

A Quantitative Simulation of Coevolution with Mutation Using Playing Cards



RECOMMENDATION

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ABSTRACT

Active-learning approaches can improve understanding of core biological concepts. We describe a revised hands-on simulation for teaching evolution by natural selection, which focuses on prey–predator coevolution in escape/pursuit speed. It illustrates how selection pressure on individual speed increases average population speed through differential survival, while also reducing variation in speed among individuals. A simulated beneficial mutation helps differentiate the generation of individual traits from the process of natural selection and illustrates the effects of a beneficial mutation on immediate and subsequent generations. Overall, this exercise addresses several common misconceptions and allows students to collect and assess their own data, quantitatively. We report results from pre- and post-assessments in an introductory, undergraduate biology class, which indicate significantly improved understanding associated with the simulation.

Key Words: Active learning; card game; coevolution; math anxiety; mutation; natural selection; predation; sorting process.

Introduction

Evolution—one of five core concepts for biological literacy (AAAS, 2011)—presents a teaching challenge because it requires conceptual understanding of a long-term process (Catley & Novick, 2009). Many students also harbor preconceptions or personal beliefs that hinder understanding of underlying mechanisms (Alters & Nelson, 2002; Bardapurkar, 2008; Gregory, 2009). An important breakthrough for students is to recognize natural selection as a sorting process separate from mutation (Price, 2013). They should also realize that (1) “need” does not drive adaptation, (2) variation among individuals is raw material

The game and accompanying calculations clearly illustrate how natural selection and beneficial mutation are separate but interacting mechanisms of evolution.

for selection, and (3) adaptation does not necessarily change all members in a population (Bishop & Anderson, 1990; Gregory, 2009). Consequently, instructors have both devised active-learning approaches to engage students with the process of natural selection (e.g., Lauer, 2000; Riechert et al., 2011; Weber et al., 2016) and applied basic statistical techniques to increase conceptual understanding and reduce math anxiety (Stuckert & Vance-Chalcraft, 2016; Lee et al., 2017).

Tatina (2007) proposed a playing-card exercise to simulate a coevolutionary “arms race.” It focuses on comparative running speeds between predators and prey, demonstrating natural selection as a sorting process, highlighting the significance of variation among individuals, and revealing the mechanism of adaptation. Here, we present a revised, quantitative version of this simulation, suitable for introductory undergraduate or advanced high school courses.

Tatina (2007) emphasized that (1) coevolution changes mean running speed in prey and predator populations, (2) variation among individuals induces differential survival within each population, (3) only traits in the reproducing population can compose the next generation, and (4) average, not individual, running speed changes between generations. Our revised simulation adds (5) calculation of standard error for mean running speeds to represent intrapopulation variation, (6) simulation of a beneficial mutation within the coevolution process, and (7) increased emphasis on quantitative skills. We also modify the number of prey vs. predators to illustrate a somewhat more natural scenario. We provide before-and-after data for four semesters from 18 laboratory sections to show that the simulation improved student understanding.

○ Materials

- The simulation requires regular, numbered UNO cards (or any numbered cards) with a range of five consecutive numbers (e.g., 1–5).
 - Each prey–predator combination requires 60 cards (50 prey, 10 predators).
 - Each simulation requires spare cards of the higher numbers in the sequence (e.g., 4 and 5) for constructing subsequent generations.
- We provide students with tables for data entry and accompanying worksheets for all data summaries and calculations.
- Students provide writing utensils and calculators.

○ Simulation

Laboratory sections of our introductory biology course, Principles of Zoology, hold 20–30 students, whom we divide into five or six prey–predator combinations. Each prey–predator group receives an envelope with numbered cards presorted into prey and predators. Each card represents an individual. Each number represents its flying, running, or swimming speed. Card-number frequency distributions overlap between prey and predators (e.g., Table 1). Prey outnumber predators in a 5:1 ratio. We label envelopes to represent real-world prey–predator scenarios such as (1) gazelle vs. cheetah, (2) snowshoe hare vs. Canada lynx, (3) fur seal vs. white shark, (4) eastern cottontail vs. ermine, (5) mallard vs. peregrine falcon, and (6) blue sheep vs. snow leopard.

○ Rules of Play

1. Starting with the provided cards, prey and predator teams calculate the beginning mean and standard error of running speed for their populations (Table 1).

Table 1. Example starting card distribution for a prey–predator group with starting means and standard errors of card numbers (i.e., running speeds). Card numbers can be any consecutive sequence of five.

Team 1 Card Numbers (Running Speeds)	Snowshoe Hare (Prey): Number of Cards	Canada Lynx (Predator): Number of Cards
3	5	1
4	10	2
5	20	4
6	10	2
7	5	1
Total card count	50	10
Mean ± SE	5 ± 0.2	5 ± 0.4

2. Each team shuffles its cards and places them in a pile face down between itself and the opposing team.
3. Play begins as the prey team turns over the first five cards while the predator team turns over one card.
4. The outcome of each interaction depends on the relative speeds of prey vs. predator.
 - a. Prey with an equal or higher speed (i.e., card number) than the opposing predator outrun that predator and escape to contribute to the next generation.
 - i. Prey win ties based on the rationale that predators must both catch *and* subdue prey, giving equally fast prey an advantage (this oversimplifies reality but provides a framework for simulation).
 - b. Predators subdue all opposing prey with lower speeds.
 - c. Each predator must subdue at least two prey to avoid starvation and contribute to the next generation.
 - i. This modification of Tatina (2007) provides increased “realism” because
 - (1) A predator does not have to subdue every prey it encounters to survive.
 - (2) A predator that ultimately starves can still subdue some prey.
5. Teams retain cards of survivors to determine the next generations.
6. Teams discard cards of subdued prey or starved predators.
7. The game continues with each team revealing its cards five prey to one predator at a time until all interactions are decided.
8. We assume that all survivors are reproductive equals. Thus, each team simulates reproduction by rebuilding the population to the original carrying capacity of 50 prey or 10 predators based on the proportions of each speed (i.e., card number) that survived (Table 2).

Table 2. Example first-round results for predator group based on a simulation using the starting card distribution in Table 1. Calculation of the next predator generation is illustrated.

Team 1 Predator Card Numbers (Running Speeds)	Canada Lynx: Starting Number of Cards	Canada Lynx: Surviving Cards	Canada Lynx: Next Generation of Cards
3	1	0	0
4	2	1	2
5	4	1	2
6	2	2	4
7	1	1	2
Total card count	10	5	10
Mean ± SE	5.0 ± 0.37	–	5.6 ± 0.34

Table 3. Mean (\bar{X}) and standard error (SE) of running speed for each generation based on a simulation run using the starting populations in Table 1. Generations with an “m” notation (e.g., 3m) are those in which a beneficial mutation occurred for one prey individual (in this case, a mutation converted a 5 to an 8).

Generation	Prey		Predator	
	\bar{X}	SE	\bar{X}	SE
1	5.0	0.16	5.0	0.37
2	5.4	0.14	5.6	0.34
3	5.8	0.12	6.4	0.16
3m	5.9	0.13	6.4	0.16
4m	6.7	0.08	6.6	0.16
5m	7.1	0.03	7.0	0.00

- a. Each team also calculates the mean and standard error of the speed of their new generation for comparison with the parent generation (Table 2).
9. Using their second generations, teams play the second round of the simulation like the first (steps 3–8).
10. Once the third generation is established, one individual from the prey population receives a **beneficial mutation** that increases its speed to one number above the highest number in the population.
 - a. To simulate this, the prey team haphazardly pulls one card from their third generation and replaces it with a “wild” UNO card or a card with a number one higher than the highest in the population.
11. Following the simulated mutation, the prey team recalculates the mean and standard error of the speed of their population in the third generation, which now includes one mutant.
 - a. The predator team does not experience a mutation, so their mean speed and standard error remain constant (Table 3).
 - i. It is best if members of the predator team participate in the mutation process with the prey team.
12. Thereafter, a third and (if time allows) fourth round of the simulation are run.
13. After the fourth simulation, students also calculate the characteristics of the fifth generation.

○ Practical Considerations

Our lab periods are 110 minutes, and the majority of student groups complete four rounds and calculate speeds of a fifth generation within that time. If less time is available, the main trends are visible in fewer rounds (Tatina, 2007), but at least four rounds are needed to include the mutation simulation (Table 2 and Figure 1). It is also possible to play the game in stages (say, from one class period to another), until several rounds are completed.

The analytical results are means and standard errors of running speeds per generation (Table 3). However, students also report card-number frequencies as part of their calculations, which helps

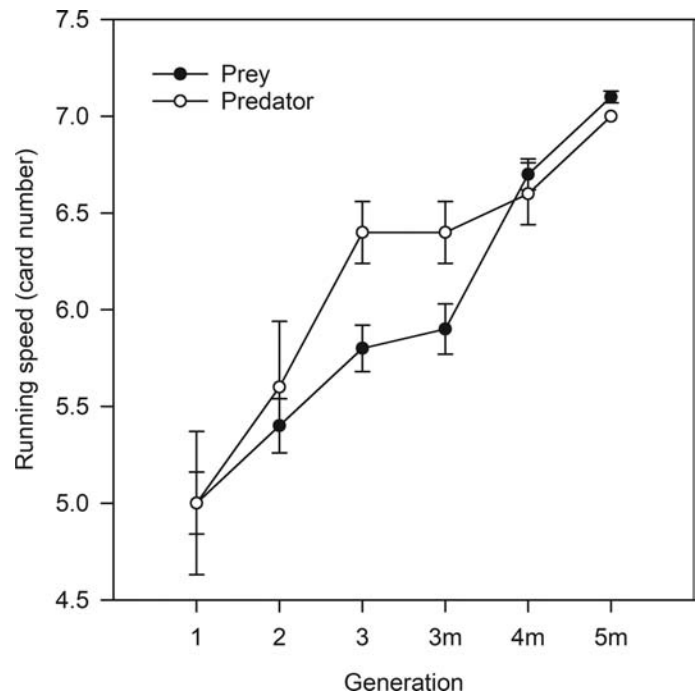


Figure 1. Graphed results from Table 3 showing mean running speed with standard error as required for homework. Students graph their own results. Results vary depending on play.

clarify the mechanism of natural selection. The calculations slow some student groups at first, but once they master them in the first round, groups typically are proficient in subsequent rounds. This meets our goal of strengthening quantitative skills and reducing math anxiety.

We suggest that students form groups of four or five so that at least two students collaborate on each prey and predator team. Teamwork allows students with more confidence to coach and assist others needing help. Students can also cross-check each other's calculations within and among teams to reduce the errors.

As increased engagement is one goal of active-learning pedagogies (Nelson, 2008), it is important to note that students generally enjoy this simulation. It consistently keeps students engaged for an

entire lab period. It also succeeds in getting students working together and interacting throughout the learning process.

○ Homework Assignment & Follow-up Discussion

As homework, each student plots the mean and standard error of speed for each prey and predator generation in their simulation. They transcribe data from their opposing team during lab and graph both results together. This makes use of in-lab calculations and employs graphing skills introduced during previous lab assignments completed earlier in the semester.

Students see several trends in their graphs (Figure 1), which we discuss as a class in the subsequent lab period. First, they see coevolution in the parallel increase in speed for both populations (Tatina, 2007). They also see shrinking genetic diversity in the standard error, and they see the limitation that the traits of individuals within the population set on the potential to increase population speed. They further see that a beneficial mutation has a limited immediate population-level effect but influences subsequent generations. In the case shown for predators (Tables 2 and 3), strong selection eliminated all speeds below 7, demonstrating negative or “purifying” selection (Loewe, 2008). In addition, the beneficial mutation in the third generation of the prey population allowed mean speed to exceed 7—the maximum speed of the predator population—by the fifth generation. Overall, the game and accompanying calculations clearly illustrate how natural selection and beneficial mutation are separate but interacting mechanisms of evolution.

For further class discussion, the data and analyses demonstrate natural selection as a process of sorting among varied individuals. For instance, students quickly see that selection pressure favors faster individuals, especially as selection eliminates the slowest predators, which cannot encounter two catchable prey (Table 2). Students also see that adaptation and coevolution change population averages through differential survival, but that natural selection is not “all or nothing” because a predator with average speed sometimes encounters slower prey. Further, students can see that although natural selection affects the reproductive success of individuals, the results of natural selection become evident across subsequent generations.

If desired, students can calculate survival probabilities for different speeds or track the changing proportions of specific speeds

across generations. Calculating the percentage of each number surviving each generation illustrates higher survival for faster individuals (i.e., higher numbers) and that for individuals having average speed in the starting population, survival decreases by generation, as the overall population gets faster. Similarly, calculating the percentage of the population comprised by each number, by generation, illustrates the disappearance of low numbers, the decrease of average numbers, and the increase of high numbers. Students can tabulate or graph these results to see the trends, which are also excellent fodder for in-depth class discussions.

○ Assessment of Student Learning

To assess student learning, we administered pretests and posttests, available to students online in the week preceding and the week following simulations, respectively. These tests were voluntary and received approval from the Institutional Review Board of Weber State University (protocol nos. 2016-COS-3 and 2017-COS-6) prior to implementation. We asked students to complete an informed-consent form about this study before responding to the pretest. We excluded students from the analysis if they elected not to participate in the study. We also excluded students who only responded to either the pretest or posttest. With these caveats, we accumulated data for 298 students from 18 lab sections over four successive semesters.

For the assessment, we used the same questions in pretests and posttests within each semester and for all lab sections. We held nine multiple-choice questions constant across all semesters for long-term analysis of student learning. Paired t-tests using these long-term data indicated that posttest scores exceeded pretest scores each semester, with average improvement from 11% to 13.8%, depending on semester (Table 4).

To discern the simulation’s relative effectiveness for students with different levels of prior understanding, we classified students into one of three groups based on pretest scores: (1) $\leq 50\%$, (2) 51–79%, and (3) 80–99% (excluding students earning 100%). Paired t-tests showed significantly higher posttest scores for all three groups (Table 5). Students in the first group showed greatest improvement (~27%), possibly reflecting higher potential for improvement. It is nevertheless encouraging both that the simulation most benefited students with poorest prior understanding

Table 4. Paired t-test comparisons of students’ overall performance (percentage) on pretests and posttests, by semester.

	Fall 2016	Spring 2017	Fall 2017	Spring 2018
Pretest percentage ($\bar{X} \pm SE$)	77 \pm 2	66 \pm 2	67 \pm 2	71 \pm 2
Posttest percentage ($\bar{X} \pm \pm SE$)	91 \pm 1	77 \pm 3	80 \pm 3	84 \pm 2
n	107	55	65	71
t	8.878	3.786	5.504	7.439
p	<0.001	<0.001	<0.001	<0.001
Cohen’s d	0.858	0.511	0.683	0.883

Table 5. Paired t-test comparisons of percentage improvement on pretests and posttests for students grouped by level of prior understanding, based on pretest scores (excludes students earning 100% on the pretest).

Groups (Pretest Percentage Earned)	One ($\leq 50\%$)	Two (51–79%)	Three (80–99%)
Pretest percentage ($\bar{X} \pm SE$)	44 \pm 1	65 \pm 1	84 \pm 1
Posttest percentage ($\bar{X} \pm SE$)	71 \pm 3	80 \pm 2	92 \pm 1
n	51	113	108
t	7.952	9.969	8.252
p	<0.001	<0.001	<0.001
Cohen's d	1.114	0.938	0.794

Table 6. Chi-square goodness-of-fit comparison, by semester, between pretest and posttest percentages of students correctly responding to the question “If no mutation occurs to affect the running speed, what will most likely happen to the running speed of predator and prey populations over time?”

	Spring 2017	Fall 2017	Spring 2018
Pretest percent	18	28	23
Posttest percent	49	52	59
n	55	65	71
χ^2	11.77	8.21	19.7
p	<0.001	0.004	<0.001
Cramer's V	0.462	0.355	0.527

and that almost all students gained some benefit. We are confident that students also benefited from completing the calculations and working in teams.

Importantly, after the simulation, students better distinguished natural selection from mutation (Table 6). Over three semesters, we asked the additional question “If no mutation occurs to affect the running speed, what will most likely happen to the running speed of predator and prey populations over time?” In the pretest, only 18–28% chose the correct answer, “The average running speed of both predator and prey populations will first increase and then remain the same.” Many chose “The average running speed of predator and prey populations will never change due to lack of mutation.” Encouragingly, 49–59% (depending on semester) identified the correct answer in the posttest. A chi-square goodness-of-fit comparison indicated that improvements were statistically significant every semester (Table 6).

Conclusion

In summary, this simulation exposes mechanisms of natural selection that are commonly misunderstood. It also allows students to work as teams, practice and apply quantitative skills, and draw their own conclusions. Ideally, an active-learning exercise that distinguishes genotype from phenotype by calculating separate allele

and phenotype frequencies (e.g., Lee et al., 2017; Jördens et al., 2018) would follow this simulation. However, we find that this simulation is ideal for initial exposure to the theory of natural selection.

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