THE EVOLUTION OF TEACHING EVOLUTION

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Abstract

Like many other scientific theories, teaching biological evolution involves two fundamental challenges. First, the theoretical conceptualization is complex and includes many mathematical and genetic models. Second, timeframes required by biological models to demonstrate evolutionary processes make it challenging to visualize and understand them, especially in the context of introductory courses (e.g., high school, first-year undergraduates). Typical approaches to this challenge include simple narratives of events and evidence to get the students to grasp the basic idea that evolution exists. Alternatively, the evolution class is included later in the programs when students have been more exposed to natural sciences and biology information. Unfortunately, this late arrival of evolutionary theory study may leave some students to rely on intuition and even ideas unsupported by scientific evidence. As an alternative, game-based learning allows for a different approach to engage students of any level. However, game-based strategies may be stigmatized as tools to learn scientific theories under the assumption of a trivialized version of complex phenomena. Here, I propose strategies involving play and experimentation to achieve the appropriation of concepts with a learning-by-doing approach. These strategies rely on accessible material, becoming easy to implement in any school or university around the globe. This work collects more than 15 years of experience using games to bring students closer to theoretical concepts challenging to acquire from evolutionary theories (e.g., natural selection, genetic drift, or phylogeny). Notably, while focusing on students majoring in natural sciences (biology and earth system sciences), I also include experiences with a student from other disciplines. The systematization of this process includes interviews with students who inquired about crucial concepts before and after the experience and with participants that subsequently used these concepts in their advanced courses in biology or other natural sciences. The research indicates that the implemented games fostered an understanding of the theory developed general thinking skills, and are efficient tools for learning complex topics such as vicariance or evolutionary convergence. Remarkably, these results have proven to be replicable and support a central role of gamification to address issues in genetics, ecology, or socio-ecological systems, without compromising the rigor with which scientific theories support them should be addressed.

Keywords: *Biological evolution, game-based learning, science games, student engagement.*

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1. Introduction

Evolution is considered the basic theory of biology (Dobzhasky, 1973). Since the publication of The origin of species through natural selection (Darwin, 1859), the theory of evolution has been strengthened and has been changing. One of the most decisive changes was called The modern synthesis, where discoveries in genetics, both organismic and population, are added to Darwinian theory and articulated with systematics and new discoveries in paleontology (e.g., Fisher, 1930; Haldane, 1932; Simpson, 1944). After this, evolutionary processes have been articulated in The Neutral Theory (Kimura, 1983), Sociobiology (Wilson, 1975), and Evolutionary developmental biology (Carroll, 2008), among many other areas of biology and genetics. It makes evolution a science with a high content of mathematical modeling, especially in the population component. For this reason, it is usually taught superficially in high school and, generally, is not taught in the first undergraduate semesters because it is considered that students do not know enough genetics and mathematics (Mead et al., 2017). Because of this, more emphasis is placed on the history of evolutionary biology than on the evolutionary processes or the mechanisms that allow species to adapt to their environments, leading students to be unclear about the accepted model for science and to confuse the postulates presented by pre-Darwinian authors with those presented in the theory of evolution by natural selection.

Consequently, the student builds responses and routes intuitively, trying to explain biological phenomena without the key concepts to explain them. It leads to inadequate responses from a scientific point of view (Tidon & Lewontin, 2004; Andrews et al., 2012). Many of them reinforce common errors such as linearity in evolution, the search for perfection or adaptation as a response to necessity, or even affect the understanding of other areas of biology, such as ecology (Tolman et al., 2021). Despite this, there are few efforts to ensure that students at these levels, high school and first semesters of undergraduate, receive evolution courses, even though it has been shown that in the cases in which this is done, the understanding of biological phenomena becomes simpler (Jördens et al., 2016) as a consequence of having greater clarity in the basic theory of the discipline.

In this article, we show the impact of teaching evolution using game-based strategies to first-semester students of natural sciences majors in two groups of students: students who were studying the class that semester and professionals and natural science students whom they had seen the class at least two years earlier.

2. Presentation of the experience

The question of how to teach evolution without using a robust mathematical foundation first arose in 2002 when the challenge of how to teach the basics of evolutionary theory to elementary school teachers so that they could replicate the experience with their students arose. In Colombia, primary school teachers (children between the ages of 5 and 11) receive specific training in pedagogy and didactics, but their disciplinary knowledge is introductory. In most cases, a single teacher is responsible for teaching children concepts and skill development in literacy, mathematics, natural sciences, and social sciences, so their specific knowledge in subjects such as biology is minimal. One answer was through a game that would allow the interaction between predator and prey to be evaluated in a straightforward way; thus, it could be explained how there are no perfect solutions for this interaction. This game involves two fundamental elements: silverware, which are the predators, and buttons, which are the prey. The buttons are placed on a flat surface, and then each player chooses an item to be a predator and, for a specified time, "eats" as much as possible. After each round, simple statistics are performed to identify population changes. As a result of participating in the game, the teachers learned that diversity in populations is part of their success and that each individual can perform better or worse depending on environmental conditions, competition, and their own abilities, a reflection of their genetics and interaction with the environment.

Between 2004 and 2013, while I was teaching biology courses for students from different health sciences majors, the challenge of teaching evolution reappeared as the theory allowed us to explain phenomena such as bacterial resistance to antibiotics or the problems that occur in populations due to inbreeding. It led to expanding the game using buttons with similar physical characteristics (size, weight) that show the possibility of survival of a fundamental character (color) over the generations depending on the rules with which the reproductive processes are generated. This version also shows the effect of mutation, genetic drift, and gene flow on populations.

In 2014 the Universidad del Rosario created the major in Biology. There, I had the opportunity to design and offer a first-semester general biology course called Evolution of Life, whose purpose is for students to understand, from the beginning of their undergraduate, how evolution is behind all biological phenomena, from cell diversity to ecosystem interactions. Once again, the challenge is that the students do not know enough mathematics or biology, and their knowledge of genetics is, in the best of cases, simple Mendelian inheritance. In this course, the laboratory space is used to build new experiences and new games, such as allopatric speciation and vicariance, using colored pencils and paper cards; reconstruction of kinship relationships using shoes; or showing students that science is not unambiguous and a problem can have several valid solutions from a scientific point of view, using colored geometric figures. In this already matured educational experience, two questions arise: did they really learn and adequately manage the concepts presented? Especially those considered difficult such as genetic drift or vicariance; did the skills and concepts developed through these types of games serve them in their subsequent classes?

3. Strategy evaluation

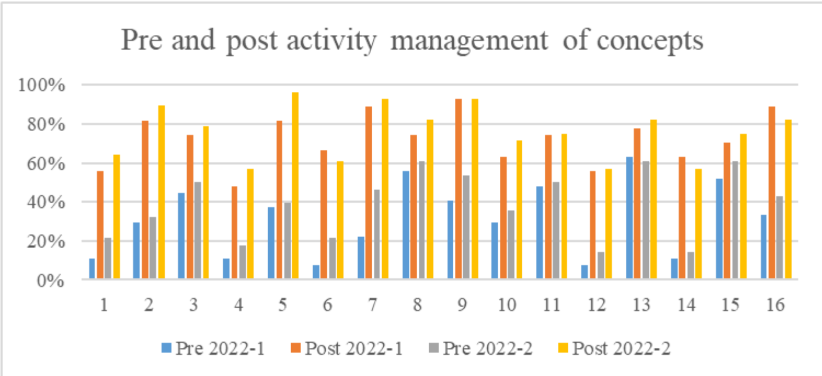
To evaluate the experience, two different strategies were designed: Concept management evaluation before and after the experience with active students in the class and retrospective evaluation of the appropriation of concepts by former students of the course.

3.1. Evaluation of active students in the course

During the year 2022, I collected information before and after the activities with student volunteers to whom, through interviews, I asked about concepts that were going to be developed or to be deepened in the activity and verified understanding. I also asked about how these concepts could be used in biological contexts, no longer in simulated systems such as pieces of colored paper or shoes. After the activity, in some cases immediately after and others the following week, I asked again about the concepts and their use in biology. These data made it possible to show how precise the conceptual management and the application of these concepts were before and after. The data were qualified and quantified to facilitate their analysis. Sixteen different concepts were evaluated (How to read a tree, Homology and convergence, Phylogeny, Gene drift, Gene flow, Mutation, Bottleneck, Natural selection, Phenotypic diversity, Adaptation, Sexual selection, Sexual vs. natural selection, Allopatric speciation, Vicariance, Coevolution, and Biogeography) which are consolidated in 10 different games, each of them developed in a three-hour session, in groups of 3 or 4 students. The compared distribution for the 16 concepts before and after the activity in the first and second semesters of 2022 (Graph 1) shows that in all cases, more significant learning of the concepts was demonstrated after carrying out the activity.

In the first semester of 2022, the most significant difference was found in the conceptual management of bottleneck (7), biogeography (16), and how a mutation persists differentially in large or small populations (6). For the second semester of 2022, the most significant learning was evidenced in the conceptual management of the impact of gene flow on large and small populations (5), homology (2), and, again, bottleneck (7). The minor differences were, in all cases, obtained in topics where there was a high number of students with good conceptual management prior to the activity, such as natural selection (8) or allopatric speciation (13), which shows that the activities are more effective in cases where students did not have a good grasp of the concepts prior to the game.

Graph 1. Management of basic concepts in biological evolution, pre- and post-experience, by first-semester students of Biology and Earth System Sciences.



The topics with the slightest understanding prior to the activity are those that involve complex relationships between variables, such as genetic drift and its impact on populations of different sizes (4), vicariance (14), or the relationship between natural selection and sexual selection (12), all topics that traditionally are not covered in introductory biology courses. In general terms, students are improving their understanding of evolutionary concepts with the activities, as can be seen in the average difference before and after the experience –first semester 31% vs. 72%, and the second semester 40% vs. 76% – statistically significant differences in both cases (Student's t test, $p>0.0001$).

At the end of the course, the students were asked about the space or activity they had learned the most. All the students mentioned activities or spaces that corresponded to the theoretical activities. None of them did mention games as learning spaces.

3.2. Evaluation of former students in the course

To assess the level of recall and learning of the concepts in students who had completed the course, a survey was carried out with the following open questions: what did they remember about the course, what had they learned very well, what things they learned in that course had served them later, and what things they learned in the course besides biology. The survey was answered by 53 students who saw the course between 2015 and 2020. In order to build word clouds, and considering that the data was collected in Spanish and through open questions, they were categorized. For example, The card game, Color cards, Vicariance, The islands and Allopatric speciation were all named Vicariance.

Given the first question (Figure 1), what do you remember about the course? Most students used the word Game in their answer (10 students), followed by learning (5 students).

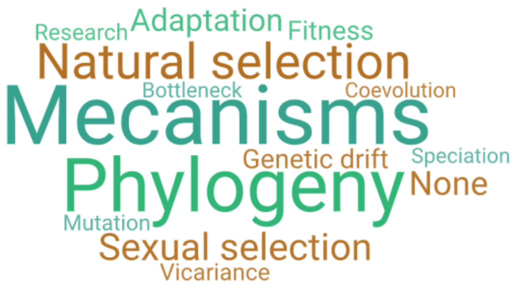
Figure 1. Word cloud is built with what former students remember the most from the course.

Talking about the learning of the course in general (Figure 2), 16 participants said they had learned what natural selection is, followed by the concept of gene drift, which was mentioned by 15 of them, and by evolutionary mechanisms (i.e., gene drift, gene flow, mutation, and natural selection). Some of the former students mentioned more than one learning.

Figure 2. Word cloud is built with the concepts that former students remember as learning.

Participants were asked for the practice with which they learned the most. Thirty-one students mentioned button practice (evolutionary mechanisms), eight phylogeny, and six vicariance. When asking former students for the concepts they found most helpful in their subsequent courses (Figure 3), evolutionary mechanisms (25) are highlighted, followed by phylogeny (12).

Figure 3. Word cloud of the concepts that former students identify as the most useful in later courses.



Asking participants about other things they learned in the course, in addition to biology (Figure 4), critical thinking and communication (each with ten mentions) and creativity and reading (with eight mentions each) stand out. Only one of the students who answered the survey did not remember any activities or work carried out in the course.

Figure 4. Cloud of words shows other things former students recognize as learning in the course.

4. Lessons learned from experience

The data presented in this article is not conclusive due to the low number of students and former students surveyed; however, it does show a trend worth considering. In all cases, the participants are reaffirming concepts related to biology and evolution, and learning of particularly complex concepts such as genetic drift, vicariance, or the relationship between sexual selection and natural selection is evident, topics that are not usually included in most basic courses because it is assumed that without advanced mathematics and genetics, students are incapable of learning these concepts.

The collected data from the former students is exciting in several aspects. First, most of them remember the course experience as fun and pleasant, and they highlight the use of games as a learning strategy. When asked about their learning and subsequent use, they indicate the use of complex concepts such as phylogeny or the mechanisms that drive the evolutionary change. In addition to the concepts related to biology and evolution, it is noteworthy that former students identify the class as a space for developing communication and research skills. Several refer to soft skills that allow them to perform better in diverse groups, such as active listening, creativity, and appreciation of diversity.

It is crucial to consider that this approach of using games to appropriate concepts in evolution is a process under construction since groups and strategies also evolve. For example, in 2015, I used caminalcules for tree and phylogeny activities. These animal-like shapes had the drawback that students spent much time trying to match their structures to the structures of real animals. It was solved when the caminalcules were replaced by shoes. At that point, the discussion stopped being whether or not a stain was an eye and became what the characteristics that define a specific group of footwear were. It is essential to keep this in mind because the students are changing, and in the same way, the games cannot remain static over time. The primary tool to improve the games is the improvements that the students propose when using them. The data obtained before and after the games clearly show that the students consolidate their knowledge during the practices, although they are not being aware of this. It is striking that games are much more critical for students who took the course at least two years ago than for those who are taking it. It may be due to the need of first-semester students to say what they think the teacher expects, while former students do not have these restrictions, and therefore their opinions are more explicit.

Finally, these data confirm two fundamental aspects. The first is that it is possible to teach evolution, including complex concepts, to students who do not have advanced genetics or mathematics knowledge, getting them to learn. Second, early learning of evolution, its mechanisms, and its impact on biodiversity allow students to use these concepts in later courses and their research processes.

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