Handbook of Research on Serious Games for Educational Applications

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A volume in the Advances in Game-Based Learning (AGBL) Book Series

IGI Global
DISSEMINATOR OF KNOWLEDGE

www.igi-global.com

Published in the United States of America by
IGI Global
Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

CIP Data Pending
ISBN: 978-1-5225-0513-6
eISBN: 978-1-5225-0514-3

This book is published in the IGI Global book series Advances in Game-Based Learning (AGBL) (ISSN: 2327-1825; eISSN: 2327-1833)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

For electronic access to this publication, please contact: eresources@igi-global.com.

Chapter 7
Designing BioSim:
Playfully Encouraging Systems Thinking in Young Children

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ABSTRACT

In this chapter, we discuss the design decisions made when creating the game mechanics and rules for BioSim, a pair of game-like participatory simulations centered around honeybees and army ants to help young children (ages kindergarten through third grade) explore complex systems concepts. We outline four important design principles that helped us align the games and simulations to the systems thinking concepts that we wanted the students to learn: (1) Choose a specific and productive focal topic; (2) Build on game mechanics typically found in children's play; (3) Purposefully constrain children's play to help them notice certain system elements; and (4) Align guiding theories to game rules, and vice versa. We then highlight how these guiding principles can be leveraged to allow young children to engage with complex systems concepts in robust ways, and consider our next steps and goals for research as we continue to iterate and build on these games.

INTRODUCTION

Recognizing the many interrelated systems at play in the world around us is difficult. Many adults have trouble understanding systems, such as how many different living creatures interact to survive, or how highway traffic is produced, as decentralized and multilayered (Hmelo-Silver & Azevedo, 2006; Resnick, 1999). Systems thinking allows us to better understand how these many systems that we can see in the world operate. However, the majority of learners do not fully understand the ubiquitous systems around

DOI: 10.4018/978-1-5225-0513-6.ch007

us on a deep level. This has led to several efforts to strengthen education around systems thinking, or systems literacy (Booth Sweeney, 2012) and make these concepts clearer at earlier ages (Assaraf & Orion, 2009; Danish, 2014). One promising approach to helping young students learn about systems concepts is to have them engage in games which allow them to take on a new perspective within a system, and thus help them to appreciate the system dynamics at play (Peppler, Danish, & Phelps, 2010).

In our work on the BioSim activities, we engaged in iterative design-based research (Brown, 1992) to explore how to support these ideas through gaming. First, BeeSim (Peppler, Danish, Zaitlen, Glosson, Jacobs, & Phelps, 2010), was created as a "game-like" participatory simulation -- an embodied experience where participants interact to form the simulation, and are supported by computational technologies (Colella, 2000) -- for young children that provides a first-person look into the life of a honeybee and the complexity of nectar foraging behaviors. In BeeSim, students in grades K-3 wear electronically enhanced bee puppets to "become a honeybee" and work together to collect nectar from a field of electronic "flowers." They also communicate with one another through waggle dances, a real-life phenomenon through which honeybees share locations of known nectar sources. BeeSim stemmed from, and is paired with BeeSign (Danish, 2009; 2014), a computer software simulation that provides the third-person perspective ("bird's-eye view") of this honeybee system. Recently, we have expanded this work by designing AntSim; looking at complex systems through army ants gives rise to analogous systems concepts, making transfer an interesting possibility, and both insects offer familiar and fascinating lenses into how systems work.

This chapter explores the design decisions made when creating the BioSim set of games to help children engage with complex systems. We work to address the following questions: How do we design games to be simultaneously educative and engaging? What tensions arise in the design process when trying to parallel what is known about complex biological systems while essentializing them into a simplified model of game play? We use our latest game-based iterations and refinement of BioSim as illustrative examples of the inherent tensions in the design process of creating serious games in science.

This chapter is part of a larger NSF-funded research project that is currently in progress. Current and future research aims to conduct full-scale interventions in early elementary classrooms to iteratively refine both our designs and the undergirding theory guiding this work. To date, early pilot implementations with small groups in after-school clubs have spurred crucial technology iterations, and allowed us to fully test out the activities with our target age group. One of these implementations is described below to help readers visualize the excitement and engagement that occurs during the curriculum.

A Scene from BeeSim

Six young children in two groups are busy, each group hidden behind large swaths of bright yellow fabric. This fabric indicates there are two hives, and the children are pretending to be honeybees searching for nectar to bring back to their hive. They need to come up with a method of communication to share good nectar sources with their hivemates, but they cannot point or use their voices. One group is having trouble -- they don't know what their sign system should be. The facilitator suggests they think about other signs and signals they've seen around them. Do any of them play sports? One active boy in the group lights up. "Baseball!" His group decides they will swing an imaginary bat toward the right or the left of the room to indicate which direction their teammates will find the desired nectar source. The other group is attempting to emulate a real honeybee's waggle dance. They scurry around in little figure eights, waggling their bodies in the direction of the flower.

When it is time for the game to begin, they line up inside their hives, excited and fidgeting, with larger-than-life bee puppets in their small hands. The facilitator presses a button on the computer and says, “Go!” Lights flash on the puppets, and one child from each hive darts into the field. They quickly survey the landscape and make a choice to explore individual flowers. One girl realizes she has found nectar at the first flower she explored. “Yes!” she exclaims. She quickly fills up and scurries back to the hive to share the good news. Once back inside the hive, she shuffles around in her figure eight, hoping that her message has been conveyed as the next little bee heads out to the field.

The boy from the other hive has not had as much luck. He checks three flowers before finding one with nectar. He does not pause to pick up any more, rather immediately running back to his hive to swing an imaginary bat toward the right side of the room for his fellow bees. In the end, the hive with the baseball swings collected more nectar than their waggling counterparts. “If this hive collected more nectar than the other one, what does that mean?” The facilitator asks. “It means they’ll have more nectar for winter,” answers one slightly disappointed girl from the waggling hive. Undeterred, this team is determined to improve. With the help of an adult aid, they decide that they need to convey distance as well as direction with their waggle dances because they wasted time checking the wrong flower in their prior run. Borrowing from the honeybees themselves, they decide to waggle faster for a close flower, and more slowly for flowers that are farther away.

In our initial run of BeeSim, we did not show the students the simulation screen, rather focusing on how they interacted with the e-puppets. In the more recent pilots, however, we have two screens that the teacher and students can interact with. First, during the actual simulation there is a simple “hive” display, which depicts the one or two hives that are part of the game, and allows the students to see how much nectar is present in each. This supports them in comparing the speed and success of their hives. The second is a full replay of the prior simulation that is organized around key events (e.g., collecting nectar or returning to the hive). Much like a video replay, this allows the students to see the simulated bees which mirror their own actions move from the hive to a flower, collect nectar or find it missing, and move on. We have been able to use this as a reflection prompt to ask students what led to specific actions or outcomes, and why. For example, we noticed early on that many students who found nectar nevertheless continued to search for new flowers, which is rather inefficient. When we were able to replay the simulation, we could easily highlight these moments and ask the students to not only explain, but begin to recognize the inefficiency of this.

BACKGROUND

Games and Participatory Simulations

One interesting definition of a game comes from philosopher Bernard Suits: “To play a game is to attempt to achieve a specific state of affairs..., using only means permitted by rules..., where the rules prohibit use of more efficient in favour of less efficient means..., and where the rules are accepted just because they make possible such activity....” (Suits, 2005, p. 190). This emphasis on rules may unnecessarily exclude some engaging games and activities, but for our purposes, designing games for learning involves a great deal of thought about these rules and constraints. For us, this means that children playing our game for learning try to reach a goal in a way that isn’t necessarily the easiest or quickest way. For example, the quickest way to tell other bees/players about a nectar source might be to simply point and say "I found a lot of nectar in that pink flower on the left." However, using this method of communication ultimately does not convey the work that honeybees do to collectively gather nectar. With this in mind, there are other things we think games for learning should involve. Fun has been a controversial topic in the past, with some opting to look at engagement alone instead. While "fun" can be difficult to measure or observe, engagement can be seen in voluntary prolonged attention and involvement. However, we do hope our activities are fun and that children will want to play, leading to sustained engagement.

There has been much thought about why games (often video games) can be good for learning. In his book *Good Video Games and Good Learning*, Gee (2010) outlines several ways video games help players learn about the game such as just in time information, distributed knowledge, systems thinking, and meaning as action. He conjectures that these elements would be useful if mirrored in schools and other learning activities. While BioSim is not a video game, we think some of those elements are present and important for making it a good game for learning. In particular, Gee's principles of systems thinking and meaning as action (Gee, 2010) are well aligned with the core goals of BioSim. Gee describes how games themselves are complex systems, as they encompass sets of rules that give rise to effects based on decisions made (Gee, 2010, p. 42). In this way, BioSim's goals are naturally aligned to the genre of games and seeks to help children learn about systems thinking by mirroring a biological system inside a game system. Additionally, Gee's notion of meaning as action claims that meanings of words and concepts is made as we associate actions or experiences with them. In a game, the concepts being learned become meaningful through the actions performed in the game (Gee, 2010, p. 42-43). BioSim fits in with this idea as the rules we create prompt children to act in certain ways that make the concepts salient and meaningful.

Additionally, BioSim is not simply a game, as its theoretical roots come from the idea of the *participatory simulation* (Colella, 2000). In this kind of interaction, students "are" the simulation instead of "watching" the simulation. A participatory simulation is specifically designed -- based on agent-based modeling simulations -- to help children think about complex systems from the agent's first-person perspective. In this project that brought about the term, children act out a virus epidemic and made decisions about how to stop the virus and save each other. Students wore electronic tags that track their actions in the system (Colella, 2000). Similar to role-playing games, participants in a participatory simulation enact the roles of individuals in a system, enabling them to create personally meaningful understandings of behaviors and roles in the system (Collela, Borovoy, & Resnick, 1998; Klopfer, Yoon, & Rivas, 2004). Colella (2000) also notes that a major benefit of a participatory simulation is the emotional and affective connection that students experience as they immerse themselves within. Most prior work that uses participatory simulations to teach about complex systems concepts has targeted older children, teens, and adults because complex systems concepts have proven very challenging for people at any stage to grasp. However, this previous work has not considered the alignment between participatory simulations and play practices of young children, who already explore new topics through play-acting and games (c.f., Danish, 2014; Vygotsky, 1978; Youngquist & Pataray-Ching, 2004). Also, several projects have shown that young children can deeply explore a variety of ideas when interacting with technologies that leverage physical embodiment (c.f., Levy & Mioduser, 2008; Montemayor et al., 2002; Rogers & Muller, 2006). For our work, it was important to allow children to see the system from a third person, or outside perspective as well. As a result, we pair the participatory simulation/game with an innovative screen-based simulation to prompt thinking about the system across the two levels.

In addition to providing multiple perspectives on a system, we feel participatory simulations have the potential to provide a game-like environment, and thus enhance students' engagement. For example, Anand, Meijer, Duin, Tavasszy, and Meijer (2013 take a similar perspective and label their activity a "participatory simulation game" (p. 3). They characterize this work as combining beneficial aspects of role-playing games and simulations by allowing participants to directly influence outcomes of simulation models. The game is based on concepts of agent-based modeling (Wilensky & Reisman, 2006), meant to help students better understand complex systems (much like BioSim). It models city logistics involved with ordering, shipping, and receiving goods. The game can support 5 different agents; this 2013 paper focuses on students acting as a shopkeeper. They must make decisions about which goods shipper to select, the store's maximum stock abilities, and how and when to order the goods. For this "proof of concept" study, players worked in teams, and the team with the most profits at the end of the game won (Anand et al., 2013).

In contrast to our approach and work like Colella's (2000) study, this work used a simulation run through a computer program and did not involve wearable technology, This raises key questions about how we define immersive and embodied experiences in participatory simulations. We believe that the inclusion of wearable technology helps students to truly immerse themselves into the simulated environment and engage with their peers in that environment in ways that a screen cannot support as easily. While this work helped to elucidate features of a simulation that can support engagement, it did not yet link these explicitly to learning gains. We hope to build on such work by making those connections more explicit. Work on participatory simulations is growing, but more work is still needed to help identify the features that make participatory simulations effective learning environments, something we aim to do by exploring the value of these different perspectives (1st and 3rd) explicitly.

Utilizing Design-Based Research Methodologies

Our plan of approach for creating BioSim games fit within the Design-Based Research paradigm (The Design-Based Research Collective, 2003). This method was useful as it allowed us to engage in iterative design cycles and incorporate insight from others to create the most engaging and effective experience possible. This paradigm started from the early ideas of Brown's (1992) design experiments and Collins' (1992) design science. Brown (1992) brought about the idea of testing out implementations in actual classroom settings, and moving back and forth between the classroom and more experimental (laboratory) settings (Brown, 1992). Additionally, Collins (1992) pushed the idea of "flexible design revision" -- changing elements of the design on the spot and often based on what seems to work and what doesn't -- and multiple evaluations of success or failure -- looking for engagement and learning as the implementation is in process (Collins, 1992).

Following these Design Based Research principles, we are conducting a series of iterative mini quasi-experiments meant to help us understand whether or not the students are learning the content, and which features of our design seem to support this learning. To do this, we have been developing conjectures during the design process about specific features of the game we believe will lead to students deeply exploring the content (Sandoval, 2004). We also evaluate those conjectures as part of our summative evaluation. We have also been working with children and teachers to adapt to their needs and opinions while building the software, physical tools, and curriculum plans.

We also use Activity Theory (Engeström, 1990; Kaptelinin & Nardi, 2006) as we design BioSim. Activity Theory is a theoretical framework, grounded in the work of Vygotsky (1978) which focuses on learning happening in rich socio-cultural contexts. It helps us to focus on the intersection between individual students' ideas, the technology that mediates their work, and the way in which their social interactions helps them in generating and transforming their ideas about how systems work. An advantage of using activity theory as an analytical framework is that it helps us build embodied conjectures (Sandoval, 2004) -- documented predictions of how we think each element of the system will support learning -- in ways that explore intermediate social processes (Sandoval, 2013). Once we have these predictions, we can work to verify them as we evaluate our design. Our goal through this process for learning is that children will begin to gain new understanding of complex systems thinking concepts.

Systems Thinking

A system is recognized as "complex" when the relationships within it are not obvious or intuitive, and the individual elements of the system give rise to new overall properties that are difficult to see or explain (Hmelo-Silver & Azevedo, 2006). This is especially true in biological systems where individual organisms may act in ways that seem counterintuitive when compared to the behavior of the system as a whole. For example, individual honeybees spend a considerable amount of time "dancing" to communicate nectar location to other bees in the hive. However, this behavior gives rise to faster and more efficient nectar collection for the hive as a whole. This is not intuitive for young children - they tend to assume this time spent dancing is wasteful (Danish, 2014). This surprising interaction between levels (Wilensky & Resnick, 1999) in the system is known as emergence; we knew emergence would be an important concept to cover in our games. Other important complex systems concepts that guided design include feedback loops, iteration, and constraints. These concepts are relevant and salient in the honeybee and army ant systems, and are also useful in other contexts including the circulatory system and traffic jams.

Much of the work around systems thinking education has been through biological systems; much thought has been given to teaching biology, or life science, to young learners, as it is a topic children are familiar with and curious about. For example, Hmelo-Silver has often studied children's understanding of aquatic and respiratory systems (e.g., Hmelo-Silver, Marathe, & Liu, 2007), while Wilensky has looked into large ecologies involving wolf, sheep, and grass (e.g., Wilensky & Reisman, 2006). Although these studies were not conducted with children in our target age range, their findings help us see the benefits of exploring complex systems through biological systems. Wilensky and Reisman (2006) found that simulations employing agent-based models helped students think more deeply about complex systems and relate the agent-based occurrences to the aggregate level occurrences.

We follow this history of diving into biological systems, while adding in the element of game-like simulation. Understanding the simultaneous differences and connections between various levels of interaction is a crucial part of systems thinking (Jacobson & Wilensky, 2006). Games are especially powerful because they allow children to take on new perspectives through play, supporting productive learning (Enyedy, Danish, Delacruz, & Kumar 2012; Vygotsky, 1978). Research has shown the importance of allowing learners to switch between first-person (seeing as main actor) and third-person (seeing all actors) perspectives of a system in helping them recognize the effects of these multiple levels (e.g., Wilensky & Resnick, 1999). Games can allow this switching between perspectives - both the first-person and third-person perspectives are crucial. First-person allows students to understand constraints, while third-person helps them see how individual actions add up to aggregate behavior. In our activities, we create situations that intended to bring about "double-binds," a mismatch between students' current ways of thinking, their needs, and the possibilities in the environment (Chaiklin, 2003; Engestrom, 1987). The goal of the game is to make constraints in the honeybee system visible, creating a double-bind, then allow children to notice solutions, such as the waggle dance. For example, throughout game play, students may notice that it is hard to find nectar every time, as not every flower will have nectar. They may discover their hive has not collected enough nectar to make it through spells of bad weather, and they will realize they need a more efficient method of nectar collection. The double-bind may occur when the students see the waggle dance as a possible solution, but may think at first it wastes time instead of saving time. We then design the features of the game to lead them to recognize that this method of communication is actually the most efficient method for the hive as a whole. We also developed constraints within the game that mimic the actual constraints the insects face, so the children notice them, and recognize the system mechanisms that overcome them.

Transfer

Aside from enhancing systems thinking abilities in the case honeybees or army ants alone, another goal of this work is to promote transfer between these and other systems. One aspect of the system, previously known as BeeSign, is useful in helping students see aggregate (third-person perspective) patterns of a hive. The puppet play aspect was built in to provide a first-person perspective of nectar collection and highlight communication inside the hive. These additional perspectives are important, particularly for this younger age group, as we know it is necessary to learn about complex systems from several analytic levels simultaneously to fully understand the relationship between levels (Hmelo-Silver & Azevedo, 2006). Research has shown that a first-person (agent-based) perspective can provide students with additional resources to help them reason, and may support transfer into other domain areas (Goldstone & Wilensky, 2008). This is why we find it crucial to help students explore honeybees and army ants from a first-person perspective as well as a third-person perspective.We expect BioSim to increase the likelihood of students learning the content, as well as being able to transfer between honeybees and army ants, and to other outside systems. This is because it has been suggested that an agent-based perspective where students reason about the behaviors of individual agents within the system increases the potential of students to transfer their understanding to other systems (Goldstone & Wilensky, 2008).

MAIN

Design Principles

Across our multiple design iterations outlined in our process below, some key design principles emerged that can help us align games with systems thinking. These included the following four principles:

1. Choose a specific and productive focal point (real-life system, similar system)
2. Build on game mechanics typically found in children's play
3. Purposefully create rules for children's play to help them notice certain system elements
4. Align guiding theories to your rules, and vice versa

These guiding principles helped us hone our focus on the salient parts of the system crucial to complex systems understanding. We also envision that these principles will be useful to others wanting to take up these principles for other games to promote systems thinking among learners of all ages. We outline the utility of these principles here.

KEY DESIGN CONSIDERATIONS IN BIOSIM FIRST-PERSON GAMES

1. Choose a Specific and Productive Focal Point

While biological systems provide a fruitful starting point for design, it can also be challenging as we design games based on complex systems to choose a central focal point since there are a number of feedback loops within each of these systems as well as nested systems at play (e.g., bees collecting nectar are simultaneously pollinating flowers). In this case, we chose to focus on nectar collection because we felt it could be more meaningful and more easily aligned with young children's perspectives, to help students think about the needs of the bees and what drives their actions.

There are several reasons the phenomenon of pollination did not align well with our purposes. This occurrence seems less intuitive for young children to understand than gathering food. For the honeybees, while they eat and use some of the pollen they collect, the act of bringing pollen from one flower to another is less explicitly need-driven than nectar collection, and in fact is more of a side effect of the food collection. Additionally, for young children, the vast impact of pollination on flowers and plants is more difficult to see directly than the need for nectar to make honey.

Nectar collection, on the other hand, worked as a focus for us due to several factors. First, many children already know that honey comes from bees, so it can be a familiar entry point when they realize bees use nectar to make honey. From here, the process of gathering food is something children have learned about and can quickly come to understand. It is important to get across that this food gathering process is affected by events like bad weather. Children's previous experiences with bad weather can help them appreciate how difficult it may be for a such a small insect to fly and forage in those kinds of conditions. Nectar collection is the main purpose behind the bees' communication and foraging, so it is possible to explain this phenomenon either with or without reference to broader ecological factors. Pollination, on the other hand, really requires some broader information to be correctly described and understood. Finally, as a main goal of the project is to explore transfer of systems thinking from one system to another, it is important that the process of nectar collection draws parallels to other animals' food collection, such as army ants.

Leveraging Content Expertise in Real-Life Systems

With a focus children can relate to, gathering food, in mind, we worked closely with a biologist to find interesting behaviors and constraints in the honeybee and army ant systems.

Bees as Systems

Honeybees are divided into multiple classes. The queen bee, a subject of fascination for young children, lays eggs and surprisingly does little else. Drones, the only male bees in the hive, are useful mainly for mating with the queen to produce new workers. The bees that go out and search for nectar are female worker bees. These workers perform many different kinds of tasks throughout their lifespan, such as feeding larvae, but for the purposes of our game, we focus on the phenomenon of forager honeybees quickly and efficiently collecting nectar to turn into honey.

These foragers search for flowers with good sources of nectar. Once a good source is found, they will then fly back to the hive and share the flower's location through the waggle dance. The waggle dance in the hive, conveying only positive information, creates a positive feedback loop, a crucial concept in systems thinking. Other bees will go to this location, come back to the hive, and also perform the waggle dance. If the flower is emptied or otherwise becomes undesirable, the bees will simply stop sharing information about the particular flower and collectively switch to a new source. The forager bees are constrained by bad weather, predators, fluctuating nectar levels, and limited distance capabilities, which we strove to mirror in our game system.

Ants as systems.

Army ants were an interesting partner system, as they create an analogous positive feedback loop to honeybees, although the system looks quite different from the outside. These forager ants move around in forests and jungles looking under rocks and leaves for food, such as smaller insects or their eggs, to bring back to the massive nest. As they move along the forest ground, they leave trails of pheromones behind them. If an ant finds a food source that is too big to carry alone, it will follow its own trail back to the nest to recruit help. This movement back and forth along the same path reinforces the strength of the pheromone trail. The more these trails are reinforced, the more ants continue to follow them, creating the positive feedback loop. Similar to honeybees, army ants do not spend time sharing negative information. Trails that result in no food are not reinforced and simply fade away. Ants also have a remarkable way of spreading out their search areas by relocating their nests every few weeks.

To build the game rules, we asked of these systems: What are the insects' main needs, and why? What issues do they face in pursuit of meeting these needs? What roles do various members of the system play?

2. Build On Game Mechanics Typically Found in Children's Play

In addition, we wanted to build upon game mechanics that are typically part of children's play. For example, with bees we drew upon puppetry play and perspective taking as well as children's games where they explore a space (like hide-and-seek). Similarly, since army ants forage for food in dense forests and jungles, traveling long distances under and around large obstacles, it seemed appropriate to give children a similar constraint by asking them to crawl or crouch to move from place to place.

Young children start playing very early in their lives. Research has shown the importance of play for children's social, emotional, and mental development. Notably is the notion of social pretend play, or pretending to be someone/thing else (Vygotsky, 1978). Children play house, pets, doctor, teacher - the list goes on as long as their imaginations can reach. This kind of play helps children learn about social roles by allowing them to emulate, then bend, societal norms (Vygotsky, 1978). This play also helps children practice perspective taking. Our activities ask children to pretend to be a honeybee and try to consider all the environmental challenges that honeybees must face as they attempt to collect food and survive. Children also play with toys, dolls, and puppets, giving them names and personalities. These characters, often animals, are anthropomorphized as children act as and through them, further practicing perspective-taking and pretend simultaneously.

Additionally, typical children can often be found playing physical and active games, such as hide-and-seek or tag. Even toddlers will run around a space, perhaps with no explicit purpose at all. Our game capitalizes on this by spreading the play area out as far as we are able, taking up an entire classroom when possible. Children zipping around a large space like this better emulates the honeybees' search in fields of flowers, makes them think about constraints such as energy depletion, and makes the game a little more difficult. For AntSim, having the children crawl around on the ground seemed a logical addition, fitting well with the traditions of pretending and physical play.

Last, many children play video or electronic games, and thus have some understanding of symbols for feedback about a character's status, and may understand certain colors to convey key information. Our system indicates energy levels of the bees and ants by changing colors and flashing; children immediately recognize that a green energy bar means they can continue to search for nectar, and a yellow or red bar that they are out of time. It does not take much explanation to demonstrate what these indicators mean, and allows students to quickly respond to changes in their insects' energy status. However, we did try to stay away from using only the common red/yellow/green color combination in attempt to accommodate those with varying vision in color.

3. Purposefully Create Rules for Children's Play to Help Them Notice Certain System Elements

Other design decisions were based on trying to constrain children's play in productive ways to help them understand the mechanisms of the system (Enyedy, Danish, Delacruz, & Kumar, 2012). For example, since both insects are small, they must be economical with how long and how far they go in search of food. However, children (especially distracted children) have a tendency to search indefinitely, causing the game to lose momentum and the science to be difficult to understand (Peppler & Danish, 2013). To mirror the situation of the insects, we needed ways to alert the players to their waning energy levels that can only be restored by resting at the hive or nest. As discussed in the previous section, our bee and ant puppets use differently colored lights to let children know when their energy levels have changed. We may need to occasionally remind players to attend to this information -- "Uh oh, Alyssa, what color are your eyes right now?" -- but this feature makes it possible to put useful limits on children's movements that direct them to think about particular elements of the system.

Similarly, children have no way of knowing which flowers in the "field" have nectar and which do not. This means that efficient search tactics and communication about where nectar can be found is necessary. Additionally, they must stay in the "hive" (usually large swaths of fabric draped over bookshelves or mobile walls) while they are not searching, and thus cannot see the flowers in the field or their hivemates' actions. Often, especially early in the sequence of activities, a child may be seen discovering nectar at a particular flower, but investigating a new flower immediately thereafter. As the game goes on, we typically set up fewer flowers with nectar each round. While children might find nectar in every other flower early on, there may only be one or two with nectar near the end. The earlier method of randomly moving from flower to flower becomes less effective, and the communication element becomes more consequential.

For BeeSim, as the children learn more about the importance of communication, we have them move from verbal to nonverbal forms of communication. This constraint makes being precise harder but even more important. As the class separates into two hives, children notice fairly quickly that the hive with

Table 1. BeeSim and AntSim Rules of Play

	BeeSim	AntSim
Need to gather food	You are a forager honeybee, search for nectar to bring back to the hive.	You are a forager army ant, search for food to bring back to the nest.
Search necessary to find food	The flowers are scattered around the field; some have nectar and some do not.	Piles of leaves are scattered around the area; some have food underneath, and some do not.
Communication and collaboration	Bees cannot talk with words; they use a special dance to communicate to other bees about nectar location.	Ants cannot talk with words; they leave trails of pheromones leading to food sources for other ants to follow.
Energy constraints	You only have a certain amount of energy. To restore low energy, rest at the hive a while.	You only have a certain amount of energy. To restore low energy, rest at the nest a while.

the best communication collects nectar more quickly. This realization takes several iterations of increasing constraints, but brings across one of the most important systems concepts - that taking a moment to communicate actually leads to more efficient outcomes rather than wasting time.

These are a few examples of what we chose to include in the design and the rules to push students' thinking about the reasons and motivations behind the actions these organisms take (see Table 1).

4. Align Guiding Theories to Design, and Vice Versa

Last, it was important for us to make sure our design and guiding theories were aligned. In the Design Based Research paradigm (The Design-Based Research Collective, 2003), not only does theory inform the design, but the design should push and advance theory. The three principles outlined above illustrate how we worked to align our design decisions to what we know to be true about learning systems thinking skills.

In using real-life systems for our focus, we knew the systems thinking concepts we needed to convey, and how they are best learned, and were able to build the game system around those principles. For example, we knew feedback loops were a crucial systems thinking concept, and could be explored through the communication patterns of honeybees collecting nectar. Additionally, we have advanced our thinking around feedback and what kinds of questions to ask to help children engage with the concept through several iterations of interview protocols.

Research on play helped us think about the kinds of practices children already engage and how they are useful for learning. This helped us think about the play mechanics that would be useful in our game. Additionally, through several iterations of the game, we enhanced our understanding about how children play. For example, in early versions where children collected cork pieces that stood for nectar, we realized children will "cheat" whenever possible to beat their friends at the game. We also learned it is helpful to try and curb running, and that walking (albeit quickly) around a play space can be as robust as running.

Last, our game rules were designed to align to particular systems thinking concepts as well as various constraints and purposes present in the lives of honeybees and army ants. The process of refining these rules through various tech and non-tech versions helped us rethink our understanding which rules are important to be enhanced by technology, such as energy levels getting lows are getting low, and which can be non-tech, such as staying in the hive while waiting for other bees to search.

RULES OF PLAY: THE CASES OF BEESIM AND ANTSIM

As part of the iterative design process, we started with no/low-tech playtest sessions before eventually moving to integrate the technology in the BioSim project. This allowed us to see how the game rules worked, where technology would or would not enhance the activity, and whether or not children seemed motivated to participate.

BeeSim

To play BeeSim, children scurry around the play space checking "flowers" for nectar. An area of the room is blocked off to serve as the hive, such that the players cannot see the room, and must communicate through the waggle dance to convey nectar location. This mirrors the real-life phenomenon wherein bees communicate inside the hive in the dark. The children may also encounter flowers with poor or no nectar, and they must decide what information to share, just like real honeybees. Several iterations of BeeSim took place before the current technology was finalized. In the beginning, there was a version where children collected pieces of cork (serving as nectar) hidden around the space (Danish, 2009). This, however, unexpectedly led to children simply gathering all the corks they could possibly hold, ending the game rather quickly. The cork method gave way to having children use an eyedropper as a proboscis to collect nectar (colored water; Peppler, et al., 2010). Next, technology was introduced to further productively constrain the play to help students notice important elements of the system. Electronic feedback was added bee puppets that were first hand-sewn with electronic-textile materials, and later fabricated through partnerships with designers. The added technology has enhanced the game play in deep and interesting ways, but is still second to the overall game rules. We have found that game elements such as competition between hives and nonverbal communication are the crucial pieces that guide students toward learning goals effectively and robustly.

AntSim

As with BeeSim, we spent a good deal of time designing good game rules before adding in the technology aspects for AntSim. This piece of the overall BioSim puzzle has also been through two smaller iterations, with a third higher-tech version in the works. The rules and action of this game are very similar to BeeSim. Through multiple iterations of playtesting both with groups of graduate students and children at an after-school club, our designs settled on actors taking the role of army ants. These insects follow pheromone trails to food sources; stronger trails are further reinforced, suggesting more desirable food. Players also must recruit help to carry food pieces, as ants are highly collaborative and work together to bring large finds back to the nest. To simulate the pheromone trails, we gave players brightly colored game chips (similar to those found in Bingo) to leave on the ground as they crawled around searching for food. We also hid paper food sources under fake leaves, just as ants must look under brush for food. A challenge was encountered here as chips on the ground can be easily moved around or prove difficult to pick up. This reinforced that advanced technology such as indoor real-time positioning could enhance this portion of game play in future iterations. Specifically, we aim to use position tracking so that we can record the ant's virtual positions, and then use that information to provide real-time feedback (e.g., vibrating the puppet) when the ants are on the right track or not. This technology also allows us to help the students explore concepts such as how the trail dissipates over time.

POSSIBILITIES FOR TRANSFER

Here, we explore some of the similarities and differences between honeybee and army ant systems as they pertain to possibilities for transfer between them. We see promise here as research has suggested that a first-person (agent-based) perspective can support transfer into other domains (Goldstone & Wilensky, 2008).

Similarities

These two systems share a good deal of similarities that we feel are promising as we design for transfer across the games. In both honeybee and army ant systems, the workers need to search for food to sustain the collective population. However, each search attempt will not always result in finding food. The search process is dangerous and taxing, and it is also possible for a previously abundant food source to disappear or otherwise become undesirable throughout the process. This must be learned throughout the game as children may believe at first that, for example, they will find nectar at every flower they check.

Additionally, in both systems, feedback loops are positive. In this case, it means balancing of the system occurs through a lack of positive information rather than sharing information to stop visiting a particular location. For example, when army ants discover that a food source has been depleted, they simply stop going there, and the pheromone trail fades away. They do not, as children may predict, go back to the nest and report that the food source has been emptied. Within the positive information, the insects must also decide what information is better, or worth sharing. There may be two flowers with nectar, or two strong pheromone trails, and they must choose which dance to do or trail to follow. Another choice might be whether to wait and gather information from others rather than add to the search efforts. As we work to move children away from verbal communication throughout the game, these decisions become more difficult, showcasing that these are not simple system.

Differences

Along with their similarities, honeybee and army ant systems have several differences that make them interesting and useful as different games under a larger umbrella. At least to the outside observer, communication appears more "on purpose" in honeybees. While we know honeybees come back to the hive and perform the waggle dance when a good flower is found, army ants always leave pheromone trails as they travel along the forest floor. The reinforcement of these trails by more ants going back and forth is more of an outcome or side-effect of the ants continuing to find food.

As a result of this difference, the communication in BeeSim is entirely orchestrated and co-designed by the children. They must come up with ways to get across the information they need to convey. In AntSim, the technology is meant to take more of the burden of sharing information. Thus, children's decisions are more about *what* information to share, and not as much about *how* to share it. This also provides new opportunities to explore other related issues such as how long the pheromone trails might remain. If the pheromone trails never dissipated, they would soon lose their value as the entire forest floor might be criss-crossed with old trails that lead to food sources that have long since been exploited. Therefore, this is a productive variable for students to explore as they attempt to find a sweet spot where the trail persists long-enough to bring more ants to the food source, and yet dissipates quickly enough that only a few ants continue to follow the trail once it no longer leads to food.

Additionally, the army ant system involves a different level of cooperation. Here, individuals must sometimes work together to physically carry a food source back to the nest. This level of physical coordination does not take place with honeybees.

CONCLUSION

Through this work we realized that some constraints need to be made salient to fully bring across the concepts we have identified as crucial, meaning there is exciting space to leverage technological affordances. The game space provides interesting opportunities to make salient those constraints that create productive double-binds. By choosing a central focal point, building on children's common play mechanics, and productively constraining play, we were able to build games that engage young children with complex systems concepts in interesting ways.

FUTURE RESEARCH

Further iterations of this work are currently underway to better utilize design based research methodologies to evaluate the effectiveness of our activities and articulate the ways in which participatory simulations and games help students to engage with specific complex systems concepts. To fully benefit from these methods we will need to gather data over a longer period of time, assessing the parts of the system that do and do not work, and adjusting with each iteration. These studies include not only multiple choice assessment measures, but targeted interviews to explore students' experiences and evaluate their understanding through their own words. These studies seek to pin down the importance of combining first- and third- person perspectives for young learners, as well as show the benefits of embodiment as young children explore complex systems. We are currently conducting implementations in classrooms under quasi-experimental conditions, while iterating and designing closely with the classroom teachers as they lead the instruction efforts.

Although we have shown that previous versions of BeeSign (the third-person only component of the game) and BeeSim (the first-person component) produce positive learning outcomes for young children (cf. Danish, 2014; Peppler et al., 2010), we have explored the unique benefits (and challenges) using both perspectives together with our newly enhanced technologies. Along with outlining the general efficacy of this overall game and program, data collected in classrooms over the next several months will also help us illuminate transfer between and across BeeSim and AntSim. Down the line, we also hope to explore other systems through similar game mechanics. For example, other BioSim games could look at ants and bees together in an ecosystem, or perhaps branch out to other biological systems such as sheep and wolves, or the circulatory system.

Of course, aside from these planned studies, other potential research around this area could also prove illuminating. It might be interesting to compare this game-based method to less playful versions of the same content. An experiment of this kind would set up two otherwise equal classroom groups, one exploring our entire BioSim curriculum, and the other learning the same content in less playful, or even traditional ways. We would hypothesize that children in our game-based method would outperform children in the traditional class, but comparison could help us pinpoint more precisely where and how the learning advantages of BioSim are located. It could also be interesting to experiment with rules of play, continuing to tweak the current system, and playing with where the technology plays a role. Finally, further work could explore BioSim in an informal space, such as a museum. The system would need some deep redesigning to be efficacious in a museum space with high turnover and high volumes of learners, but it might prove useful as a spark for further and deeper science learning.

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KEY TERMS AND DEFINITIONS

Complex System: System made up of many interconnected elements on various levels; interactions on lower levels give rise to events on higher levels.

Double-Bind: When students' current modes of thinking, needs, and the possibilities in the environment are not aligned; students must think in new ways to realign these elements.

Embodiment: Physically representing actions of another actor or occurrence.

Participatory Simulation: People involved act out a simulated process rather than watching the simulation in a computer model.

Pheromone: Secreted chemicals that are perceived by other actors as messages to act in certain ways; army ants leave trails of these chemicals to trace travel paths.

Play: Acting in particular ways possibly aligned with rules that govern an imaginary space.

Positive Feedback Loop: Circular process where one event leads to another, eventually circling back to the original event occurring again; may spiral out of control unless a balancing event occurs.

Waggle Dance: Scout honeybees do this to communicate location of nectar sources to other foragers.