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Can Random Mutation Mimic Design?: A Guided Inquiry Laboratory for Undergraduate Students

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ABSTRACT

Complex biological structures, such as the human eye, have been interpreted as evidence for a creator for over three centuries. This raises the question of whether random mutation can create such adaptations. In this article, we present an inquiry-based laboratory experiment that explores this question using paper airplanes as a model organism. The main task for students in this investigation is to figure out how to simulate paper airplane evolution (including reproduction, inheritance, mutation, and selection). In addition, the lab requires students to practice analytic thinking and to carefully delineate the implications of their results.

> The marks of design are too strong to be got over. Design must have had a designer.
> William Paley, *Natural Theology* (1802)

> I do not think I hardly ever admired a book more than Paley's *Natural Theology.*
> Charles Darwin, letter to John Lubbock, November 19, 1859

THERE is an emerging consensus that undergraduate biology courses should teach scientific thinking in addition to science content (*e.g.*, National Research Council 1996, 2000, 2003). Laboratory investigations offer an ideal opportunity to teach both, but there is a shortage of inquiry-based labs for teaching biology. In particular, there are very few inquiry-based labs available to teach evolution. This is especially unfortunate, because evolution is a notoriously difficult concept for students to understand (*e.g.*, Brumby 1984; Bishop and Anderson 1990). Students often believe, for example, that evolution occurs because individuals "need" to change and that individuals pass on acquired traits.

The most commonly used labs to teach evolution are natural selection labs in which representations of prey populations evolve cryptic coloration in response to predation (*e.g.*, National Research Council 1998; Lawson 2003). For the purpose of this article, we shall call these investigations "pepper moth" labs, because the labs are conceptually similar to the evolution of melanism in British populations of pepper moths. The National Research Council (1998) lab serves as a good example of the genre. Moths are represented by circular chips of colored paper (made with an ordinary hole punch), and the moths' habitat is represented by a rectangle of cloth with a floral pattern. The moth population initially has two different color morphs, one that blends in with the colors on the cloth and one that contrasts with the colors on the cloth. Students play the role of predators by removing three-quarters of the moths from the cloth as quickly as possible. Moths that are difficult to locate (*e.g.*, green paper chips on a green pattern) are more likely to survive than moths that are easy to locate. After students prey upon the population, the survivors "reproduce" and the next generation of predation begins. After a few generations of predation and reproduction, cryptic forms increase in frequency and less cryptic forms decrease in frequency.

The popularity of the pepper moth lab is justified by at least three strengths. The lab uses simple, inexpensive

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materials. Its relationship to natural selection in nature is readily recognized. And the lab is an effective antidote to the misconception that individuals (as opposed to populations) evolve. Nonetheless, the lab has two substantial weaknesses. First, it is essentially a "cookbook" exercise—more of a demonstration than an investigation. This makes the lab a poor exercise for teaching scientific thinking. Second, the lab presents a simplistic view of evolution. Fitness is determined by a single trait that has two variants, and the population evolves only as the least fit individuals are removed. There is no mutation, so new adaptations never arise, which means that the creative element of evolution is entirely missing. This is a substantial shortcoming, because many students have an especially hard time understanding how random mutation can create adaptation (Bishop and Anderson 1990).

The lab that we present here was designed to reduce both of these weaknesses. First, instead of simple paper chips, the lab uses paper airplanes as a model organism. Paper airplanes are an excellent model organism for evolution because the "fitness" of a paper airplane (how far it can fly) is a complex function of airplane morphology. The airplane model that we have selected (Figure 1) is particularly suited because it has several discrete characters that can mutate independently. Second, the lab is framed as an investigation to answer one of the great questions in biology: *Can random mutation create adaptations that appear designed?* We describe the lab below.

LAB DESCRIPTION

Westerling (1992) first used paper airplanes as a laboratory model to teach evolution to junior high school students. In this article, we present a revision of Westerling's lab that we use in a college-level introductory course on ecology and evolution. For most of our students, this course is their first introduction to evolution. Labs meet once a week for 3 hr, and students work in groups of two to four. A graduate student teaching assistant (TA) guides each investigation. The lab has two parts, each intended for a 3-hr lab period. On the first day, students are introduced to the lab and design their experiments. On the second day, the class conducts the experiments.

The TA begins the lab with the following introduction:

> Historically, there have been two widely accepted explanations for the origin of species—evolution and special creation. In this week's lab we are going to investigate the plausibility of the evolutionary explanation. We are, however, going to start by reading an essay arguing that living organisms were designed by a creator. The essay is from a book called *Natural Theology* that was written by Reverend William Paley in 1802—seven years before Darwin was born. Paley's argument dates back to Cicero and is a key principle in the intelligent design movement today. Darwin read Paley's *Natural Theology* while he was in divinity school, and just before the *Origin of Species* was published, he wrote to a friend that "I do not think I . . . ever admired a book more."

The TA then hands out a one-page excerpt from William Paley's *Natural Theology* (1802) that contains the crux of the famous watch and watchmaker analogy (see the Appendix). The class is told to read the essay and to analyze Paley's argument. Specifically, the class is told to identify the following: (1) the main claim made by Paley, (2) the observations or evidence used to support the claim, (3) the logic used to support that claim, and (4) any unstated assumptions made by the author.

Close reading of the text reveals the following reasoning. After Paley has introduced his question, he notes that watches are complex structures with parts that interact with great precision to keep time (Appendix, sentences 9–15). From this he infers that watches had a designer (sentence 16). Finally (sentence 17), he argues that each of these previous two points are also true for biological organisms, from which he concludes that plants and animals must have been designed.

Students should note an implicit assumption in Paley's reasoning—that there are no other possible explanations for the origin of biological complexity other than design—and that the accuracy of his conclusions depends entirely on the accuracy of this assumption. In essence, Paley argues by analogy: watches are made by a watchmaker; plants and animals are like watches in their complexity; therefore, plants and animals also must have a maker. Analogies are a powerful scientific tool, but conclusions reached from analogies are valid only to the extent that the analogy is valid. In the case of Paley's analogy, Paley does not account for the fact that living organisms can reproduce, that mutations occur during reproduction, and that the most fit organisms are most likely to have offspring of their own.

Once the class has analyzed and discussed Paley's argument, the TA tells the class:

> Paley wrote this essay over fifty years before Darwin published the *Origin of Species*, at a time when there was no credible alternative explanation to special creation. Darwin proposed evolution by natural selection as an alternative, and cited extensive evidence to support his theory, but Paley's reasoning must still be dealt with. After all, most of us would probably agree that biological organisms look designed. What we are going to investigate in this lab is whether evolution *could* have produced the elaborate features that Paley interpreted as evidence of design. In other words, we are going to ask if structures such as this [the TA points to a diagram of an eye] could be created by evolution. While we are working on this question, I want to emphasize that the purpose of this lab is to investigate whether evolution could create complex structures, but not to test whether evolution actually occurred or not.

The TA asks the class for a brief review of how natural selection works. In this review, the TA draws out from the class that mutation is an important component of evolution—without it evolution would come to a halt.

FIGURE 1.—Straw glider paper airplane used in this lab. Each "wing" is made of a strip of paper taped in a circle to the straw "fuselage."

The TA then asks the class how it could test the idea of whether mutation and selection could create adaptation. The discussion is led to the possibility of answering this question with models, and models are described as an attractive method for studying complex processes. Several examples are given: computer models for studying climate, small-scale physical models for studying engineering problems, and simple organisms with short generation times (*e.g.*, fruit flies) for studying development and genetics.

The TA then introduces the model organism that will be used to test whether mutation and selection can mimic design. The "straw glider" is a paper airplane made from a drinking straw and two strips of paper taped in a circle (Figure 1). The class is told that the lab will have two parts. First, the class will design paper airplanes themselves and then will test whether evolution can create similar designs.

The class is divided into groups to begin the first task—designing a straw glider that flies as far as possible. To simplify the problem, the class is instructed that they must retain the basic morphology of the straw glider; *i.e.*, they must use two circular wings taped to a straw. The TA then gives the class 45 min to design an airplane that flies as far as possible. While each group works on their design, the TA circulates around the classroom and asks each group what kind of strategy they are using to find the optimal design (in our experience, most students rely heavily on trial and error). The goal of these conversations is to confirm that students are dealing with the combinatorial complexity of their task. For example, the TA might ask, "How many possible designs for this plane are possible?" There are an infinite number of possible designs, but if each of the six traits that define a straw racer (position of front wing, position of back wing, circumference of front wing, circumference of back wing, width of front wing, width of back wing) had 10 possible values, there would be 10^6 possible ways to make a straw glider (see LAWSON 1995 for a discussion of the value of combinatorial thinking). Once the TA is sure that the students understand the complexity of their task, she asks them how they are searching the multidimensional parameter space to find the best design. One way to do this is to optimize one structure on the airplane at a time. While not perfect, this strategy is likely to reach a good first approximation.

After each group has tested a series of airplane designs, the TA asks the class which design flew farthest. Students will report that a small front wing widely separated from a large back wing flew farthest.

Next, students are told to develop a model of paper airplane evolution to see if it can mimic the designs that they came up with. The class is told to work on the problem in groups. The discussion that follows is a valuable learning experience, because it forces them to apply their understanding of natural selection to paper airplane evolution. There is no single correct way to model evolution with paper airplanes, but a model will have to have reproduction, mutation, inheritance, and selection. Mutation, for example, may be incorporated by rolling dice and flipping coins. The roll of a die can be used to select which one of the six characteristics of the airplane will mutate, and a coin can then be flipped to determine whether the mutation results in an increase or decrease in the value of that trait. Students will have to decide whether mutations all have the same magnitude of effect, whether paper airplanes are sexual or asexual, whether genotypes need to be explicitly modeled, and how large a population is to be studied. Finally, students will have to decide exactly how selection will operate. For example, will only the airplane that flies the farthest each generation survive and reproduce? Or will more than one plane survive each generation? And how will flight length be measured? As the length of a single flight, the longest of several, or some other way? At each juncture, the TA can instigate a discussion of whether the feature in question makes a difference for the test being performed.

Once each lab group has developed a model of evolution, the instructor begins a class discussion to compare models. Each group shares their model with the class, and the instructor assists the class in combining these approaches into a consensus model, which everyone in the class will use when their evolution experiments begin. We have used the following parameters with good results. The "ancestral" airplane that begins the simulation has two wings made from strips of paper 2 cm wide × 20 cm long, which were taped to the wing 3 cm from the end of the straw. All mutations change parameters by 1 cm, and this change was just as likely to decrease a parameter as to increase it. We assume that airplanes are asexual and that only the plane that flies the farthest of three throws survives to the next generation.

The first lab session ends when the class has finished developing a consensus model of evolution. In the second lab session, the class is given 2 hr to simulate several generations of paper airplane evolution.

When this work is done, the TA asks the groups to report to the class, "What kind of airplane did evolution come up with?" We ask each group to present a graph of how far the airplane flew in each generation of their simulation and to produce a scaled drawing of the cross

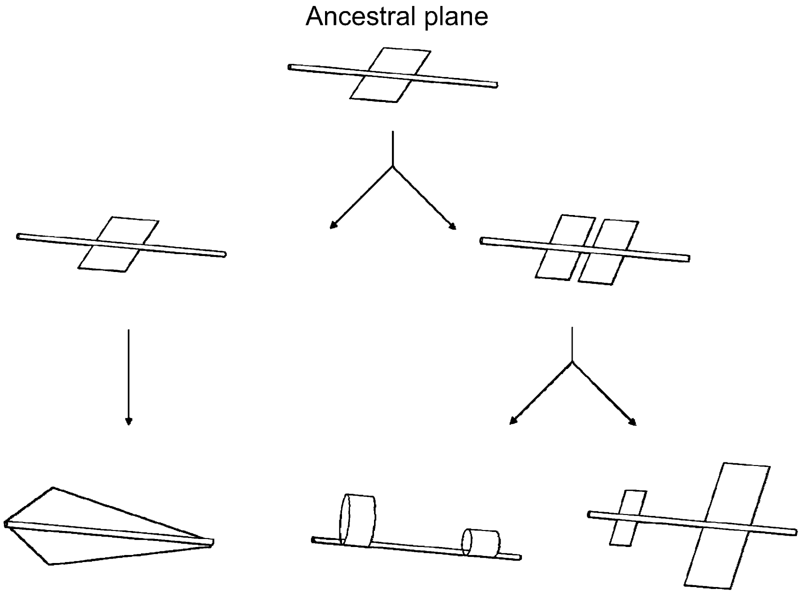

Figure 2.—A hypothetical phylogeny showing the origin of the straw glider paper airplane (bottom center), and its evolutionary relationship to other paper airplanes. Note that wing bifurcation was the first step in the evolution of the straw glider, followed by wing circularization.

section of the final plane. Groups present consistent results—a small front wing and a large back wing is the most effective design for maximizing flight distance, whether designed by students or created by evolution.

The TA then asks the class, "How did the *evolutionary process* compare to your *design process*?" Most students will see a similarity. Their design process depended heavily on systematic trial and error—similar to evolution, except that changes were not random. The TA may ask the class if this is how airplanes are really designed. Engineers use extensive knowledge of aeronautical principles to design airplanes, but testing (and even trial and error) has played an important role in airplane design. The TA might ask the class if they are likely to end up with a substantially different airplane if they had a better understanding of aerodynamics. We argue they would not.

The TA then asks the important questions, "What do these results show us? Have we shown that mutation and selection can create eyes and other complex traits that would have impressed Paley? And if not, what have we shown?" The answer is that random mutation, coupled with selection, can do a good job of finding a combination of sizes and shapes of body parts that maximize the performance of a relatively complex structure. This is an important component of evolution, and it suggests that mutation and selection could refine the structure of an eye from a primitive precursor. Therefore, evolution can mimic some aspects of design. However, the lab does not show where the airplane's wings came from in the first place. The model airplane is an entirely hypothetical organism, but there are several possibilities. For example, the two circular wings of the airplane may have evolved from a single flat wing (Figure 2). The TA notes that each step in this process is conceptually identical to the evolution conducted in the lab (except perhaps for the wing duplication). The TA tells the class that the origins of a few real organs (eyes, wings, legs) will be discussed in class.

INTEGRATING LAB AND LECTURE

Laboratory investigations are most effective when closely integrated with lecture, and this lab is easy to integrate with traditional lectures. The lab works well after a lecture introducing natural selection. During this lecture, we emphasize that evolution by natural selection requires variation, heritability, and selection—and that selection acts on populations, not individuals. Our experience in the classroom suggests that these are difficult concepts to teach. Students invariably report that they understand natural selection, but if we ask a probing question (*e.g.*, Are humans still evolving?), we discover severe misunderstandings. We believe that students have to learn for themselves how natural selection works, and this lab is useful in this regard.

The lab also provides an excellent introduction to the more advanced question of how complex adaptations evolve, and we devote an entire lecture to this topic after students have completed their lab. Because the lab uses paper airplanes as a model organism, we begin our lecture by tracing the history of birds' wings backward through the fossil record to reptile forelimbs and ultimately to the fins of lobe finned fish. Once we have discussed these fossils, we raise the question of whether there are any structures that could not have evolved from a more primitive form. This introduces the topic of irreducible complexity—a concept that Darwin (1859) raised in the *Origin of Species* and that has become a central tenet of the intelligent design movement (Behe 1996): "If it could be demonstrated that any complex organ existed which could not possibly have been formed by numerous, successive, slight modifications, my theory would absolutely break down" (Darwin 1859, p. 189). The eye has been proposed as a candidate for such a structure ["Who can but believe that this organ (the eye) was designed and made purposely for the use for which it serves?" (Ray 1691, p. 261)]. However, Nilsson and Pelger (1994) show in simulation that as few as 2000 small steps, each with a small fitness advantage, will transform a photosensitive patch into a complex eye. We discuss how a variety of eyes have independently evolved in diverse taxa (Oakley and Cunningham 2002; Fernald 2004). From there, we move on to complex molecules and a brief discussion of molecular evolution.

At the end of the lecture we briefly turn the tables and ask if there are any structures in living organisms that appear to *not* have been intelligently designed. As potential examples, we present the human tail bone, the back-to-front retina of the vertebrate eye, and eye development in flounder (see Dawkins 1996 for a readable discussion). The flounder example is fun to end with. Flounder swim upright as juveniles, but spend much of their adult life lying on the ocean floor. To accommodate this change in life style, one of their eyes migrates from one side of their head to the other. We suggest that this is an odd way to design a fish, but concede that a creator could have designed flounder this way—perhaps out of a sense of whimsy or possibly to test the faith of believers. We conclude that if such allowances are made, the design hypothesis is not testable—and that if a hypothesis is not testable, it is not a scientific explanation (Platt 1964).

DISCUSSION

Developing curricula to teach scientific thinking is difficult. The biggest challenge may be to decide which skills to teach. Consider hypothetico-deductive reasoning (*e.g.*, Platt 1964). Its prominence in the first chapter of innumerable science textbooks (*e.g.*, Campbell and Reece 2005) would suggest that curricula would universally emphasize this skill. Yet, few thinking skills are more controversial than the "the scientific method" (*e.g.*, Harwood 2004; Bonner 2005; Robinson 2005). This is undoubtedly because there is more to science than listing hypotheses and devising experiments to test them. However, no alternative model of scientific inquiry has replaced hypothetico-deductive reasoning as a paradigm (but see National Research Council 2000). This leaves instructors with the dilemma of what thinking skills to teach.

We recommend two pragmatic solutions. First, scientific thinking can probably be taught without definition by analyzing actual research. While doing this, we ask our class the following types of questions. What would the researcher have concluded if *X* had been observed? Why did the researcher do *Y*? And what might the researcher do next? One advantage of this approach is that it is likely to encompass a broad diversity of scientific thought patterns.

A second method for incorporating scientific thinking into curricula is to identify clearly defined, specific thinking skills that are common and useful in scientific investigation. The skills must be specific enough to be teachable but general enough so that creating practice problems is not difficult. For example, this lab was designed to practice argument analysis, model construction, and evidence evaluation. Other labs in our course emphasize designing controlled experiments, summarizing complex data, and evaluating contradictory evidence (Kalinowski *et al.* 2005). Clearly, effective science requires more than a set of narrowly designed skills, but teaching specific skills such as argument analysis is better than not teaching any thinking skills.

Given the controversy in contemporary society surrounding evolution (Alters and Nelson 2002; Scott 2004), some instructors may think it best to remove the design component from this lab. This would not be difficult to do; the focal question of the lab could be rephrased as "Can random mutations create complex adaptations?" and the design element of the lab could be neatly excised. Below we describe why we have not done this. Before we begin that discussion, we would like to emphasize that we have deliberately constructed the lab so that it is not an investigation of whether species have originated via evolution or design. The lab may refute a criticism of natural selection made by advocates of design, but it does not attempt to evaluate the design hypothesis (see Lawson 1999 for a lab that does). We discuss evidence for and against evolution and design in the lecture, but have been careful to not put our TAs in the position of leading such a sensitive discussion.

We have chosen to include the design element in the lab because it motivates the lab and because it helps to teach five important lessons:

1. Including the design aspect of the lab gives students an opportunity to read an excerpt from Paley's *Natural Theology*. As with Darwin, we believe Paley's argument is historically significant, his writing excellent, and his logic impressive.
2. Reading Paley gives students an opportunity to analyze his argument—which gives students practice with a foundational element of scientific thinking.
3. Having students design a paper airplane that flies as far as possible teaches students that there are many possible combinations of wing size and location. We believe students have a poor understanding of combinatorics, so this is an important mathematics lesson.
4. Including the design element also gives students the opportunity to clearly delineate the implications of their results, an important scientific thinking skill.
5. Finally, the design question gives students practice discussing a controversial topic with respect for students

who have other views, and this may be as valuable a skill to practice as any other component of the lab.

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APPENDIX

The following are excerpts from *Natural Theology: or, Evidences of the Existence and Attributes of the Deity, Collected From the Appearances of Nature* by William Paley (1802).

(1) In crossing a heath, suppose I hit my foot against a stone. (2) Suppose I were asked how the stone came to be there. (3) I might possibly answer that, for anything I knew to the contrary, it had lain there forever. (4) It would be difficult to show that this answer is absurd.

(5) But suppose I had found a watch upon the ground, and it should be asked how the watch happened to be in that place. (6) I should hardly think of the answer which I had before given—that for anything I knew the watch might have always been there—would be an acceptable answer.

(7) Yet why should not this answer serve for the watch as well as for the stone? (8) Why is it not as admissible in the second case as in the first? (9) For this reason, and for no other: namely, that when we come to inspect the watch, we perceive–what we could not discover in the stone–that its several parts are framed and put together for a purpose. (10) The parts are so formed and adjusted as to produce motion, and that motion so regulated as to point out the hour of the day. (11) If the different parts had been differently shaped from what they are, of a different size from what they are, or placed after any other manner or in any other order than that in which they are placed, either no motion at all would have been carried on in the machine, or none which would have answered the use that is now served by it.

(12) To reckon up a few of the plainest of these parts and of their offices, all tending to one result; we see a cylindrical box containing a coiled elastic spring, which, by its endeavor to relax itself, turns round the box. (13) We next observe a flexible chain—artificially wrought for the sake of flexure—communicating the action of the spring from the box to the fusee. (14) We then find a series of wheels, the teeth of which catch in and apply to each other, conducting the motion from the fusee to the balance and from the balance to the pointer, and at the same time, by the size and shape of those wheels, so regulating that motion as to terminate in causing an index, by an equable and measured progression, to pass over a given space in a given time. (15) We take notice that the wheels are made of brass, in order to keep them from rust; the springs of steel, no other metal being so elastic; that over the face of the watch there is placed a glass, a material employed in no other part of the work, but in the room of which, if there had been any other than a transparent substance, the hour could not be seen without opening the case. (16) This mechanism being observed—it requires indeed an examination of the instrument, and perhaps some previous knowledge of the subject, to perceive and understand it; but being once, as we have said, observed and understood—the inference we think is inevitable,

that the watch must have had a maker—that there must have existed, at some time and at some place or other, an artificer or artificers who formed it for the purpose which we find it actually to answer, who comprehended its construction and designed its use. . .

(17) . . . Every observation that was made [above] concerning the watch may be repeated with strict propriety concerning the eye, concerning animals, concerning plants, concerning, indeed, all the organized parts of the works of nature.