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Prevalence of Direct and Emergent Schema and Change after Play

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Abstract. This paper describes visitor interaction with an interactive tabletop game on the topic of evolutionary adaptations of social insects that we designed in collaboration with a large American museum. We observed visitors playing the game and talked to them about the experience. The game explores the emergent phenomena of ant behavior. Research has shown that such emergent behavior is difficult for people to understand, and that there are different emergent schemas that work best for understanding these phenomena. We tested the visitors pre- and post-gameplay and counted the prevalence of visitors expressing direct and emergent schemas of complex processes. We then considered four hypotheses measuring changes between these schemas and found that two groups shifted their schemas. To better understand this change we provide a qualitative overview of the visitors' interactions. Our exhibit, called *Ant Adaptation*, takes the form of an agent-based modeling game that integrates complex system learning with gameplay. We video recorded 38 groups (114 participants) playing the game and conducted pre- and post-gameplay interviews. We coded the groups that contained children for this analysis: 9 groups (27 participants). Our results show that visitors held both emergent and direct schemas before and after play, and three people changed from direct schemas before play to emergent schemas after play. We then examine the process of how one of these groups shifted their schemas.

Keywords: ants, complex systems, emergent schema, informal learning, tools and technologies, innovative computing education.

Introduction

Learning about complex systems can be difficult (Wilensky and Resnick, 1999; Chi, Roscoe, Roy and Chase, 2012; Jacobson, 2011). Computer mediated learning may help with complexity learning. We designed a museum game to teach emergent schemas in short interactions in a museum. Inserting the complex system content into video games may be a useful avenue of intervention because 97% of children play video games at some point in their lives (Lenhart *et al.*, 2008). One type of game, constructionist vid-

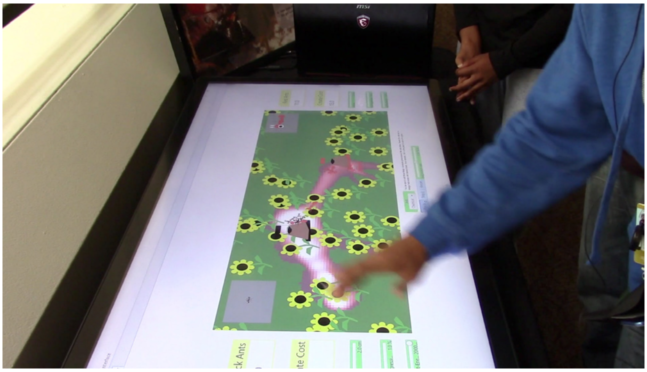

Fig. 1. Luck and skill weave the action of an emergent system of ants into the players' attempt to beat their opponents as they swipe and touch interacting with an ant microworld.

eo games, seems particularly promising. By encouraging open-ended engagement and exploration, games can support learning across a wide variety of topics and contexts, providing a powerful way for learners to construct new knowledge and understanding (Kafai, 2005; Papert and Harel, 1991). Constructionist learning games try to strike a balance between open-ended play and targeted treatment of learning content through providing learners objects to think with (Holbert and Wilensky, 2019; Weintrop, Holbert and Wilensky, 2014). Constructionist video games employ traditional game structures infused with constructionist ideals to create a game experience that both encourages exploration and engages desired content (Egenfeldt-Nielsen, 2006). These games mediate open-ended learning. In this paper we propose the use of a game, *Ant Adaptation,* to improve learning about complexity and show children's learning of it in a museum.

Social Insects in Complexity Education

The exhibit presents visitors with the opportunity to create an interactive digital ant ecosystem by exploring a microworld (Papert, 1980; Edwards, 1995). Doing so allows learners to better understand the world of ants. Our past work with agent-based models of social insects and microworlds has been effectively used for classroom teaching (Wilensky and Reisman, 2006), but less so in informal museum settings. Examples of our classroom use include *Ant Food Grab,* a yearlong block-based programing curriculum with ants (Martin, Sengupta and Pierson, 2018; Sengupta *et al.*, 2015), and *Beesmart*, a curriculum about the hive-finding behavior of honeybees (Guo and Wilensky, 2014a; Guo and Wilensky, 2014b). These examples highlight that observing and/or interacting with insect microworlds allows students to construct their own understandings of science through exploring and adapting models in a classroom setting. Like other complex systems interventions, the students build their understanding of complex systems in natural systems. The literature has depicted learning through diverse simulations of natural systems: bees (Danish, Peppler, Phelps and Washington, 2011), material science (Blikstein and Wilensky, 2009), multi-level modeling (Wilensky and Reisman, 2006), electricity (Sengupta and Wilensky, 2009) and evolution (Wagh and Wilensky, 2012). However, there is much less work that leverages the pedagogical value we discovered in these earlier microworld based interventions in museums (Horn *et al.*, 2014; Strohecker, 1995a, 1995b), a dearth our present work partially addresses. Informal education is different from formal education in a few key ways, including:

(1) Informal education does not provide teachers.
(2) In classrooms, teachers may take days or weeks, to cover a topic whereas in museums, a topic can be covered in as little as two to ten minutes.
(3) In open-ended learning there is no coercion, as the participant can walk away whenever.

In fact, *holding time*, that is, the number of minutes a participant stays at an exhibit is a key measure in museum evaluation.

Although microworlds can be useful for learners to explore about complex systems, developing robust understandings of complex systems can be challenging. Wilensky and Resnick (1999) describe the difficulties people have in “thinking in levels,” exhibiting “levels confusion” and difficulties with distributed control and stochastic processes. Not only do learners have a hard time thinking across multiple levels such as disease of the whole body resulting from microscopic pathogens, but they tend not to think about phenomena such as the flow of ink dropped into water as the processes of collectives of agents interacting (Chi *et al.*, 2012). If the glass of water changing color is explained by the individual parts of ink interacting with H^2O, then the process becomes more intuitive. Most people, however, are not familiar with ink particles. Therefore, building off earlier work in classrooms (Martin *et al.*, 2018) and theory about reasoning about population dynamics (Wilensky and Papert, 2010), we hypothesize that thinking about ants is a powerful way to restructure both of these challenges. Our Game, *Ant Adaptation,* scaffolds thinking in levels (Wilensky and Resnick, 1999) such as between the colony and the individual ant, and seeing success and failure of the colony as a result of ants interacting through processes. To research this claim, this paper explores how visitors made sense of the self-organization of ant colonies, and how this changed their schemas.

Constructionism

Constructionist thinking influences the learning sciences and educational research, particularly when addressing learning technologies and reform of mathematics and science education. Papert coined the name Constructionism, as mnemonic (Papert, 1986), to describe a species of constructivist thought. It focuses on the benefits of learning from the external construction of an artifact beside the internal construction of a mental model, or framework. Logo, the name derived from the Greek for *word* or *thought,* was the first constructionist programming language. Wally Feurzeig and Seymour Papert invented Logo in 1967 (Logo Foundation, 2015). Using tools like Logo, constructionists organized learning environments where learning was free from time constraints. Papert coined the term mathetics to describe the art of learning, and argued “My mathetic point is simply that spending relaxed time with a problem leads to getting to know it, and through this, to improving one’s ability to deal with other problems like it” (Papert, 1996, p. 12).

Constructionism burst into the public eye after Papert published his seminal work *Mindstorms: Children, Computers and Powerful Ideas* (1980). Papert used Logo to operationalize many of the big ideas described in *Mindstorms* using the idea of the turtle. The turtle is a single software agent that can represent many different organisms, such as a turtle in sheep’s clothes. This paradigm allowed for programming from an agent based perspective. While, the first versions of Logo had only one turtle, Kala and Blaho’s *Imagine Logo* (1993) included object-oriented features and multiple turtles. Since this time, the notion of constructionism has inspired many powerful tools for education including NetLogo (Wilensky, 1999), a multi-agent programming environment, and Scratch (Resnick *et al.*, 2009), a blocks based programming environment. These environments have been used to make powerful mathematics and scientific exploration tools that afford learners the ability to act in sequence or simultaneously on multiple representations of a phenomena (Schwarz and Hershkowitz, 2001; Kaput, 1992). Such a creation can produce contexts in which group-level understanding is constructed and contested. These novel restructurations have powerful impact on learners (Wilensky and Papert, 2010). For example, they describe when accountants moved from Roman numerals to Arabic numbers, operations such as multiplication and division became significantly easier because of the new representation’s affordances. The various new representations are the focus of both internal reflection and external action that foster shared meaning, positively mediating groups’ sense making.

Papert (1993) argued that the advent of the restructuring of digital worlds that children can explore will create less patient, accepting students. “Children who grow up with the opportunity to explore the jungles and the cities and the deep oceans and ancient myths and outer space will be even less likely than the players of video games to sit quietly through anything even vaguely resembling the elementary-school curriculum as we have known it up to now” (p. 9). Though constructionist environments have often been long term explorations of motivating problems, in the museum setting we needed to deploy a system to explore, but that provides an experience in as little as two minutes. This design constraint motivated our use of the constructionism to teach complexity. With this model, we examined the type of learning that occurs between a user, and a complex system model because we, like Papert, agree that in the coming educational environment, learners will be less patient as they seek their own meaning. In this paper, we provide an example of a learning environment that scaffolds individual meaning-making through touch, discussion, and play for museum patrons.

Ant-based Modeling

Early work on social insects motivated work on agent-based modeling. Early work on agent-based modeling was inspired by the behavior of social insects (Resnick and Wilensky, 1991; Wilensky and Resnick, 1993; Langton, 1997). Ant behavior has inspired games. SimAnt (McCormick and Wright, 1991) is based on Hölldobler and Wilson's (1990) *The Ants*. The collective behavior of ants has been simulated using agent-based models many times. StarLogo was used to model the collective behavior of social insects (Resnick and Wilensky, 1992, 1993). Wilensky (1997a; 1990) modeled food source preferences resulting from pheromones as well as the formation of ant trails (Wilensky, 1997b). Bonabeau investigated the role of agent-based models in pattern formation (1997), and more broadly, looked at swarm intelligence (Bonabeau, Dorigo and Theraulaz 1999). Pratt (2005) modeled collective nest selection of *Temnothorax albipennis* also using an agent-based model. Sumpter and Pratt's joint work explored the importance of group decision making with quorums (2009). Their work showed that when choosing a destination together, cooperation reduces the probability that an individual will suffer predation. Robinson, Ratnieks, and Holcombe (2008) used an agent-based model to explore attractive and repellent pheromones in pharaoh ants. Likewise, frameworks, such as Anthill, have been used to support the design, implementation, and evaluation of technical systems, such as peer-to-peer networks (Babaoglu, Meling, and Montresor, 2002). Their work drew on examples of complex adaptive systems to justify engineering and user applications because complex adaptive systems exhibit resilience, adaptation, and self-organization that are seen as valuable in social applications. While these earlier models provided insights and enjoyment, none of them delivered their lessons in the short interaction times typical of museums. These earlier works helped experts understand ant colonies and applied lessons learned to understand other self-organizing systems. Taking this previous use of ants as a means to understand, research, and teach complex systems, we designed a complex system model to deliver complexity learning in the short, open interactions normal for museum's educational experiences without the mess of installing 20 million safari ants in the Midwest.

Making Sense of Complexity

Chi *et al.* (2012) argued that all processes can be categorized into two types: sequential and emergent. All processes share seven characteristics:

(1) They can be described at the agent or at the pattern level[1]. In ant colonies the pattern level is the whole colony, whereas the individual is the behaviors of each ant. She provided the caveat that the agent itself is a collection of patterns at the micro organismal level. Though in some systems, we can leave this aside in studying sense making in complexity, the aside becomes important in ants. The colony is a superorganism, that is composed of a number of ants. The ants can be decomposed into microsystems like their microbiomes, and macrosystems like colonies, or collections of colonies. Mentally moving up and down these levels lets us think about causation.

[1] Our work describes this as the "aggregate" level. The word pattern suggests that there is not a pattern at the agent-level.

(2) At both agent and pattern level, agents can be clustered into aggregates of subgroups, such as chasing wolves or blocking wolves on a hunt, or workers that clean up a colonies waste, or forage for food.
(3) Behaviors can be distinguished into levels and behaviors can differ in different levels.
(4) At the agent level, behavior of agents can be conceived of as interactions between agents and not simply individual agents.
(5) Conditions that elicit behavior at each level differ.
(6) Processes can be visible or invisible. For instance, in our model, we hide the actions that occur inside each colony.
(7) Information about each level can be infinite, but misunderstanding them is not the same thing as lacking this information.

Processes, all of which share these seven characteristics, can be categorized in two ways – sequential or emergent. Sequential processes can be subdivided into a sequence of events, like an assembly line where the metal is rolled, pressed, stamped, and smoothed before being turned into cans and filled with tomatoes sauce. This is a process with multiple agents: the machines, their operators, and a manager. It makes sense to speak of sequential processes resulting from a single agent's actions. For example, we could say the manager increased efficiency of the assembly process by increasing the speed of the conveyor belt. Even though all the agents participated in the process we can focus on the goal setting manger's actions to account for the change. As a result, Chi *et al. (2012)* say one can give special controlling status to the agent that caused the change. And this control means that interactions at the agent level are done *in order* to reach the goal of producing cans of tomato soup. The causal mechanism that leads to the result comes from the summing of the assembly line's outcomes directed by the manager. Many people confuse this control when thinking about emergent processes.

Emergent processes, like ants searching for food, marching in orderly paths, or getting stuck in a doorway are slightly different. These processes result from each ant taking actions, where the result emerges from the repetition of the action, but no agent is in control. These processes are encountered in school standards such as osmosis and diffusion, electrical current and buoyancy. These processes also appear in serious issues for humanity like climate change and nuclear arms proliferation. In ant colonies we can see emergence (Wilensky, 1997; Wilensky, 1997b) in ants searching for food, then filing in a straight line along a scent trail toward food, made by each ant leaving pheromone as it returns. Then when the flow of ants returning from the food fades, the ants discover and construct new trails, and through feedback, select to file along that pheromone scent's gradient. The pheromone trail is a self-organizing process, that organizes ants without a central agent controlling their actions.

Users could understand this process as either a sequential process, where a queen tells them what to do, or an emergent process. In an emergent process, all of the agents follow simple rules of taking a random walk until they find food or a strong pheromone trail. If they find food they return it to the nest leaving a pheromone trail. If they find a pheromone trail, employing a hill-climbing mechanism (Russel and Norvig, 2016), they follow it toward the strongest scent; the strongest scent is always toward where the last ant just came from carrying food. An emergent process can be identified by four characteristics (Chi *et al.*, 2012):

1. Cannot attribute action to one agent, such as a queen.
2. All ants have equal status.
3. No actions are goal directed.
4. Pattern is a collective outcome.

As a result, Chi *et al.* argues that people misconceive emergent processes as sequential processes. "Misconceptions reflect the use of attributes of an alternative Direct Schema to explain non-sequential processes that ought to be explained by attributes of an Emergent Schema" (Chi, *et al.*, 2012, p. 12). They assume the emergent schema is missing for most students. We set out to test people's beliefs in direct or emergent schemas and to test whether a short interaction with an agent-based model might shift their schemas.

Chi posits that the direct and emergent schemas are incommensurate, that there are not transitions, and that emergent schema have to replace direct schema. Wilensky *et al.* (Sengupta and Wilensky, 2009; Levy and Wilensky, 2008) rejects the claim of incommensurability, and argues that many features of direct schemas, can be used to understand emergent phenomena, and there is a continuous back and forth between these schema. Some of the data we describe below supports that shifting in as little as 10 minutes.

Research Question

Working with agent-based models of insect colonies may improve students' understanding about macro level, emergent patterns, such as population graphs that result from all the agents' actions. In this paper we explore how users make sense of the self-organization of cooperation between ant colonies in competition with each other while they use an agent-based model built in NetLogo (Wilensky 1999). In this way, we are building off the arguments of Wilensky and Papert (2010) to test Chi *et al.*'s assumptions and assertions about emergent schema. Wilensky and Papert argued that people can better reason about populations when they can observe the individual agents in them:

> *Students can reason about and visualize individual animals in an ecology far better than they can population levels. They can draw on their own body and sensory experience to assess and/or design sensible rules for the behavior of individuals. They can therefore make much greater sense and meaning from the agent-based representations.*
>
> (Wilensky and Papert, 2010, p. 8)

We researched how users shifted their schemas when using the model of ant colony life. We asked the following question:

> How does an experience designed to facilitate change in users' direct schema affect users in a short interaction in a museum?

To test this, we specifically asked before and after the use of an agent-based model how ants know what to do, how they collect food, and how they deal with traffic. Each question was asked to elicit an understanding of people's emergent or direct schema. If they answered that it is the queen ant that tells them what to do, this would show direct schema of a single agent. If they answered that the collective action of all the ants following and leaving scent leads the ants to do what they do, it would show an emergent schema. If they said animal instinct guides them, we inferred whether they meant that some global force controlled the individuals (direct), or whether they meant that the agents' individual actions led to global patterns (emergent).

We coded the data for users pre- and post-gameplay for direct and emergent schema. We had four hypotheses:

H_1: *Users had a direct schema before and after* (Direct → Direct).

H_2: *Users had a direct schema before but changed to an emergent schema after* (Direct → Emergent).

H_3: *Users had an emergent schema before and after* (Emergent → Emergent).

H_4: *There was one more possibility, that people changed to a direct schema from an emergent schema prior, but based on previous theory (Chi et al., 2012), this seemed highly unlikely.* (Emergent → Direct).

Design: Agent-based Modeling Game for a Museum

We will describe our model/game and discuss the design decisions we took as a result of implementing in the museum, both of which we will describe next.

*The Game: **Ant Adaptation**, Agent-based Modeling in Museums*

With the *Ant Adaptation*, we aim to realize the promise of agent-based modeling originally illustrated by systems such as Gas Lab (Wilensky, 1997) or NetLogo Investigations In Electromagnetism (Sengupta and Wilensky, 2009), but in a rich tangible interaction form factor for walk-up-and-play use in an informal learning space. As shown in Fig. 2a, *Ant Adaptation* simulates two ant colonies side by side. It tracks a user's touch placed on the digital displays surface. The sensing area of the screen contains five widgets for each team. As demonstrated by the corresponding indexes in Fig. 2a: (1) At the top, there is a counter of the ants' population labelled "Black Ants" on the left, and "Red Ants" on the right. (2) The three widgets at the bottom left and right are sliders players can use to adjust their ant's size, aggressiveness, and the maximum amount of energy, or basically how long ants can walk without eating. Adjusting any of these sliders will change the Create Cost. These sliders can be adjusted at any time during the game to experiment with different settings. (3) In the middle, *Ant Adapta-*

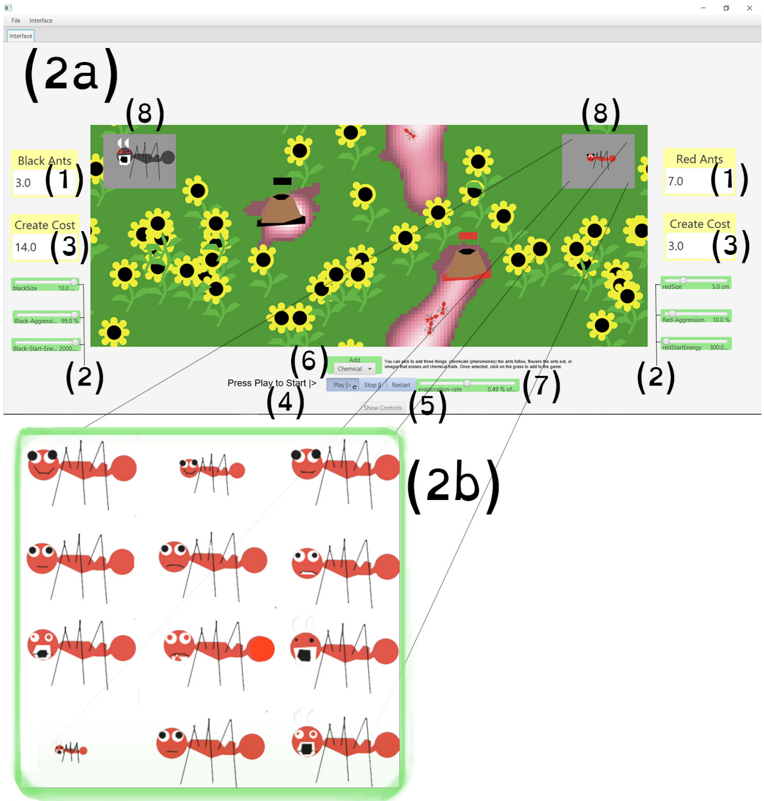

Fig. 2. 2a: Above, Ant Adaptation has two ant colonies that players interact with through touch and control widgets that count the ant population, display the cost to create another ant, and set what the user adds to the model. 2b: We see nine ant displays for varying aggression and size. There are 100 total possibilities to display providing immediate feedback to players as they adapt their ants.

tion provides a widget "Create Cost." The Create Cost widget shows the summed value that it currently costs to produce one more ant. This is an example of what Chi *et al.* call an opaque summing mechanism that NetLogo designers employ (2012), where "the collective mechanism is computed by the NetLogo system itself, thus [left] opaque to the students" (p. 21).

Specifically, the colony produces a new ant when the stored food is greater than the Create Cost. The cost is calculated by adjusting three sliders. A colony's Create Cost is equal to the current size of ants divided in half, plus the current aggressiveness divided by 15, plus the current maximum energy ants can pick up divided by 1,000. So if players set their ants to be size 10, with 100 aggressiveness, and starting energy of 2,000, each new ant would have a Create Cost of 14 food stored in the colony. In other words, because 10 / 2 = 5, 100 / 15 = 6.6, and 2,000 / 1,000 = 2, if we round up to the nearest integer, the Create Cost equals 14. Because the outcome of the calculation is the current cost for the colony to birth one more ant, this summing mechanism was the topic of many players' strategizing as they tried to maximize their populations.

To supplement NetLogo (Wilensky, 1999), we have developed software designed for touch interaction with the model, NetLogo Touch (Martin, 2018). The software allows users to adjust the slider widgets and swipe on the screen to interact with the model with their fingers. The users share five widgets in the center of the screen. As shown in Fig. 2a, (4) Play and Stop, which control the model's time. (5) Restart, which sets the model back to initial conditions. (6) Add, which allows users to control what is added to the model when they touch the screen. They can choose to add chemical, flowers, or vinegar. Chemical is a pink pheromone that attracts ants toward the highest concentration of it displayed in whitish-pink shades. Flowers are these ants' main food source. Ants collect and eat the flowers to feed themselves and bring food back to the colony for collective rearing of young. Vinegar erases ants' trails allowing the player to mask pheromones, disrupt communications, and clear the ground by applying vinegar to the chemical trails. (7) A slider to control the evaporation rate of pheromones. (8) Lastly, there are two representations of the players' ants in the top right and left of the play space. These show the user how large and aggressive their ants are when born. As shown in Fig. 2b, the display changes according to the mixture of aggressiveness and size the player chooses for their team. This provides the player immediate feedback for changing slider parameters, giving them a better sense of cause and effect in the model. This is important because adjusting the sliders only affects new ants born, instead of extant ants. So the effect of the interaction is longer than the 30 to 60 Hz, 16.6 to 33.3 millisecond periods, people associate with cause and effect within games (Gregory, 2014).

In this paper we present findings of how users shifted their schemas with our platform design by reporting on a deployment in a major natural history museum – the first deployment of NetLogo Touch (Martin, 2018).

In order to provide context for our analysis below, we describe action of the game with and without user interaction. Even without user interaction, in the game we created, *Ant Adaptation*, ants go out to collect food and return to the nest. As they return to the nest, ants lay down a pink pheromone that attracts others nearby. Other ants walk toward the strongest chemical smell, which in most cases is where the first ant just arrived. When ants find a flower, their food source, they return, lay down more pheromones, and thus reinforce the pink trail. This creates an emergent feedback loop that routes more and more ants to successful sites of forage. As the ants exhaust a food source, they must find new locations and thus repeat a cycle. When two or more ants of opposing colonies encounter each other, they fight or scare each other away also leaving chemicals that attract more ants. For the winner, this works to protect the food source from competing colonies. The ant queen reproduces when the ants in her colony collect enough food, in other words when collection surpasses the current Create Cost. Flowers periodically growing up around the map, add food to the game.

The player interacts with this complex system by adding pheromone trails that the ants follow, as well as adding sources of food (i.e., flowers) to the system, thus changing the amount of food in the game. Through interacting with the system, users form a functional understanding of the ants and their mechanisms of action (i.e. agents and their rules) in the model. This design scaffolds experimentation. Players must simultaneously

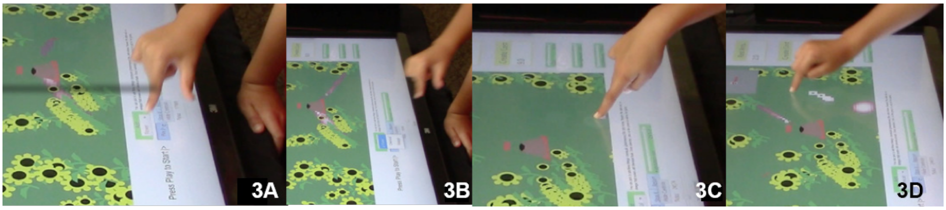

Fig. 3. John selects to add chemical (3A- 3B), experiments with the touch user interface (3C), and then lays down his first pheromone trail (3D).

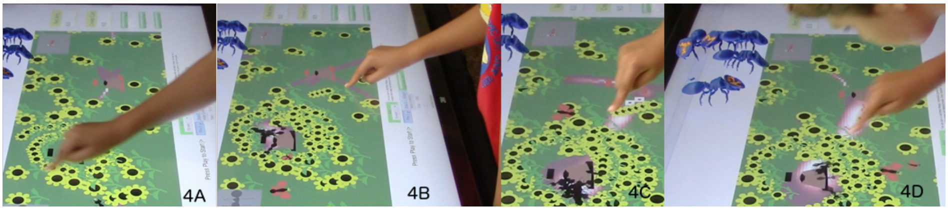

Fig. 4. Player draws flowers (4A), draws pheromones to lead ants (4B), tries to connect his two colonies (4C), and drives his ants through flowers (4D). Leaning forward as he becomes so engaged.

make choices. As shown in Fig. 3, players can touch the screen to add pheromones the ants will follow. As shown in Fig. 4A, at the flick of a switch, players can add more flowers anywhere they like in the game, acting like an ant or a seed, but with a bird's eye view. Lastly, they can choose to apply vinegar (Fig. 4B), which erases trails. Erasing trails was used by some game players (like Thomas, discussed later) to get ants out of a feedback loop that had them stuck in local optima, and was leading them nowhere. For players to achieve their goals in the competitive environment, they are required to understand the emergent consequences of simple ant behavior.

Players can decide how big and aggressive ants are. When the size of ants increases, they become slightly faster and stronger in a fight. Each level of increase adds up. At the highest levels they are 13 times stronger. When players make their ants more aggressive, it increases the radius in which ants detect opposing ants and thus the probability that they will attack. Increasing either the size or the aggressiveness also increases how much food is required to raise an ant, so the largest ant requires 13 times as much food to feed to adulthood. This gamification impacts how much food ants must collect to make a new baby ant. Increases in either of these parameters reduces the expected population of the colony, by increasing the Create Cost, though it increases their likelihood of fighting and winning through emergent interactions of parameters (size and aggressiveness) and agent actions (collecting food, leaving trails, and fighting).

This sets up the main action of the game as a series of strategic choices–to decide whether to pacifically collect food, thereby increasing the population, or to go on the warpath where big, aggressive ants conquer their opponents. Either method of play could lead to high populations or the elimination of the opponent through better-controlled food resources. For example, after learning about the consequences of strategic choices through gameplay, players strategize by increasing ants' size, aggressiveness, or both. This might lead them to win the game by annihilating the other group's ant colony. However, bigger and/or more aggressive ants consume more food to reproduce and potentially reduce the colony's population size. Thus, a player might strategize by adding more flowers and pheromone tracks around the colony to help the larger ants survive. This learning and strategy cycle interweaves the learning into the gameplay.

The game has four affordances that support two learning objectives. In *Ant Adaptation*, playing with parameters allows players to, (1) construct their colony in competition with an opponent; (2) share strategies through comparison; (3) discuss what is happening through observer scaffolding such as parents' intervention or interaction between players, including slapping hands; and (4) learn about the emergent impacts of colony behavior arising from individual ant behavior in a complex system game. This approach allows visitors to learn (1) the impacts of adaptation on ant colony life and (2) how attractants such as pheromones work in ants' organization to increase the population. These together have also the potential to scaffold learners in switching from a direct to an emergent schema. We built the game to be engaging while building off the literature of designing digital interactives for museums, which we describe next.

Designing Digital Multi-Touch Tables for Museums

Prior research on building interactives in museums informed our design. Current research on multi-touch tables for museums suggests several key design elements (Horn *et al.*, 2016; Davis *et al.*, 2015) such as enjoyment, comparability, and productive conflict. Enjoyment, expressed through affect words such as "whoa," "wow," "cool," and "hah," is significantly correlated with learning measures considered by Horn *et al.* (2016). Facilitating comparisons-aided learning in the case of a tree of life game where players who drew comparisons between lineages learned more easily and were more likely to use terms of interest in open-ended questions on post-tests. Block *et al.* (2015) and Horn *et al.* (2015) found that groups of two spend more time at an exhibit and engage more with scientific content than groups of three or more.

Finally, conflict can be productive. Davis *et al.* (2015) and Falcão and Price (2011) argue that interference between users on and across a multi-touch interface can be productive for learning when it triggers argumentation and collective knowledge construction.

From our review of this literature, we hypothesized that designers should encourage discussion and comparison in a competitive game mode where the biology and complexity science weave into the experience. To design this experience, we created interactive, agent-based, complex system tabletop games for museum settings that expedite learning in these short interaction times. As a result, (1) we implemented turns into the play, as Block *et al.* (2015) found that groups who take turns spent longer times and engaged more with biological content in the tree of life exhibit. Taking turns both increased the use of learning terms and comparisons with the biological content. (2) Our design included two teams, which allowed players to explore the game's possibilities and compare between strategies.

These two design elements facilitated comparison and discussion between teams. Exploration involves players moving their bodies and hands across a digital tabletop to engage in a game. This process engages the group at play more than mousing at a keyboard. We hypothesized based on Wilensky and Papert (2010) that a body in motion, talking out ideas would create a rich discussion and a problem-solving mindset around the game interface. The game includes hampering the competing colony through players' dexterity, or at times, physically blocking other players' hands to develop another colony's strength following on earlier work on productive conflict (Falcão and Price, 2011). This competition is mediated through the luck of the stochastic system. Trade-offs of adaptations and complex systems thinking are woven into the game, which allows users to explore and learn about complex systems and ants by making strategic choices both in the digital microworld and while standing in the museum. The design encourages talk and comparison to maximize learning about ant behavior, a complex system, in a short interaction at the museum. The argument is that highly engaged play with a compelling, complex, biological systems model teaches users about a complex system through open-ended play.

As shown in Fig. 5, in the deployment we set out a table, a large poster motivating the game, and the multi-touch display in a hallway of the museum where users could walk up and use the game. The hallway was a medium traffic zone chosen for better acoustics for recording interview audio.

As shown in Fig. 6, the poster scaffolds the interaction by proposing a scenario, that players should imagine they are playing as natural selection. Then it suggests some exciting adaptations ants have evolved. Then it suggests a few things to try, such as pressing Restart or Play. Finally, it poses several questions players should think about while playing.

Fig. 5. Setup of the game in the museum. Poster was set out to scaffold participants' interactions. A video camera recorded play sessions.

Fig. 6. Poster Displayed Scaffolding the Experience.

Methods

We tested the game in a major natural history museum outside of a large, popular exhibit. The game was used over a six-day period, and we ran a supervised treatment, with 114 visitors playing in 38 groups. Additionally, we ran the game unsupervised for two 30-minute segments on each of the six days. We collected video, audio, and field notes of all participants' play.

We developed the data in this paper by watching the videos during these periods of use and analyzed the transcripts. In the paper, we present coding of the pre- and post-gameplay interviews for the number of participants that held direct and emergent schemas before and after the intervention in groups that contained at least one participant less than 18 years old. Finally, we show through analyzing the video how one user, Thomas, taught his older brother, Ed, an emergent schema. Interestingly, he also was solidifying an emergent schema through his own interaction with the game and his family at the same time.

We analyzed each of the pre- and post-gameplay interviews for groups with at least one player between ages 6 and 18 years old. We analyzed 27 people (23.7% of the total participants) in nine groups (23.7% of total groups). We examined the participants' answers on three questions (Table 1):

(1) How do ants collect food?
(2) How do ants know what to do? and
(3) How do ants deal with a situation like traffic, where they all keep bumping into each other?

For each group there could be an answer for each individual, and so we coded each individual in the group separately. Often, however, one interlocutor answered most of the questions. We rated 20% of the data with two coders and had greater than 90% inter-rater reliability. Disagreements were discussed as a group and we reached a consensus.

In our coding, emergent schema was defined by four characteristics (Chi, *et al.*, 2012):

(1) The person cannot attribute action to one agent, such as a queen ant.
(2) All of the ants have equal status;
(3) No actions are goal directed; and
(4) The pattern is a collective outcome.

We used these characteristics to code users' statements.

We had four hypotheses about how participants would change after playing *Ant Adaptation* and discussing:

H_1: Direct → Direct

H_2: Direct → Emergent

H_3: Emergent → Emergent

H_4: Emergent → Direct

Table 1
Coding book for pre- and post-gameplay interviews Code Book

	Typical Answer Before	Typical answer After
Q1: Have you noticed anything about ants?	"They can carry, like 50 times their own body weight?"	"They make trails to follow."
Q2: How do the ants collect food?	"They use their snappy thingies. I can't remember what they are called." (Unclear)	"They would go and pick up a piece. And one by one keep working and working. They went off one by one to grab a piece one by one. Then they would bring it back to their ant. And then keep working and working." (Emergent)
Q3: How do ants know what to do?	"Well. They got big heads. They are really smart. They use their heads. They use their antenna to know what to do." (Direct)	"They just keep following the chemicals?" (Emergent)

Findings

We tested the game in a major natural history museum outside of a large, popular exhibit. The game was used over a six-day period by 114 museum visitors (87% White, 4% Black, 5% Asian, 3% Latinx). Of the players, 60 were male (51.57%) and 54 (48.43%) were female. This contrasts with the museum-wide attendance demographics of 70% White (difference of +16.61% points), 5% Black (difference of -0.54% points) and 14% Latinx (difference of -11.32% points). Fig. 7 shows players ranging in age from 2 to 55, with the age distribution skewed to lower ages. The average length of time people played was 387 seconds, as opposed to a museum-wide average interaction time with digital interactives of 105 seconds (as reported by internal museum evaluations).

The results indicate that the design held participants more than the average interactive experience in the context of the museum. Unlike Block *et al.* (2015) and Horn *et al.* (2015) we found groups of three or more spent more time at our exhibit than groups of two. Worryingly, the design seemed to appeal to certain demographics. When we bifurcated playtime by race and gender, however, we found that non-white users who engaged with the game were some of the most engaged users.

As shown in Fig. 8, fourteen of the seventeen non-white users engaged with the game for longer than four minutes. Though most players in our sample were white museum patrons (97), the non-white patrons engaged with the game longer than four minutes, on average. Because players could stop playing whenever they wanted, unlike a standardized test, this longer engagement is an interesting proxy measure for interest. More study is required to understand the implications of the design on the audience engagement.

In the results below, we will show that many participants of the 27 participants in 9 groups held direct and emergent schemas both before and after. A few shifted their schemas. Then we discuss the process two users had when they changed their schema through interaction with each other and *Ant Adaptation*.

We found that among the participants at the museum who played *Ant Adaptation*, before the game, five participants held an emergent schema and seven held a direct schema. After the game, 11 people held an emergent schema. Unfortunately, not all participants had a clearly defined trace apparent in their verbalizations. In other words,

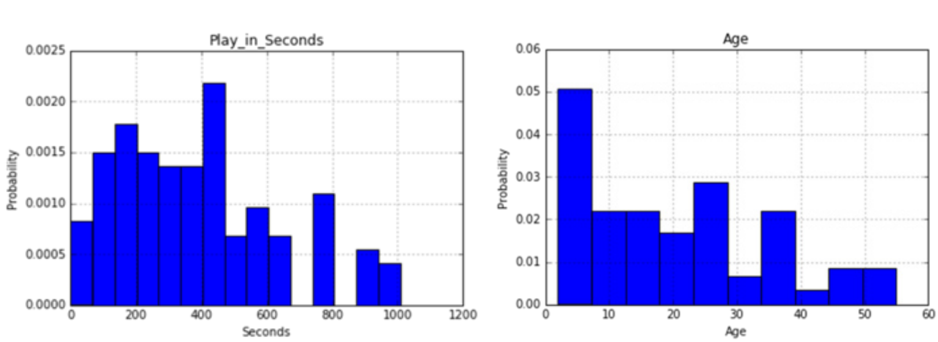

Fig. 7. Histograms of play time show that most players engaged for 400 seconds. The average age was 20 with a sizable number of players under 10 and some as old as 55.

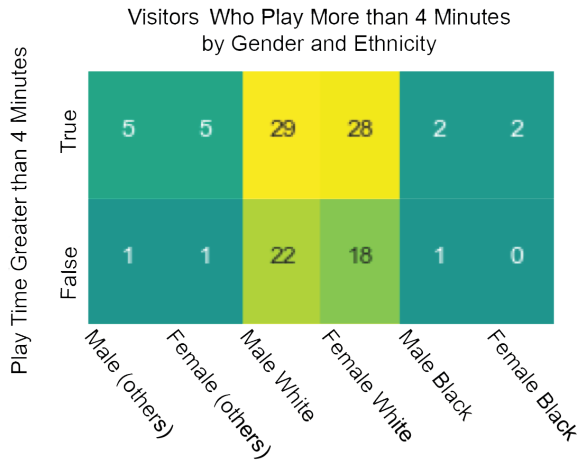

Fig. 8. Heat map of visitors' interaction time above and below twice the museum average play time (4 minutes) by ethnicity and gender. We see the majority of players, in the middle, were white. Notably, of the 17 non-white players, 14 played for twice the average engagement time in museum interactives. Visitors were gender balanced.

not all participants verbalized a codable utterance both before and after play. As such, only seven of the participants had a discernable learning trace on this item. In other words, seven participants made a statement that we could code as a schema both before and after play.

As shown in Fig. 9, we found that three people switched their schemas after playing *Ant Adaptation*, and none switched from an emergent schema to a direct schema. To be counted in Fig. 9, users had to have a learning trace, with a demonstrated schema both before and after play. This limited the sample due to language ambiguities or users not responding to the protocol completely.

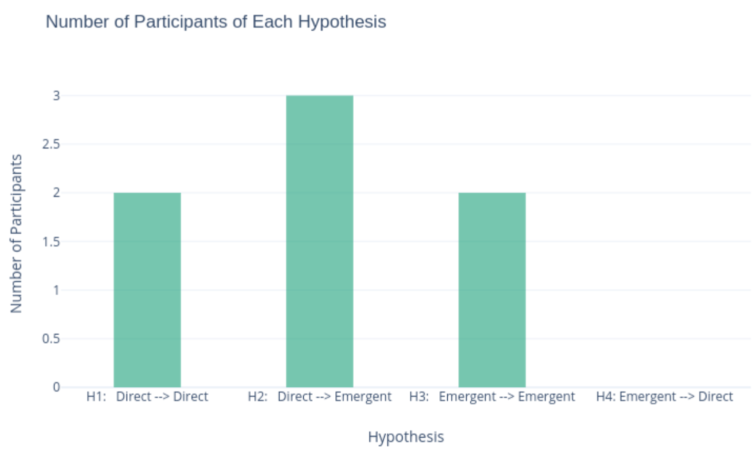

Fig. 9. Four participants held their schema constant. Three participants switched schema from direct to emergent.

H_1: *Users had a direct schema before and after*

As shown in Fig. 9, two groups with children under 18 years of age held direct schemas both before and after playing *Ant Adaptation*. Both Stacy, a seven-year-old girl in Group 20, and Pri, a sixteen-year-old girl in Group 27 held their original direct schema. When asked what she knew about ants, Stacy said, “They move around a lot. They follow paths. They are always in the cracks of cement.” When asked how ants collect food, she said, “They collect it. They go and collect it.” When we asked how ants deal with traffic she said, “Set paths.” For Stacy, paths seem to tell the ants what to do. She did not talk about how ants’ actions construct paths. Thus, she sees it as a one directional effect on ants. Afterward, her direct schema was reinforced by the game. When asked about how ants know what to do, she said, “Pink stuff kind of leads them where they want to be. But if you put too much in one space it becomes a problem, because they really don’t go anywhere else.” Here she describes the paths as organizing, and at times determining ants’ final location. She had no awareness of ants’ own actions mutually constructing paths and directions. Pri likewise held onto her direct schema. Beforehand, when asked how ants know what to do, she said, “I think [they] navigate earth’s magnetic field,” indicating that a pervasive global force directs the ants. Afterward, she argued that they follow paths to “where the ants are supposed to go,” indicating a controlling nature of pheromone trails.

$H_{2:}$ *Users had a direct schema before but changed to an emergent schema after*

As shown in Fig. 9, three participants in two groups changed their schema from direct to emergent. For example Ed, a thirteen-year-old white child in Group 10, while playing with his younger brother Thomas, changed from a direct schema to an emergent schema after playing.[2] Before the game, he had some idea about ants. When asked what he knew about ants he said, “They can carry 50 times their body weight”, indicating that he has heard about ants in some cursory way. When asked how they collect food he said, “They, they scavenge for they--they’re scavengers,” which indicates he knows something about different animal feeding habits. His brother, Thomas, age nine, then interjected, “Like, they can like go hunt for food. They can like, um, try like, get to some, like, maybe some food on the ground like in the city or like in a park, or they can just eat a leaf.” The interviewer immediately asked them how the ants know what to do. They replied with a direct schema:

Ed: *Um, animal instincts.*

Interviewer: *Animal instincts.*

[2] An additional group also changed from direct to emergent schema, but their interaction was half in Chinese, and so while we translated it, due to the nuisances of language we feel presenting it here would go beyond the current study. We will present it in future work, as it may contribute a cross cultural dimension to emergent schema.

Ed:	*Or the queen tells them to, if there's a queen ant. I don't know.*
Interviewer:	*So what's the diff--how does the queen tell them to?*
Ed:	*It's something with their antennas [sic].*

Ed thinks either a global force of animal instinct or the queen provides ants directions. His younger brother Thomas seems to agree with him but does not verbalize completely. After playing *Ant Adaptation*, Ed changes his mind. And Thomas became more clear about how he was thinking about how ants are directed.

After playing, Thomas held an emergent schema. When the interviewer asked the group how to play the game, Thomas argues that feedbacks plays a big role:

Thomas:	*If you just do one path that leads to the sunflowers ants will just get the energy and just keep going back and forth and back and forth and that's how we got 21 [ants].*
Interviewer:	*And how did they get--how do they go back and forth and back and forth? What are they doing?*
Thomas:	*Like they bring the energy back, then keep going. It's like a cycle.*
Interviewer:	*So how do they know to go back to that same place instead of somewhere else?*
Thomas:	*Because they just keep following the chemicals.*

Here Thomas articulates (1) if there is a path, ants will follow the path, (2) ants bring back energy that creates a cycle of fetching food and following a path, and (3) that this cycle leads to their highest population of 21 ants. Taken together, these three points indicate that Thomas understands the role of ants in following paths cyclically leads to higher population. This is a connection between the micro-level agents' actions and the macro-level pattern of population change. His older brother Ed agrees with Thomas. After Thomas' explanation, when the interviewer asked Ed what the pink chemical does, he said, "It attracts the ants to a certain location." And Thomas affirms him, "Yeah, it does that." Because this coding is crucial to our analysis there is one caveat to it. The interviewer did not ask them, as the protocol dictates, "How do ants know what to do?" From watching the video, and his self-report, it seems he was about to ask but hesitated, because, it seemed to him in the moment that he would get the same answer of the question. The participants had already established that they think ants follow chemicals. So instead, he asked Ed, "What does the pink chemical do?" to check if Ed agreed with Thomas. Therefore, we argue that in this context, "How do you think the ants know what to do?" and "What does the pink chemical do?" are the same question in different formats. Thus, we think the participants hold an emergent schema. In other words, these two visitors do not think ants follow the queen but the chemical, which they lay down to form cycles of food collection.

H$_3$: *Users had an emergent schema before and after*

As shown in Fig. 9, two users, a 37-year-old mother and a 19-year-old participant in a second group, both accompanying younger participants, held an emergent schema both before and after the intervention. These were beyond the scope of this paper, which is examining school age children's change, but we hope to explore these cases in future work.

H$_4$: *Users changed from emergent schemas to direct schemas*

As we mention, there was one more possibility, which is people changed to a direct schema from an emergent schema, but based on previous theory, (Chi *et al.,* 2012), this seemed highly unlikely. Indeed, as shown in Fig. 9, we found this never happened in our data.

It should be kept in mind, that of the 27 people in the 9 groups who played the game, our coding only found seven people with a learning trace, who we could clearly code both before and after play. In future, we want to improve our coding schema, and protocol to more deeply understand the processes and frequency by which people change their mind about process schema. After completing this coding for frequency, our question became how did Ed change his mind? What process of change during the game affected him? Below we will present and analyze the experience in more detail.

Ed Changes his Mind

Ed, Thomas, Sam and Sally ages 13, 10, 7 and 6 played the game together. The group was all white. The experience started when an interviewer asked if they wanted to play a game about ants. When they agreed, along with their parents, we told them about the study. Then after consenting, standing by the multi-touch display, Thomas watching the display, and Ed standing off to one side to represent the group, the interviewer asked them a series of questions from a semi-structured protocol. When they were asked, "Have you ever noticed anything about ants," the oldest, Ed, showed some prior knowledge. When we checked how much they knew about ants self-organizing behavior they showed some conflicting idea of the process:

Interviewer:	*How do ants collect food?*
Ed:	*They, they scavenge for they--they're scavengers.*
Interviewer:	*What do you mean?*
Thomas:	*Like, they can like go hunt for food. They can like, um, try like, get to some, like, maybe some food on the ground like in the city or like in a park, or they can just eat a leaf.*

To clarify how ants, know what to do, following the protocol, the interviewer next clarified how ants know to scavenge. With this question we were identifying whether the visitors had a direct schema, or an emergent schema. They offered both:

Interviewer:	*Okay. That's fair. And then, how do ants know what to do? So you said they pick up leaves, or they scav enge, but how do they know to do that?*
Ed:	*Um, animal instincts.*
Interviewer:	*Animal instincts.*
Ed:	*Or the queen tells them to, if there's a queen ant. I don't know.*
Interviewer:	*So what's the diff--how does the queen tell them to?*
Ed:	*It's something with their antennas [sic].*
Interviewer:	*Okay.*
Ed:	*I think.*

Here Ed offers the idea that queen ants control all of the other ants somehow through antennae, or the ants individually have an "animal instinct" that organizes behavior globally. The first idea is a direct schema. The latter possibility could either be an emergent schema, in which each ant follows simple rules that emerge in a pattern; but it seems more like a direct schema, wherein a global force animal instinct is giving orders.

To clarify this dual understanding, next in the protocol we asked how ants would deal with traffic.

Interviewer:	*Fair. Okay, so let's imagine we're in a colony and there's all those ants. How do you think they deal with something like traffic? Are they all bumping into each other? How do they fix that?*
Thomas:	*They make paths.*
Interviewer:	*They what?*
Thomas:	*Make path--more paths.*

Thomas indicates that the ants organize by constructing paths to get around the emergent issue of traffic. While not very elaborate, this seems to indicate he may already have an emergent schema in that he organizes his thinking through self-directed activity. Alternatively, we could interpret this to mean that ants are ordered, by the queen or animal instinct, to accomplish the goal of constructing more paths.

Thus far, Ed is of two minds, either ants are organized by their internal instincts, or the queen directly tells them what to do. Through the intervention, on the one hand, Ed shifts his understanding, which seems to annoy him. On the other hand, Thomas builds on his understanding of self-directed behavior, which he shares with his family.

In summary, before the game, when he was asked how ants know what to do, Ed said he thought it was animal instinct or that the queen tells them what to do. He also suggested that there is something in their antennae that makes them do what the queen tells them to. To us, this is the direct schema because he attributes ant behaviors to a higher power, whether instinct or the queen ant.

The Instructions to Play

The interviewer then explained the game. First, the interviewer organized the four players into two teams, then he showed them how to set the size and aggressiveness of their ants by moving sliders all the way to the right. Then he instructed the players in using the selector to choose to add chemicals or flowers to the game by touching the screen, and he reminded them to take turns. He demonstrated ants following his finger as the chemical is placed, and showing the flowers appear as he drags his finger across the screen. Then, he said that with the chemical "you can kind of control them." Then he showed how increasing each slider increases the "Create Cost," or how much food the ants would need to collect for the colony to reproduce another ant in the colony. Afterward, players chose how big and how aggressive they wanted their ants by talking to each other and setting their sliders.

The Game Play

Ed says, "I don't want to be too aggressive" as the two teams stare at the touch screen. Then Sam touches the sliders on his side to increase the size of their ants, and the little sister increases their ants' size. Ed and Thomas adjust their controls and say, "We will be [size] seven. No, six." Then they ask each other "Ready?" Sam controls the screen pressing Restart and then Play.

Ed asks "How do I create?" tapping on the "Create Cost" widget on his side of the display then placing his finger on the screen he says "Boop," as if to imitate the interface feedback he is expecting when playing a game and pressing a button. He expects to be able to intervene in the game and add an ant directly. Thomas then says, "Make more flowers." It is ambiguous whether Thomas is responding to Ed, because as he says it, he is placing flowers on the table. Meanwhile, Sam is pressing on his Create Cost widget mimicking Ed's action moments before.

They proceed tapping the screen. Then Ed asks, "How do I do this?" Thomas shows him how to add flowers. And Ed imitates him, adds his own flowers, and says, "Here have some flowers," as if he is talking to the ants.

They then lean back a bit and view the ants as they collect the food they have put next to the colony. Ed says, "They are gaining food, I think." Thomas adds some more flowers close to the colony and says, "We have 15 ants." Then he turns a bit toward Thomas and says, "Just keep doing what you are doing." When a flying ant emerges, Thomas asks, "Is that a queen?" Then pointing at the population counter on the heads-up display of their ants, he shows he understands the population level. "We have 21 black ants." Following up he says, "Hey look at our aggression," while he points at the heads-up display widget controlling aggression. Then Thomas and Ed stop playing. Ed says, "Ahh we're doing pretty good, I'm just gonna let it do its thing," indicating he understands the ants are organizing their own behavior.

Then Ed suggests an intervention. "Oh wait, we need chemical. Excuse me," he says and pushes Thomas' hand out of the way while he was adding flowers right next to the ant colony, and begins to just place chemical everywhere first, but then says, "We need to draw," and starts trying to draw the ants to the flowers. "We need to get all these flowers. All of these." Thomas then inquires, "We have 16 ants. What is going on?" His head leans forward as he examines the contest. Then Ed starts to take control of the ants, forcefully drawing a pheromone trail he says, "Go this way." It sounds like he is trying to order them. But instead he has added the chemical in such a way that the ants are going in a circle, getting stuck. When they don't do as he wants he says, "Vinegar will kill everything. Kill everything." Thomas switches to the vinegar and begins to erase the ants' pheromone trails. He methodically removes the pheromone from between the flowers and then from around the colony. Ed then says, "OOOOOOOOooohhhh I see what you are doing. Smart." And then they start drawing the ants toward them by laying down new pheromone trails.

Thomas shows he knows that misplaced pheromones lead the ants astray. When Thomas adds new pheromones, he always adds them starting from the colony so that that ants will walk towards the most intense part of the trail. When Ed adds pheromones to the screen not originating from the colony, Thomas swats his hand away, demonstrating he has a theory of the optimal placement and direction of pheromone trails.

Thomas teaches Ed that the direction of pheromones leading successfully toward food increases the ants' population. As he draws the pheromone trail to the flowers closest to the nest he says, "See they are adding more energy," indicating that the ants gathering food increases the colony's energy. Ed says he will just watch, arguing, "You know what you are doing, so I will just watch," and leans back a bit setting his hands on the edge of the table the screen is sitting on. Thomas then crosses his arms and says, "All right let's just see it go on." Meanwhile, Sam has also learned through watching these two to use pheromone trails to direct his ants, drawing a long pheromone trail from Thomas and Ed's colony to his own, potentially confusing Thomas and Ed's ants. Thomas realizes this and says, "Hey, hey, hey!" demonstrating annoyance with the first aggressive move of the game. Through scaffolding, Thomas taught both his older and younger brother how to draw pheromone trails so that the ants interact with them, and how to use them to have the ants initiate a feedback loop of grabbing food and returning it to increase the population. When Sam tries to add another trail, Thomas hits his hand. "And that's when you ruined our plans," Sam responds. When they stop messing with it Thomas bemoans the falling population.

Thomas:	*We have four. We have three--what? We have five, yo. That's even worse than what we had. We used to have 20 [ants].*
Ed:	*It's like--we had like 21 [ants].*

Ed corrects Thomas, indicating they both think their population has fallen. Then to recover, they see their ants are fighting the red ants. Thomas says, “Vinegar. They are not getting enough [food]”. Ed echoes the idea and says, “Clear out everything.” He swipes his finger over the fight to try to clear the fight. Then even Sam reaches over and tries to help clear the fight out.

All of the sudden while they are trying to break up the fight, Thomas and Ed’s colony dies. “Wait what?” Thomas says. “Oh wait, where--where--where’d our thing go?” Ed responds in reference to their colony. Sam celebrates, “We’re won it--we’re--we won!” Sally joins in, “Yay!” Ed seeks confirmation, “Wait, we died?” Sally says, “It was smart to get some food,” but Sam is a little less gracious about Thomas and Ed’s play. “Cheaters,” he says under his breath. Ed responds, “Cheaters? How do--I don’t--I never knew how to play the game in the first place,” referencing again that he did not feel completely in control of the scenario.

Unprompted, Thomas offers why he liked the game. “Yeah, you had to figure it out and the-- you have to have some flowers, see, and then you put the chemicals and lead it to there, then they’ll bring it back, and like, if you want to get rid of the chemicals you use the vinegar.” He says this as if he is teaching his siblings, telling them what they should think of the situation. Additionally, it shows he now understands that drawing trails to flowers starts a process where the ants will bring food back to the nest. He then mentions that if the process goes wrong, you can use vinegar to break them out. He then goes on and links this process to a repeating cycle that leads to a population level change. “So, um, you put some sunflowers down, then you get the chemicals and lead it to the sunflowers and if--if there’s too much then the ants aren’t getting the sunflowers and you--then they’ll just like, then you use the vinegar and erase it. But if--if you just do one path that leads to the sunflowers, it’ll just get the energy and just keep going back and forth and back and forth and that’s how we got 21 [ants].”

Thomas’s breakthrough was reflected in Ed’s change of how he thought. He moved from his equivocal answer that the queen controls the ants to a more nuanced view.

When Ed was asked whether this game shows an ant colony or a computer program, he answers, “ants,” reasoning that because the ants would not listen to him, they must be ants and not computer programs. His answer implies an assumption that programs should be controllable. When asked whether he thinks this game is scientific, he answered, “Definitely,” because ants in the game would not follow his direction.

Though the interviewer did not ask the question, “How do ants know what to do?” from his answer, it appears that Ed started changing the schema from direct schema to the emergent one. He used to think that the queen might direct ant behaviors based on his answer to the pre-gameplay interview. And in the game the players attempted to play the agent role of the queen ant directing others. We infer this may be because as a gamer, he has assumptions he is in the game as a leading agent with the higher hierarchy than other agents in the video game. Instead, it appeared to him that no other agents followed his orders as the queen. In other words, he learned ants were self-organizing, and that annoyed him. He had an expectation of the video game that as the player he was in charge and through the intervention came to understand ants as autonomous, non-goal-oriented agents in the system.

Discussion

The example of Ed changing his mind could be alternatively interpreted. He could have ceded the idea that he knew how the game worked. In that analysis, he did not change his mind; instead, Thomas stated an emergent schema and Ed simply parroted his younger brother to avoid the embarrassment he seemed to be manifesting in his inability to understand the game. Regardless, the presence in our data of people who employ an emergent schema both before and after, and the potential that some of them changed their mind through play indicates interventions like this one may be able to effect rapid change on people's emergent schemas. Given that experts have employed emergent schemas to understand crucial situations like climate change, global oil markets, and nuclear proliferation, we find the potential to increase people's use of emergent schemas through this restructuring, or restructuration (Wilensky and Papert, 2010), of informal learning important. So finding emergent schemas in a single data collection, and some evidence that a short museum intervention can impact participants' thinking is a hopeful development in complexity education. It seems we can design practical small scale interventions that move the needle on the dissemination of this difficult and important mental schema to understand multi-party, multi-level interactions, such as currencies' value.

One limitation of this work is that we have no data on whether these ways of thinking about a complicated situation transferred beyond this scope or impacted longer-term thinking. Another limit is that we could not track the parts that affected Thomas and Ed's mental construct development. This second limit we will address in a forthcoming paper (Martin *et al.*, *in press).*

One design feature we found during testing NetLogo Touch was that the close timing of players' actions with changes, such as adding pheromones to the model, change how ants move, and may have accelerated learning about pheromone trails. In digital game design, it is often argued that when actions and results happen within one frame, or approximately 10 milliseconds, connections between cause and effect happen better. This seems important when designing future complexity learning games. When effecting change, people need to map between the actions they take and the results. For instance, here we present them with tangible controls, to control the model, and see how the agents respond to those actions. This is not unique to *Ant Adaptation*. Every agent-based model uses a control interface to allow the user to directly control the conditions of the simulation and through observation form an understanding of (1) How the agents in the model react, and (2) The patterns or outcomes of the model, i.e., the emergent phenomena of interest. Using a mouse and keyboard to change sliders, or in this case a touch-screen to affect this controlled observation, allows the user to come to understand an emergent pattern, a process, through repeated observation. So though touch-based manipulation is different in the user interface, it is not fundamentally different in the fact that the user learns by employing a user interface to control the agents and observe their simple rules. The difference here is the effect of touching the model, and how the agents react to those changes is much faster, usually within milliseconds. It seems this closer connection between cause and effect may hasten users' learning with the model. Further study will be needed to explore this, but it seems an exciting avenue for future learning game design research. But if it bears out, we will likely make the sliders directly affect extant ants on screen's size and aggressiveness, instead of only changing the attributes of the ants born afterward.

The approach developed here can allow us to identify and describe learning by examining how players reconstruct provisional theories considering dialogue between theory and evidence (Wilensky and Reisman, 2006). Through this approach to teaching natural history in short interactions, we can bring theory-building to players, who can, like Newton, Einstein, or Darwin, organize abundant data as part of the theory they are building (DiSessa and Cobb, 2004). The decision built into the main action of *Ant Adaptation* – whether to peacefully collect food to increase population by employing feedback cycles, or go to war to eliminate their opponent – sets up a crucial engagement where the uncertainties make the testing immediate and productive (D'Mello and Graeser, 2012).

Conclusion

One young man seems to have shift his schema from a direct to an emergent schema through interacting with his younger brother around a game in a museum. We built the interaction particularly for museums.

Our design had its intended draw to users. The design of the experience drew users in, with people playing for up to a quarter of an hour with average playtimes over twice the normal interaction times with exhibits in the natural history museum. In light of the engagement with this design, we conclude it reasonable to extend the design principles of *Ant Adaptation* and create complex systems arcade for natural science learning in informal settings. The game in the museum had the following four perceivable effects:

(1) Construction of their own colonies, in competition with an opponent, afforded comparisons, which allowed for dynamic theory validation and imitation. For example, Thomas placing ants close to the nest and drawing ants to them by laying chemical trails showed he understood proximity and connection to flowers to the nest aided population growth. This is an example of learning to make micro- to macro-level connections through an agent-based model.

(2) The other team copied his strategy. Sharing strategies allowed players to update their operating theory.

(3) Taken together, these scaffolds facilitate players' exploration and learning about the complex system.

(4) Within less than a quarter of an hour of play, the game facilitated one player to switch from a direct schema to an emergent schema during a conversation with his brother.

People have argued that learning about complex systems is hard (Chi *et al.*, 2012), and for an individual it is. When people engage part of a complex system, attempt their best theories in real time, and receive dynamic feedback from the computer and each other, we can design better ways to facilitate complexity learning. These learning moments may happen most when they notice breaks where to get out of their confusion, learners must engage in effortful – intense, purposeful, psychological effort – and problem-solving activities (D'Mello and Graeser, 2012). That effortful solving activity is the process of science, and that is the process players in *Ant Adaptation* took. While Ed vocalized most of the learning, Thomas was showing him how, and their younger siblings tested their approaches and copied them. During this research, we noted that the social aspect of the multi-touch interactive allowed discussion to guide the theory exploration. As a result, in future work, we hope to better share the joint sense making mediated through technology and each other.

We claim that an interactive game – built around a complex, multi-agent model of ant behavior placed in a public space in a large museum – not only attracted many interested players but shifted at least one of these players' schemas from a direct schema to an emergent schema about how ants know what to do. In other words, a computational environment, thought to be extremely difficult to understand, can elicit complex learning behavior in a few players in an informal setting that lasts only for short periods of time, less than 15 minutes. This learning happens through group discussion around a game on a touch screen through self-directed learning.

The theory-building exercise at the heart of the game was engaged with in the process of this motivated play. The game afforded that type of play to happen. This work, in short, expedites the activities found in earlier agent-based modeling and theory-building exercises that have been used in schools and with swarm intelligence researchers. The design allowed us to work in a novel context – fast interaction times typical in informal learning environments.

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[3] `https://tidal.northwestern.edu/`

[4] `http://www.ccl.sesp.northwestern.edu/`