Small Bugs, Big Ideas: Teaching Complex Systems Principles Through Agent-Based Models of Social Insects

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Abstract

Complex systems are challenging for students, especially younger students, to learn. In this paper, we argue that agent-based models (ABMs) of social insects provide an engaging and effective space for students to learn powerful ideas about complex systems. We designed a curricular unit called BeeSmart centering on ABMs of honeybees' collective behavior. Preliminary results from an implementation at a high school showed that ABMs of social insects could be a promising approach to introduce complex systems to a younger audience.

Introduction

The study of complex systems in the past few decades has provided scientists with powerful frameworks to investigate phenomena that were difficult to understand through classic scientific methods (Bar-Yam, 1997; Jacobson & Wilensky 2003). Through a complex systems lens, scientists see the behavior of a system at the macro level as emerging from the interactions of its individual elements (or agents) at the micro level (Epstein, 1999). The complex systems approaches are not only scientifically powerful, but also pedagogically important, because concepts and methods, such as emergence, self-organization, positive feedback loop, and agent-based modeling, have the potential for students to develop new intellectual horizons and new explanatory frameworks that cut across multiple disciplines (Jacobson & Wilensky 2003).

Teaching students complex systems principles is both an opportunity and a challenge. Educational research on students' learning about complex systems shows that they have significant difficulties in understanding complex systems: The aggregated properties of complex systems usually appear to be disconnected from their constituting agents' details (Miller & Page, 2007), which makes emergence counterintuitive to students. Wilensky and Resnick (1999) describe students' difficulties with complex systems as a "deterministic-centralized mindset" (aka DC mindset). Novices tend to see complex systems as a deterministic "clockwork" system, where elements of the system are interconnected like gears in clockwork (Jacobson, 2001). Novices also tend to think that for patterns to emerge, centralized leadership is necessary.

Empirical studies suggest that Agent-Based Models (ABMs) can lower the threshold of learning complex systems and are effective in helping students overcome their DC mindset (e.g., Sengupta & Wilensky 2009). ABMs are computational models that simulate the actions and interactions of agents—individual parts of a complex system—and provide a view to assess the effects of these interactions on the system as a whole. NetLogo (Wilensky, 1999) is a widely used agent-based modeling environment in both scientific research and in education. Much work has been done using NetLogo ABMs to teach existing curricular contents with a complex systems view (Levy & Wilensky 2008; Sengupta & Wilensky, 2009), but few projects focus on explicitly teaching complex systems principles.

ABMs of social insects—honeybees, ants, wasps, and termites—could be a productive way to teach complex systems principles. Social insects' behavior demonstrates several core complex systems principles that are prevalent in natural and artificial complex systems, including positive feedback loops, randomness, interaction, and homogeneity. These principles can explain the apparent disconnection between the system and its parts: how the intelligence of swarms emerges from a collection of non-intelligent insects that follow a set of very simple rules. Learning about social insects' behavior can help students make sense of complex systems principles in rich contexts and provide students a mental model to think with when explaining similar complex systems.

What makes social insects more appropriate as an entry point to study complex systems is that they are both familiar and foreign to students. Students have learned many aspects about bees and ants from an early age, because these social insects have been a popular topic in children's fairy tales, in school curricula, and even embedded in many different cultures and languages. Yet, very few people understand the details of insect colonies' behavior, especially how the overall behavior of a colony can emerge from simple interactions between individual insects. ABMs of social insects allow students to draw prior knowledge about familiar topics to build new knowledge about complex systems.

The BeeSmart Curricular Unit

We designed a curricular unit called BeeSmart for high school students to learn complex systems principles. The unit is based on Seeley's (2010) research findings about how honeybees pick their new hive site. The swarm's decision-making process is best explained through a complex systems lens. The system consists of *multiple agents* that obey simple behavioral rules: if a scout bee discovers a potential hive site, she inspects it. Then she goes back to the swarm and reports the location, distance, and quality—the suitability of the site is shown by doing a waggle dance. The waggle dance is bees' *medium of communication*. Bees have the instinctual ability to assess the quality of potential hive sites. If the quality is high, bees dance enthusiastically for a long period of time to advertise it; if the quality is low, they make a few brief lackluster dances or do not dance at all. In this way, bees encode differential preference into the dances: the longer the dance, the better the site, and the stronger the signal. Because dances for higher quality sites are presented in the swarm for a longer time, neutral scouts—the observers in the swarm—are more likely to see such dances. When they see a dance, they become recruited and proceed to inspect the advertised hive site. Such simple behavior and interactions between dancers and observers at the *micro level* result in a *positive feedback loop*: signals advocating high quality hives are amplified. Usually, the hive site with the highest quality eventually receives all the support and wins out.

In the BeeSmart Hive Finding model (See Figure 1), each bee obeys the rules described above. In addition, students can use sliders to manipulate environmental variables and bees' behavior. The plots show the count of bees with different states and how their support converges over time. In addition to the model, we designed instructional materials including short readings on complex systems and bees, short videos of bees' waggle dance, illustrations of bee's hive-seeking environment in the real world, instructions of how to use the model, and questions about the model.

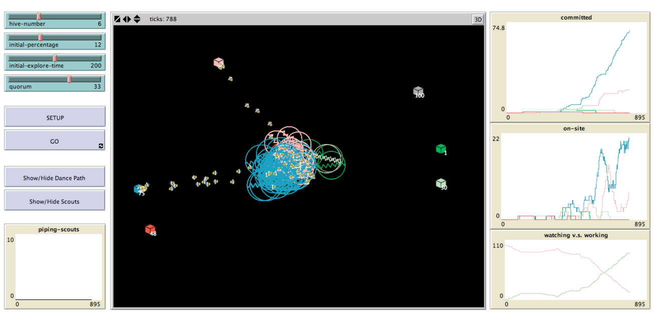

Figure 1. BeeSmart Hive-Finding Model.

School Implementation and Results

We conducted a small-scale pilot study of the BeeSmart unit in a high school mathematical modeling class at an ethnically diverse suburb of Chicago. All 14 students in the class participated in the study. The intent of this study is not to generalize the findings from such a small sample. Instead, we would like to look closely at how students interact with BeeSmart and what is possible to achieve.

Through the 5-day unit, students were highly engaged in honeybees' hive-finding phenomenon and were motivated to answer the driving question "How does a swarm of 10,000 bees pick the best potential hive site from many choices?" The 14 students in the class worked in pairs, interacted with the model, went through the materials, asked questions, and participated in discussions. To test what complex systems principles students learned from the unit, we conducted pre- and post-tests asking the students to explain the hive-finding phenomenon. In addition, we asked students to interact with another NetLogo model about ants' foraging phenomenon (Wilensky 1997) and explain how it works using principles they learned from the honeybees. Nine students completed both the pre- and post-tests. Four students were selected as focal students to represent different gender and prior knowledge with computational modeling. We interviewed the focal students both before and after their using the unit.

In the pre-test, the students showed relatively high knowledge about bees. They knew that bees' behavior was shaped by evolution, and one student even knew about "swarm mentality". However, most students' answers showed a deterministic mindset, such as the bees splitting into certain number of groups to find new hives. In the post-test, all students provided more sophisticated explanations with complex systems principles such as randomness, interaction, feedback loop, and homogeneity to explain the phenomena of both honeybees and ants. The four students interviewed elaborated on the mechanism of bees' hive finding, incorporating randomness involved in insects' movement and interactions to explain how the group level behavior emerged from simple rules and randomness.

For future work, we will develop more curricula centering on ABMs of social insects for students to explore complex systems. We will also conduct studies at a larger scale to test the effectiveness of this approach.

Acknowledgements

This work is supported by the National Science Foundation under Grant #DRL-1020101 and #DRL-1109834.

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