Agent-Based Modeling and Complex Systems Concepts as Useful Prior Knowledge in Secondary School Science Students' Understanding of Evolution

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Abstract

We have shown that agent-based modeling and complex systems concepts can be practical and effective tools for middle school science and high school physics learning (Klopfer, 2009). This study builds on that experience, extending the use of agent-based models and complex systems simulations from the physical sciences to the secondary school biology curriculum. To this end, we designed and implemented a sequence of interactive off-computer and agent-based model building activities that would enable students to experience and experiment with the mechanisms that drive the emergence of large-scale global phenomena from smaller scales of agent actions and interactions. By including the act of model building (in many cases through computer programming) in the learning experience, students were able to participate in the full spectrum of interactions with simulations (Klopfer, 2009). Our objective here was to determine whether these modeling activities would provide the right prior knowledge (Schwartz, 2007), that when coupled with appropriate scaffolding and learning resources, would help students overcome misconceptions and build a robust understanding of evolutionary processes

Analysis of early student programming strategies revealed a need for instruction in systematic design and problem solving skills. The trial and error process employed by most students was inefficient, but it was good enough to help them discover an important complex systems principle; that in some systems, small code (behavior) changes could yield dramatic changes in the resulting systems-level patterns. To assess how the concrete act of programming affected the understanding of emergence, students were asked to explain how patterns in their simulations happened. While it has been reported that a coherent understanding of complex systems eludes most students (Jacobson & Wilensky, 2006), more than 85% of the students in this study were eventually able to make connections across scale by describing how population patterns emerged from individual agent behaviors and interactions. Post-activity written and oral discussions revealed that the simulation experience proved to be the right prior knowledge to account for evolution.

Keywords

simulations, complex systems, programming, prior knowledge, evolution

Theoretical Framework

Both off and on-computer simulations have been used in classrooms to explore how complex dynamic systems evolve over time (Scheintaub, 2009). These simulations can support new forms of classroom interaction and can serve to catalyze the engagement with complex ideas, fostering the kinds of higher-order thinking and problem-solving skills that are called for in science and mathematics learning (Wilensky & Stroup, 1999; Collella, 2001).

Agent-based computer models are especially well suited for student inquiry and science learning (Jacobsen & Wilensky, 2006). Pre-built simulations can provide students with accessible visualizations, immersive learning environments, and opportunities to analyze data from virtual experiments. However, they do not give students the intimate knowledge that comes from building simulations, an important part of scientific practice; nor do they afford them the freedom to express their ideas or express their interest in a given phenomena, an important motivator of the sustained learning necessary for meaningful science learning (Edelson & Joseph, 2001). By including the act of model building (in many cases through computer programming) in the learning experience, students are able to participate in the full spectrum of interactions with simulations (Klopfer, 2009), thereby providing experiences that can serve as the 'right prior knowledge' to support future learning (Schwartz, 2007). The algorithmic thinking involved in programming emphasizes processes rather than facts (Cohen & Kanim, 2007) and programming provides students with a means of expression that is precise and compact (Sharin & diSessa, 1993). Subsequent use of the simulations proceeds from the experiential knowledge of its construction, providing useful prior knowledge upon which students can build new understandings.

Though recent advances in science and medicine, along with an abundance of observations and experiments over the past 150 years, have reinforced evolution's role as the central organizing principle of modern biology (Ayala, 2008), teaching evolution has proven to be extremely difficult and many misconceptions abound (Caldwell et al, 2006). Interactive lessons have been found to help students recognize many misconceptions and understand why evolution is considered one of the strongest of scientific theories (Flammer, 2006). To be most effective, interactive lessons need to be linked to and build on the foundation of a unifying idea. For evolution learning, the complex systems concept of emergence may be such a theme. It can facilitate the understanding of evolution by providing a unifying theme across scales of time, space, and size (Holland, 1996; Solé & Goodwin, 2000). Therefore, we designed and implemented a sequence of interactive off-computer and agent-based model building activities that would allow students to experience and experiment with the mechanisms that drive the emergence of large-scale global phenomena from smaller scales of agent actions and interactions. We wanted to study whether these activities could provide the right prior knowledge, when coupled with appropriate scaffolding and learning resources, to help students overcome misconceptions and build a robust understanding of evolutionary processes. Here we report on the development, implementation and outcomes of such a series of activities into ninth grade biology classes; and the effect of these activities on the ninth graders' understanding of evolution is documented.

Context and Methods

We used *StarLogo TNG (Klopfer et al., 2009)* as the modeling and simulation tool for many of these activities. *StarLogo TNG* has proven to be an effective tool for introducing agent-based modeling and programming to secondary school students (Klopfer & Scheintaub, 2008; Klopfer, 2009). *StarLogo TNG* builds on the tradition of Logo-based languages designed to facilitate the development and study of simulated systems in classrooms. It includes a graphical programming language which lowers the entry barrier to programming (Begel, 1996), and the game-like 3-D world helps provide the motivation necessary for students and teachers to experience the power of programming.

We report here on a sequence of programming and simulation activities and the resulting outcomes in terms of conceptual changes, as manifest in the curriculum of freshman biology classes over a two-year period in an independent school outside of Boston, MA. Additional implementation details for these activities can be found at "Biology Curriculum" at http://education.mit.edu/drupal/starlogo-tng/learn. Data sources in this study included: a) Multiple classroom observations and analyses b) Student-generated curricular products c) Student blogs, discussions and self-assessments and d) pre- and post-implementation student surveys.

Students used *StarLogo TNG* to program the actions of agents and then observed system-wide patterns in the complex-systems simulations they had built. In the first three activities, (See Table 1) students learn to build models and use simulations. They acquire a set of skills that are technical and general. Simulated experiments provide concrete examples of the abstract concept of emergence. While the activities are grounded in relevant content, that content is not their learning objective. The content objective doesn't come until the fourth activity where students apply their experience with simulations and their working knowledge of emergence to their efforts to understand the fundamentals of evolution.

Activity 1- Introduction to Programming in a game-like Environment: The first programming activity, Vants (Virtual Ants), introduces students to the idea that a program can define a set of rules of behavior for an agent (Figure 1). They are empowered to modify a program and motivated to create visually pleasing results. Through engagement in this activity, students get some first-hand experience with the important complex systems concept of emergence. They see how small changes in rules for agent behaviors can lead to large changes in observable systems patterns.

Figure 1. Small changes in initial conditions and movement of agents give very different looking patterns. The pattern in the figure on the right is generated from a very small variation in the code that produced the original pattern on the left

Activity	Emergence – from simple rules to observable systems patterns	Biology Concepts
Vants (Virtual Ants)- Programming and simulations introduction	Patterns in the landscape emerge from simple stamp and turn rules for agents	Interactions Agent/Environment Agent/Agent Environment/Agent
Population Growth -	Exponential and logistic growth	Birth rate, death rate,

off-computer, and in TNG	curves emerge from simple rules for birth and death	Recognizable patterns of population growth
Community Interactions – students build a sustainable bunny /carrot community	Cyclical, out-of-phase population graphs emerge from actions of and interactions among agents	Community as a set of interacting populations Predator/prey relationship Basics of ecosystem dynamics
Fishpond - a Sequence of TNG simulations for fundamentals of microevolution	Change in a population's gene frequency emerges from randomness and slight differences in genetically determined actions of individual agents in the community.	Population as the unit of evolution Evolution is the change in gene frequency in the population

Table 1. Simulations, Emergence and Curricular Concepts

Activity 2 – Population Growth: This section begins with a tabletop simulation where pennies are given a set of simple rules for reproduction (Collella et al., 2001). Students plot growth curves of their penny populations and discuss how rule changes might affect their results. When students build those rule changes into a *StarLogo TNG* simulation (Figure 2), they see how exponential and logistic growth curves emerge from rules for birth and death. As in the previous activity they see how small changes in those rules affect their population growth patterns.

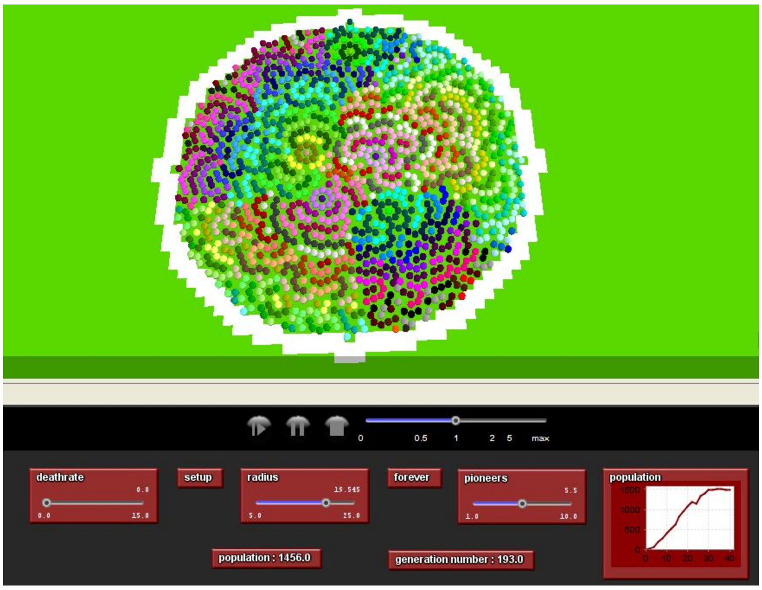


Figure 2. Students use sliders to change variables that affect population growth dynamics. Discussions reveal how the area of the circle could represent available resources.

Activity 3- Community Interactions - Building a sustainable producer-consumer community: This weeklong, self-paced programming unit builds on experience and the students' developing concept of emergence. Students build a virtual ecological community of producers (carrots) and consumers (bunnies), within which they can run experiments, by working through a set of instructions that progress from highly structured to more open-ended. Students program essential behaviors for bunnies (move, eat, reproduce, die) and carrots (spread seed, die). They focus on individuals and interactions; no population scale behaviors are defined. While the student's attention was centered on the actions of agents in the programming panes (Figure 3) of their simulations, macro- scale organization emerged in the 3D world on the screen (Figure 4).

As in the previous two activities, they see how their programmed individual micro-scale actions and interactions caused ordered patterns to emerge at the population scale. Interacting in and with simulations in Activities 2 and 3 gave students an immediate experience with the concept of emergence that could be codified and brought to bear later in their study of evolution (Schwartz, et al, 2005).

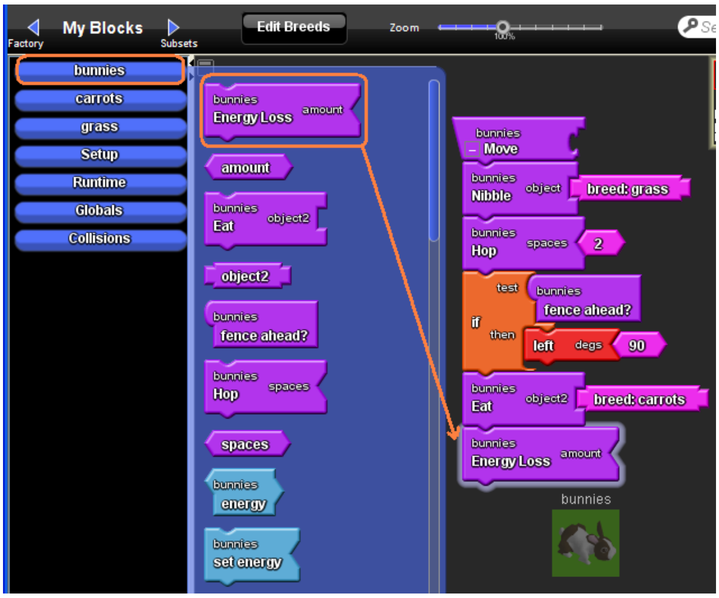
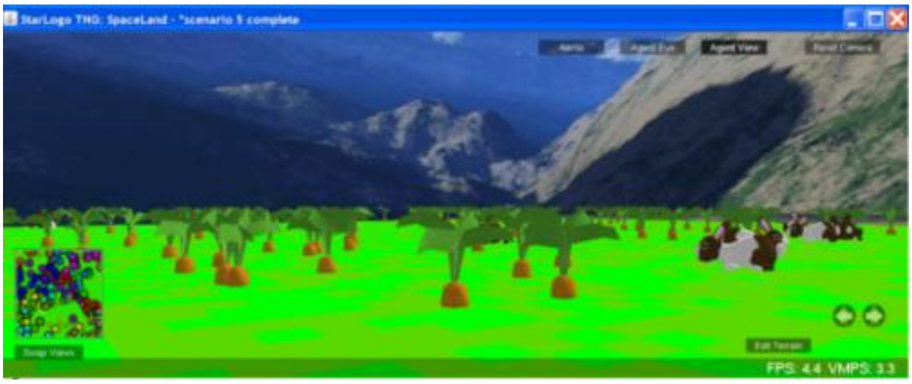


Figure 3. Screen shot of graphical programming language of StarLogo TNG used by students to build community interactions simulation.



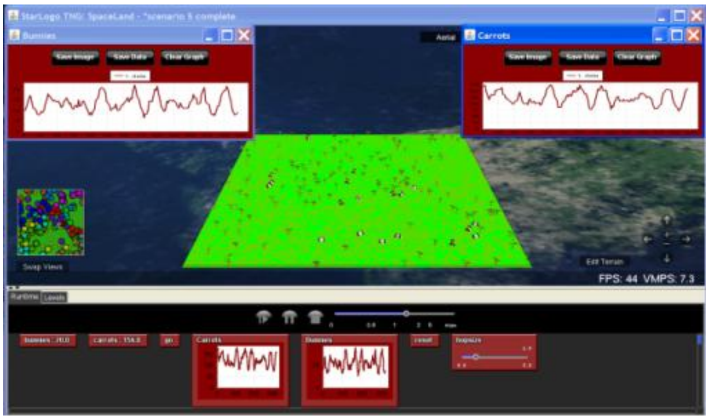
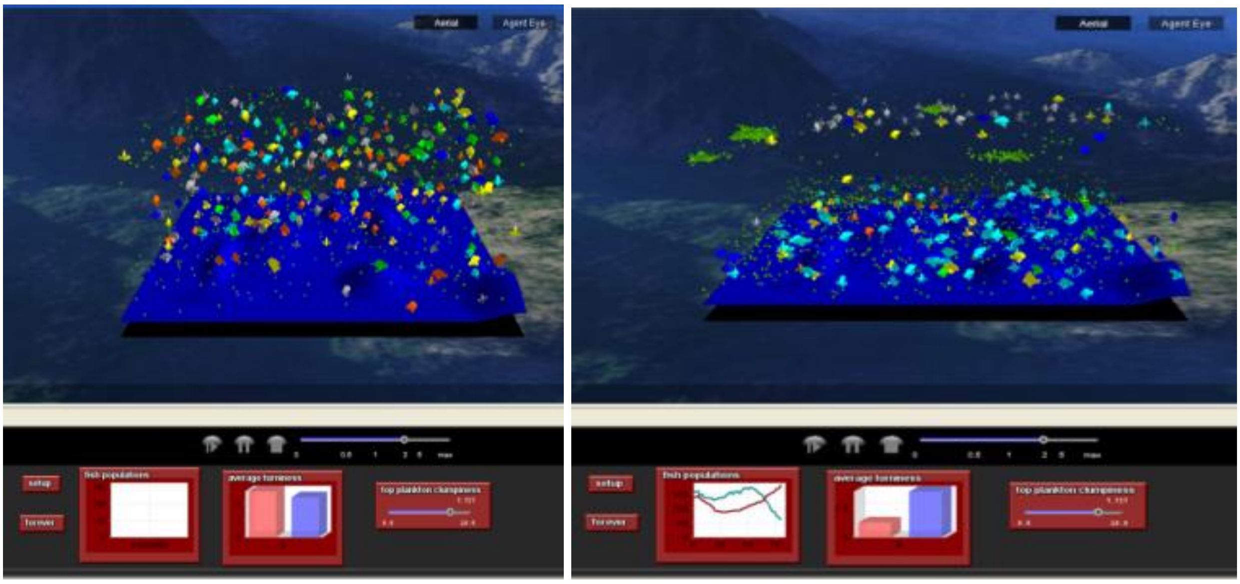


Figure 4. Screen shots of community interactions simulation from the first person (top) and third person (bottom) perspective. The two views let the students experience the simulation as both a participant and an observer.

Activity 4 – Evolution: Misconceptions about evolution are widespread (Caldwell, et al, 2009). The fact that evolution is a unifying theme in modern biology makes dealing with those misconceptions critical. To address one misconception, “individuals evolve”, we developed a series of agent-based evolution simulation activities that leveraged the students’ concrete programming experience and complex systems learning from the previous activities. The evolution simulations focus on fish in a pond. The first of the series is essentially the same as the bunny and carrot simulation students built earlier. It serves as a review of how out-of-phase producer-consumer population cycles emerge from actions and interactions of fish and plankton in a pond. In the second of the series, two varieties of fish in an initial population separate over time, one variety lives near the top of the pond, one near the bottom. There are two varieties of plankton in the pond. One type of plankton grows best near the surface, one near the bottom of the pond. Experience looking to agent interactions to explain population patterns helps students eventually see that one variety of fish prefers the plankton that grows near the surface; the other prefers the bottom growing variety. The concept of evolution, as the change in the genetic composition of a population is introduced in the third simulation. In this simulation there is only one type of plankton and an initial population of fish of different colors. Fish and plankton are set up in random locations on the screen. Randomness is programmed into the movement of the fish. Fish color is a programmed ‘genetic’ characteristic that is passed on to offspring, but serves no survival value. Students recognize that the now familiar dynamics that lead to population cycling cause the elimination of certain color fish from the population when the food supply is low. When food is scarce, the survival of a particular color fish depends randomly on its position near plankton. They see evolution occurring, in this case without natural selection. In the final simulation (Figure 5) color is linked to a trait that affects survival, and evolution proceeds through the natural selection and the random processes seen in third simulation.



Figures 5a and 5b

Figure 5. One diverse population of fish (5a) evolves into two (5b). Fish at the top of the pond are better suited to forage on clumps of plankton while the characteristics of those fish near the bottom are better suited to eating the dispersed plankton found there.

Misconceptions about evolution often center on reasons why organisms change over time (Caldwell, 2006). To avoid such misconceptions we kept students actively involved with the concrete actions occurring in and the appearance of their simulations. They performed concrete tasks that helped them focus alternatively on agent behaviors and population patterns. Instructor-aided analysis was integrated into these activities to help students see how the evolution of the fish populations emerged from:

- randomness - in initial conditions and movement.
- genetic variation - as manifest in recognizable programmed behaviors of those fish.
- selection - that derived from understandable interactions between fish and plankton.

Data and Results

Both the process of student inquiry and the results of their learning were subjects of this study. A teacher/researcher and outside observers made multiple classroom observations over the entire school year. Observational data as well as written test results, student-generated curricular products, blogs, self-assessments and surveys served as the data sources. The data detail how the guided work, reported on here, allows students to make connections across scale, account for the emergence of population patterns in biological systems, and avoid the misconceptions so often seen in student explanations of micro-evolution.

Activity 1- Analysis of early student programming strategies revealed a need for instruction in systematic design and problem solving skills. This need was met with additional scaffolding and structured worksheets in subsequent activities. The trial and error process employed by most students was inefficient, but it was good enough to help them discover an important complex systems principle; that in some systems, small code (behavior) changes could yield dramatic changes in the resulting systems-level patterns. Students appreciated the freedom to experiment and reacted with excitement when one of their small changes in code changed observable patterns on their screens. The enthusiasm generated by this activity helped establish StarLogo as favorite classroom learning tool introduce modelling as a mode of learning.

Activity 2 - This basic population growth activity began as a physically concrete penny placement and counting exercise, but its analysis and extension to StarLogo made it mathematical and virtual. The bridges from physical model to computer simulation, and concrete counting to abstract mathematical analysis were designed to help establish modeling as a mode of learning for students. The personal nature of post-activity responses spoke to the effectiveness of this strategy. For example one student wrote, “The shape of my population graph is an “S”. My graph compares to the other groups because it is exponential which means it has a steep rising point, and the whole graph is logistic, the “S” shape”. Another student’s insight into the modeling process is revealed here. “Some modifications that might enable this model to better represent living systems could be that pennies could get eaten by predators, and not (re)produce always the maximum amount.”

Activity 3 – From the results of Activity 2, the authors knew that students could use modeling and model analysis for learning. They were ready to see how the concrete act of programming impacted students’ understanding of emergence. Written explanations of how the cycling of simulated rabbit and carrot populations came about, was the test of that understanding. This was a difficult test because a coherent understanding of complex systems eludes most students (Jacobson & Wilensky, 2006). Detailed analysis of student explanations revealed that more than 85% of the students in this study made connections across scale by clearly describing how the cycling of the two populations emerged from individual agent behaviors and interactions. They noted that after the bunnies ate most of the carrots, most of the bunnies died. For the community to continue a few bunnies had to be lucky enough to be in the region where a few carrots remained. The high percentage of students making connections across scale is notable because often students have difficulties seeing the mechanisms that drive the emergence of large-scale global phenomena from smaller scales of interacting agents (Chi, 2005, Wilensky & Resnick, 1999). Analysis of explanations revealed the specifics of some of those difficulties. One student was not able to see the reciprocal nature of the interactions rabbit and carrot populations. He wrote, “The rhythm of carrots and bunnies is primarily controlled by the bunnies.” Another student did not feel that the idealized simulation represented the real world. “Nature is nature! There is no systematic pattern as there is in our StarLogo simulations. In nature, what happens, happens. It is sporadic, and there is no pattern.” These results are significant not only because the programming/simulation sequence yielded such a high percentage of students who demonstrated a good functional understanding of emergence, but also for exposing the strong beliefs about how the world works that endured in a few students even after participating in the activity.

In addition, the activity stimulated connections from the science classroom across experience. Highlights of a discussion in one freshman class revealed complex systems connections similar to those made by university students (Goldstone & Wilensky, 2008). One freshman student noted, “The pattern of supply and demand and the carrots and bunnies is relatively the same.” Another added, “When there are a lot of bunnies the supply of carrots is low and demand is high.” In that same discussion there was an exchange about the intentional, or unintentional nature of the interactions. When one student said, “It’s all about multiple organisms working together.” Another agreed, but added, “They subconsciously help each other out because they are only trying to help themselves, but they benefit each other by helping themselves”

Activity 4 – In Activity 4, students applied their experience with simulations and their working knowledge of emergence to the understanding of evolution. Fish and plankton in a pond was the setting of these simulations. Key aspects of the evolutionary process were developed systematically in a sequence of simulations. The series started at a familiar place, the interdependence of producer and consumer populations. In the second simulation, variety in the plankton population made that interdependence more complex. Inherited variability in the fish population was included in the third simulation and natural selection in the fourth. Worksheets and oral instructions helped guide students’ attention to the actions of agents. Students ran simulated experiments, collected data and answered questions. These tasks made up the concrete experience base that students would go to when developed a systematic explanation an explanation for evolution.

One of the programmed variables in the fourth simulation was the behavior of a fish after eating plankton. In the initial population, some fish turned, while others continued swimming straight. Plankton behavior varied, too. Top-growing plankton grew in clumps, while plankton near the bottom were dispersed. Plankton growth and fish turning behaviors were passed on to offspring. Fish that turned after eating were better suited to survive at the top. Straight swimming fish did better near the bottom. Eventually, the initial fish population evolved into two populations, a turning population at the top and a straight swimming population near the bottom.

Post-activity written and oral discussions revealed that students had a good working knowledge of the micro-evolutionary processes involved in the simulated evolution. Students knew that some fish had a trait that directed them to turn more than others. Some fish had a trait that directed them to swim faster than others. They saw that after a time the initial mixed population evolved into two distinct populations.

In a guided debrief, the class was able to explain how this evolution occurred. A student scribe recorded highlights of that discussion. Quotes from those notes are used in this section. Students began their analysis with a concept developed initially in the carrot and bunny simulation of Activity 3. In that simulation they had noted that bunnies survived in regions of the simulation where there were carrots. Being trained to look at producers helped them see that, "Top food (plankton) is clumped, and the bottom is spread out." This observation is important because it shows that the students realized that even though it was the fish that evolved, variability in the environment helped drive that evolution. Then their attention turned to the fish. They saw that the, "Fish separated into two populations; top and bottom. This was because fish survived where there was food. It *appeared* that they followed their food source." Though it is only implied here, it is clear that the students recognized that fish survived where there was food that they could to eat. The feeding behavior came first, then the survival. The simulation helped students avoid the common misconception that the ability to eat a particular type of food evolved to help the animal survive. When pressed for specifics of the behaviours that affected survival, they replied, "Top fish turn more and bottom fish turn less." When asked why, they reasoned, "Surviving fish are better adapted to their environment. Turning after eating works where plankton is clumped. Swimming straight and fast works where plankton is spread out." The specific path of their reasoning was recorded as follows. "If you are turny and you are lucky enough to be on top you can survive and reproduce. If you are turny and you are on the bottom you most likely die. If you are fast and you are lucky enough to be on bottom you can survive and reproduce. If you are turny and you are on the top you most likely die. Over time, this results in fast fish on bottom, and turny ones on top. This is because survivors pass on their genes to their offspring." This explanation reveals an understanding of the concept natural selection grounded in the concrete experience of their simulation. In addition, they see that to survive the fish have to be more than just fit; it has to be lucky enough to be where their inherited hunting strategy matches the food supply. This understanding of the role of randomness in the complex process of evolution is often overlooked in textbook presentations of evolution.

There are many other more naive interpretations that could be given for the evolution of the fish population, the most likely being that hunting strategy evolved to help the fish survive. The authors believe that students do not use this line of reasoning because of their experience building and using simulations. They know that code determines the behavior of agents and that the behavior of agents determines population dynamics. So they look to coded behavior for a cause of evolution. Understanding the programmed workings of the simulation leads to right reasoning and an avoidance of misconceptions. It proves to be the right prior knowledge for understanding the mechanisms of microevolution.

The debrief proceeded in a biologically and structurally sound cause and effect manner from plankton patterns through individual fish behavior to fish population patterns. It included fitness and randomness. The students saw evolution occur in their simulations, and they used their observations to account for that evolution. In contrast, students who are not able to see evolution occurring in simulations may use assumptions rather than observations to account for it. They may assume that evolution proceeds in a particular direction because individuals try to adapt (Caldwell, 2006). Students who use simulations have an opportunity to apply scientific reasoning to evolution, without the need to rely on previous assumptions.

Significance

This pilot shows that the integration of programming, simulations, and complex systems principles into freshman biology courses is both possible and promising. Students transferred the complex systems principle of emergence from a simple game-like system, into population growth models, through community interaction simulations, to the dynamics of the evolutionary process. They used their knowledge of micro-level events to explain complex macro-level phenomena like the out-of-phase cycling in a producer-consumer biological community and to provide plausible mechanisms for mysterious events (Jacobsen & Wilensky, 2006) like evolution.

In addition, the sequence of lessons employed here supported di Sessa's (2000) contention that programming can enable the individual discovery of important (biological) patterns by converting those abstract patterns into spatial and visible ones accessible to students. The activities proved to be the right prior knowledge to counteract a widespread misconception and support a sound functional understanding of evolutionary processes. Such a sequence may have wide application in the secondary school biology curriculum. To this end, we are developing "preparation for future learning assessments" to work backwards to identify the aspects of these activities that most directly prepare students to learn (Schwartz, 2007) the processes behind and the significance of evolution.

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