects of migration and drift may have been less well understood. However, these were also modeled less explicitly in the exercise. We think student understanding could be improved with more group discussion of the questions embedded within the exercise, as well as an overall discussion of individual group results. Finally, we think that this activity, or variations of it, should be widely accessible and potentially useful to a variety of classrooms and different types of student learners. The materials needed for the exercise are inexpensive over the long term and not reliant on the use of technology, thus making it easily available to schools in communities with low socioeconomic status.

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APPENDIX

LEGO Evolution Laboratory Activity Guidelines

For this exercise, we will use LEGO bricks to simulate each of the mechanisms of evolution. You will need to imagine that an organism consists of three stacked bricks. For our simulation each brick (top, middle, bottom) will represent a gene that codes for a particular trait such as pigmentation or color. Each color is a different allele of that gene. Genes can be duplicated through the course of evolution, and for the purpose of our simulation, you should imagine that the top, middle, and bottom bricks represent three copies of the same gene. Each gene produces a pigment that determines the overall coloration of the organism. Thus, these organisms can be multicolored.

The organisms are also mobile. However, like real organisms there are some physical barriers that prevent movement from one environment to another. This exercise starts with a small population that has recently been separated from other LEGO organisms.

In this exercise, we will simulate a very high mutation rate, with each colored brick in the organism being able to mutate to three different colors. As in nature, these mutations are random with respect to their consequence. The organisms are asexual, so reproduction results in a very similar organism, but mutations during replication can cause differences.

Also, as in nature, the color of these bricks can have consequences for the organism's survival and ability to reproduce. In this simulation, LEGO organisms are susceptible to being eaten before reproductive age if they do not blend into their environment.

At various points in this exercise, you will be asked to answer questions or to enter data. The prompt for doing so is indicated within the text, either explicitly or by a boldfaced ***Q*** followed by a number, which can then be found on the accompanying answer sheet (Supplementary Materials, Section II). You will work in small groups of 2–4 people. Each group will have one bag of LEGO bricks of four different colors, dice, and two pieces of construction paper (that match colors #1 and #2 in your LEGO brick set.)

1. Create **4** LEGO organisms, each made out of **3** LEGOs by stacking them on top of each other. (Use Table 1 on your answer sheet to record the assigned colors). The organisms will be built as follows:
   a. Two will have color #1 in the middle, a color #3 on top and a color #4 on the bottom (Figure 2A).
   b. Two will have color #2 in the middle, a color #3 on top and a color #4 on the bottom (Figure 2B).
2. As described above, these organisms that you are modeling have recently been separated from the rest of the population, and are now encountering a new environment. In nature, when these types of events occur, they often result in a drastic reduction in population size, referred to as a *population bottleneck*.
3. In general, population bottlenecks result in a decrease in the number of different alleles found within the population, making the new group more homogenous than the original population. ***Q1***.
4. Separate additional bricks into four piles by color, and then place one of each color of the same size in the provided bag (to be used later).
5. Each color represents an allele of the genes that control the color of the organism. In this exercise, you will be following the change in the population's overall color over the course of several generations. This will be done by observing the change in proportion (or frequency) of each color over time. ***Calculate the initial frequency of each color in the initial population and record it in Table 2.***

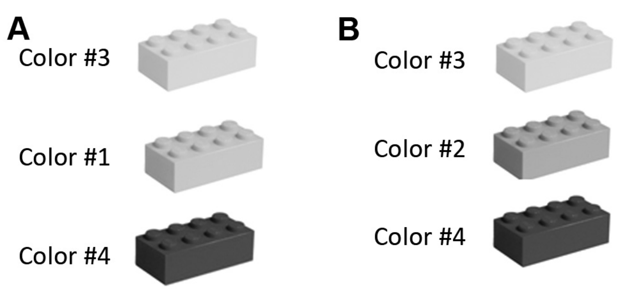

Figure 2. Organisms found in the initial population of the simulation. Each combination (A, B) shown here is represented twice, for a total of four organisms.

Part A: Simulation of Evolution in a New Population

Place the newly built LEGO organisms on the construction paper environment (each half of which is a different color). At this point, each of your organisms should have one brick that matches one of the colors of the paper; if this were not true, then the organism would not survive. In this simulation, to survive long enough to reproduce, each organism must at least partially match its background. There are no physical barriers in this part of the simulation, so the organisms are *free to migrate from one color of paper to the other*. Therefore, organisms can be placed anywhere on the colored background.

In the conditions of this simulation, organisms that match their background better also have a reproductive advantage and will be able to produce more offspring. For example, if 1/3 of the organism matches, it will produce one offspring; if 2/3 of the organism matches, it will produce two offspring; and if all colors match the background, it will produce three offspring. (Note that in nature, if an organism survives, we would not normally expect the degree of similarity to its environment to affect the number of offspring an individual would produce. However, this could apply to populations of organisms. For example, organisms that fully match their environment would be more likely to survive long enough to reproduce and therefore, on average, would produce more offspring than those that matched less well.) ***Q2.***

In each generation, there is a chance of mutation occurring at any of the three brick positions to any of the other colors. This will be simulated by rolling a single dice. After each generation reproduces, you will record color frequency and number of deaths that occur, using ***Tables 3 and 4***. Please check now that the first column in Table 3 matches the initial color frequencies you previously calculated in Table 2. ***Q3.***

1. To simulate mutation that may occur during reproduction, you will roll the dice for each offspring that a LEGO organism produces.
2. Each roll of the dice represents a reproductive event. Repeat this for the number of offspring the individual will reproduce. (Remember: one matching brick produces one offspring, two matching bricks produces two offspring, and three matching bricks produce three offspring.) After each generation is produced, *record the color frequencies in Table 3. Do NOT include parents in each new generation*.
   a. If you roll a 1, 2, or 3, there may be a mutation for that offspring. If you roll a 4, 5, or 6, there is NO mutation. A roll of 1 indicates a possible mutation at the top position, a roll of 2 indicates the middle position, and a roll of 3 indicates the bottom position. The specific mutation is determined by drawing a color from the bag. For example, if you roll a 1 and draw a red brick, you would change the top position of the offspring to red. Always return the drawn brick to the bag, and use a brick from the sorted piles to represent the mutation in the organism.
   b. Only the new organisms that at least partially match one of the colors of the background will survive. (Remember, they are free to migrate from one color to the next.) So remove any organisms that do not have at least one brick with one of the colors. Record these removals as deaths in Table 4.
3. Repeat this procedure for three additional generations. ***Record color frequency in Table 3 and deaths in Table 4 for each new generation.*** Remember, parents should not be included in the next generation. ***Q4.***

Part B: Physical Separation of Population

Imagine that after several generations (Part A), a natural disaster occurs that divides the population. With this new physical barrier, the separated populations can no longer migrate between the two different colored backgrounds. Follow Step 1 below to simulate the natural disaster.

1. Make sure all remaining LEGO organisms are on your construction paper set. Slowly pull the papers apart, allowing the LEGO organisms to stay on one of the papers. Once this has occurred, the LEGO organism must stay on the paper they are on; they cannot move to the other paper because the separation of the paper is a physical barrier for the organisms. Our organisms reproduce asexually, but the ability to sexually reproduce is common in nature. ***Q5.***
2. Now an organism can only be camouflaged by one color; specifically, it must match the color of the environment (paper) it got stuck on after the disaster. If it does not have at least one brick that matches the environment it is on now, it will be easily spotted by predators and die *before* reproducing. ***Q6.***
3. Your separated populations will continue to mutate and reproduce in their isolated environment following the protocol in Part A. ***Q7.***
4. Simulate two more generations for each organism on its isolated environment, following the same rules as above in Part A. ***Record your results in the Tables 5–7. Q8–Q11.***

Part C: What If?

In this part you will test one of the predictions that you made at the end of Part B by altering the conditions of the simulation (population size, mutation rate, strength of selection, etc.). ***Q12.*** Now, carry out the simulation and test your prediction. ***Record the results in Tables 8–9. Q13.***