In the Hive: Designing for Emergence When Teaching Complex Systems in Early Childhood

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Abstract: This Design-Based Research study explores the iterative design decisions for a participatory simulation created to teach children in grades K–2 about complex biological systems. In this simulation, children assumed the role of honeybees, whose job was to collect nectar from flowers and bring it back to a hive, learning about the social nature of honeybee colonies (e.g., the need for honeybees to communicate the location of nectar via a "waggle dance"). As we designed the simulation, we iteratively analyzed the ways that children in a range of low-tech and high-tech conditions engaged in creating a nonverbal system of communication. Findings suggest that the spatial layout of the simulation directly influenced the game's difficulty levels and subsequently impacted both the nonverbal communication and the learning outcomes of the activity. This paper presents the iterative design cycles and outlines implications for studies seeking to design participatory simulations for young children.

Introduction

Systems thinking has been identified as a useful and necessary topic to integrate into K–12 education (see Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006), operating on the belief that teaching systems thinking at an early age can help the next generation address the complex nature of an interconnected world. However, the majority of learners do not fully understand these concepts on a deep level (Resnick & Wilensky, 1993). Seeking to address these gaps as they pertain to young children's (K–2) understandings of complex systems in science, we developed a participatory simulation (Colella, 2000), named BeeSim, that provides a first-person look into the complexity of bee colonies, in particular the interconnected challenges of collecting nectar (Peppler, et al., 2010). Similar to role-playing games, participants in a participatory simulation reenact the roles of single elements within a system, enabling them to forge personally meaningful understandings of their element's specific behaviors, as well as its role in a greater whole (Colella, Borovoy, & Resnick, 1998). By situating imaginative exploration into a suite of elementary science curricula, BeeSim is designed to help young learners engage with complex systems-thinking concepts through play and technology (Peppler, et al., 2010).

One of the primary challenges of designing a participatory simulation for this purpose is finding age-appropriate ways to engage whole classrooms (or larger) in complex systems thinking without stifling young children's fluid, imaginative play. Driving our design of the game was the investigation into *which design features lead to the emergence of systems understanding, as well as robust and productive communication in the hive between game participants*. Through a series of pilot tests and design cycles, BeeSim underwent a number of transformations, both in terms of the components of the game (e.g., puppets representing the biological systems) as well as the rules of gameplay (Thompson, Peppler, & Danish, 2017) to maximize learning and engagement. This paper analyzes the iterative design cycles of the participatory simulation, particularly the ways that design decisions impacted children's learning of complex systems. Close attention is paid to the infusion of technological elements (e.g., electronic textiles and position tracking) into the game and how their presence changed the foundation for learning.

Complex systems thinking, biological systems, and children

A system is recognized as "complex" when the relationships within it are not obvious, 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. Young children, however, 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*.

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. Games are especially powerful because they allow children to take on new perspectives through play, supporting productive learning (Peppler, Danish, & Phelps, 2013).

This project emerged from a longer history of research using bees as a vehicle for teaching complex systems (Danish, 2009; Danish, Peppler, Phelps, & Washington, 2011). Most notable of these is BeeSign, a 2D computer-based program that offers a third-person perspective on biological systems (Danish, 2009). The overarching goal of adapting BeeSign to a participatory simulation was to offer a play-based, first-person perspective on the behavior of bees with a focus on the challenge of finding nectar, engaging in the design of nonverbal communication (i.e., how bees convey the location of flower nectar to other bees), and other variables, such as nectar quality, nectar depletion, and a limited flight range. We aimed to develop a high quality first-person participatory simulation for two reasons: (1) to engage entire classes of children in a single systems thinking activity, which would better reflect the collective behaviors of biological systems; and (2) we sought to create two parallel first- and third-person conditions (or at least to the extent possible) to disentangle the differential contributions of first- and third-person experiences on learning of complex systems in early childhood. The key challenge of the latter goal was to find ways to control for the overall difficulty level, depth of systems thinking concepts engaged in the activity, and overall entertainment value of the game play for each of these conditions.

Methods

Using a Design-Based Research paradigm (Design-Based Research Collective, 2003), the four most recent iterations of BeeSim discussed here were tested in two mixed-grade (grades 1-2) classrooms and one first-grade classrooms at different suburban, midwestern elementary schools; design cycles 1 and 2 at one school, cycles 3 and 4 in two comparable schools in the district. Three teams with seven to nine students in each engaged in cycles 1 and 2 (fifteen boys and eight girls), while two teams with between ten and twelve students in each (twelve boys and ten girls) participated in cycles 3 and 4. Each team included at least one member of each gender. It is important to note that earlier versions of BeeSim did take place between BeeSign and the four cycles discussed here, but designs were less pertinent to the current, optimized design reached in cycle 4.

Before each game began, participants were divided into two teams and were told about the objectives of gameplay: bees had to collect nectar and bring it back to the hive within a fixed time period, bees needed to communicate to each other about which flowers had the most nectar, and no bee could talk during the game, only signal the location of the nectar to other bees via a "waggle dance." The BeeSim curriculum covers a number of aspects of the hive system, including the constraints bees face as they struggle to feed the hive, how bees communicate, and why this communication is important. In the honeybee system, unlike other systems in the animal kingdom, communication is done through a waggle dance in which returning foragers perform a series of figure-eight movements to communicate both the direction and abundance of a food source to her sister bees. The waggle dance contains quite a bit of information about the direction, distance, and type of nectar. As children learn about the waggle dance, they invent a novel waggle dance to communicate with their hivemates in game play.

Observations from each of the four major design cycles highlighted here were accumulated through a combination of videotaped game sessions, written observations and *ex post facto* discussions between the research team and the children participants' homeroom teachers (who integrated BeeSim into additional activities in the classroom, including discussions and engagement with the BeeSign curriculum). Through discussions with teachers, as well as observations of how children engaged in the simulation during game play, the research team was able to determine which learning objectives and game dynamics could be optimized through refinement of the game rules and components between cycles.

Findings

Data collected from each design cycle helped to clarify the design elements of the simulation that were linked with children's' engagement with authentic biological and systems-thinking concepts. The sequence of observations, and the design iterations they necessitated, are presented in chronological order below in Table 1. Note that BeeSign has been included in this table as a reference to the starting point of these activities. As later iterations were built and refined, we often looked back to BeeSign as a point of comparison. We worked to mirror the productive design choices where appropriate, and departed in careful and intentional ways, such as where the shift from third-person perspective to first-person perspective changed gameplay and interactions.

Table 1: Summary of the various design cycles, including key design features and outcomes

		BeeSign *(2D computer simulation)*	BeeSim: Low-Tech Conditions		BeeSim: High-Tech Conditions	
			Cycle 1 (v1.0)	Cycle 2 (v2.0)	Cycle 3 (v3.0)	Cycle 4 (v4.0)
Design Features	Number of Simultaneous Actors	10	2	2	25	25
	Number of Flowers	2+	12	6	8–10	4–6
	Distribution of the Flowers in the Field	Selectively distributed around the hive to promote effective inquiry.	Randomly distributed in a large, outdoor space	Organized in a small grid of 2 rows of 3 flowers in a 2’x3’ area	Randomly distributed in a large, indoor space	Randomly distributed in a relatively small, indoor classroom space; in and around regular classroom furniture
	Component Design	Computer simulation, interactive whiteboard	Paper flowers, eyedroppers		Life-size flowers, Arduino-enhanced puppets, RFID tags communicate between puppet, flowers and hive	
Outcomes	Quality of Dance Communication	n/a	Infrequent, Simple	Frequent, Complex	Infrequent, Simple	Frequent, Complex
	Systems Thinking Concept of Emergence present	Yes	X	Yes	X	Yes
Design Principle / Takeaway		n/a	Include constraints that make key phenomena salient.	Include technology in ways continue to provide authentic constraints.	Iteratively test to highlight tensions between physical and computer spaces.	Check in with learning goals often.

Cycle 1: “Low-tech” condition with distributed field

In the first iteration of BeeSim, participants carried an eyedropper for use as a proboscis (the straw-like mouth of a bee) to collect nectar from twelve laminated paper flowers. The flowers were scattered randomly around a large outdoor garden space, anywhere from 20–40 feet from the hive (see Figure 1), behind each were situated Dixie cups of colored water representing nectar. Once the simulation started, each team could set out a “forager” to search for nectar in the yard, and then were asked to nonverbally communicate the location of the most nectar-filled flowers to the other bees back in the hive using an invented “waggle dance.”

Findings from this design revealed a number of challenges for the young age group. For one, (1) the children were easily distracted by the size of the field, likely exacerbated by (2) the random placement and copious numbers of flowers, which made it difficult for children to formulate and communicate meaningful waggle dances to other members of their hive. The free structure of the game also led to (3) participants not returning to the hive in a timely manner, as well as (4) cheating by surreptitiously peering at the nectar levels of all flowers, thus undermining the importance of the “waggle dance” and weakening the emergence of biological or systems understanding. Reducing the number of flowers and size of the playing space was hypothesized as a way to lower the barriers to success, as well as insert ways for adults to moderate how participants collected nectar and communicated with the hive. From these discoveries, we might suggest a concrete takeaway for other educators designing activities for young elementary learners: include constraints that make key phenomena and learning goals salient for learners, and identify ways to enforce those constraints. In our experience, a focus on "winning" a game can lead learners to circumvent rules and constraints if possible.

Cycle 2: "Low-tech" condition with optimized field

We next tested the game with the same children as before, but the total flower count was reduced to six and arranged more closely together: in a 2x3 grid approximately 20' from the hive. Additionally, childrens' adherence to the rules of the simulation were enforced by adult moderation. In this instance, a pair of two children from one hive were permitted in the field at any given time. To collect nectar, children indicated to an adult stationed by the flowers which flower they wanted to check, and after checking this flower their imaginary energy ran out and they had to return to the hive. Back at the hive, these students used their dance to nonverbally communicate which flower the next bee pair should check.

Figure 1. Field layout in low-tech cycle 2 (top) and high-tech cycle 3 (bottom) conditions.

The optimized game space and presence of adults to scaffold the rules of play resulted in consistently on-task performances from the children, including the invention of elaborate waggle dances to communicate the nectar location to team members (see Table 2). After the simulation, we observed that children's resulting conversations about nectar collection were productive and insightful about how bees communicate within the hive. In particular, many of the students began to recognize the benefit of each bee dancing for the performance of the hive as a whole—a rudimentary recognition of the emergent properties of the system.

While the emerging analyses suggest that learning may have improved through these design changes, we identified a need to make the gameplay experience more active for all participants, especially since youth not actively "foraging" had little to do back at the hive. Furthermore, while the nectar collection was more systematic in this instantiation, having to communicate first to an adult before collecting is distal to the authentic biological model. Our next design cycle was driven by the idea that a technology-enhanced environment could communicate the biological rules of the bees more consistently, reducing the need for adults to police youth children's game choices, enabling more youth to play simultaneously, as well as opening the door for more biological science to be integrated into bee behaviors due to a reduced emphasis on enforcing the rules. Design takeaways from this iteration center around the decision of whether and how to introduce technology to a learning experience. Here, the inclusion of technology was positioned as a way to provide constraints on students' behavior that was authentic to the learning context.

Table 2: Summary of "waggle dance" communication created by teams in BeeSim v2.0

Condition	Hive Name	Communicate Direction	Communicate Distance	Communicate Quality/ Amount
BeeSim v2.0	Team 1	Hand above head if on the top shelf, at neck height if on the middle shelf, mid-chest height for lowest shelf	Hold up one, two, or three fingers to indicate how far along the shelf the flower is	N/A
	Team 2	Jump and point up for top shelf, jump and point down for bottom shelf, just jump for middle shelf	Hands to the left if it is the first flower on the shelf, middle if it's the second flower or to the right if it's the third	N/A
	Team 3	Thumbs up above head for top shelf, thumbs up straight in front for middle shelf, thumbs up down low for bottom shelf	Thumb bent to to the right for closest flower, straight up for middle flower, tilted out for the far flower.	Using the other hand, thumbs up if there is nectar or thumbs down if there is not

Cycle 3: "High-tech" condition with distributed field

Seeking to increase children's autonomy and support a larger number of actors, as well as increasing biological realism in the next iteration of the game, we designed computationally-enhanced puppets and a field of uniquely designed electronic flowers into the participatory simulation. Making use of the LilyPad Arduino platform--a microcontroller board that can be stitched safely into textiles--each player used bee puppets that included an XBee 2.5 2mW wireless module multiple sets of 3 LEDs, and an RFID reader. The XBee Wireless Module allowed for wireless communication between the glove and another XBee attached to a computer via USB. During gameplay, students wearing the bee puppets could monitor through a set of three LEDs the amount of nectar currently stored on the glove, while an additional set of LEDs in the bee's antennae displayed the amount of nectar in each flower checked. To represent the finite energy levels of bees as they travel between the hive and a flower, a tri-colored LED was used as an energy meter, moving from green to red to indicate to students when they needed to return to the hive.

The flowers incorporated RFID tags that would be scanned by the bee puppet to "check for nectar." In addition to being more proportional in size to the bee puppets, the flowers were also diversified in terms of variety of flower types and collection methods, and were once again returned to a more random, distributed arrangement in the playspace (see Figure 1). When the RFID scanner in the bee puppet came near the RFID tag in the flower, the computer noted the time and flower ID of the collection. If the child returned to the hive before energy ran out, the total amount of nectar for the team increased by the amount of nectar currently stored on the bee. The initial rationale for returning to a greater number of flowers was that we hypothesized that having more actors in the field would necessitate more overall coordination of activity as a result of needing to communicate which source of nectar the bees should visit. Given that this was indoors and arranged around the existing furniture for a temporary installation for the class, this also led a random distribution of the flowers, which we had hypothesized as not being problematic given the new time constraints placed on the system.

The introduction of the technology led to some new affordances in the game. Not only could more children participate at a time, but the puppet itself communicated nectar storage and energy levels to the children, opening up the gameplay for the emergence of new biological understanding. For instance, in this version, children had a limited amount of time to collect and deposit nectar and a finite storage capacity. During the allotted time, a child would run from flower to flower and try to collect nectar. A child could collect one unit of nectar from any given flower and would also be informed as to how much nectar remains inside the flower.

Once the child's nectar stomach (represented via an LED array) was filled, he or she returned to the hive and deposit the stored nectar.

Furthermore, the electronics-based version of the BeeSim game gave the instructor more freedom and better access to data than in previous incarnations. For instance, because the energy of a bee was monitored by an adult's stopwatch in BeeSim 2.0, children often failed to consider the range to be a real constraint for bees, because it was not a real constraint for them. In contrast, the computational textile bees embedded the bees' energy into the game in a natural and familiar manner such that the children in the role of the bees had to attend very carefully to it, or suffer the consequences (lost nectar). This resulted in far more attention to details important to understanding the system. In addition to the bee range, the computational textiles also helped to model limited amounts of nectar collection, flower variables such as random nectar depletion and the difficulty of determining if a flower has nectar without visiting it, and supported easier tracking of how much nectar was collected.

However, there were key challenges in this version of the game as well. While constraints on time, etc. were all designed to help the children reflect upon the constraints that real bees face as they collect nectar, as well as the benefits of the solutions that honeybees have evolved to these constraints (e.g., the waggle dance to convey nectar sources), it also had inadvertent negative impact on the observed quality and frequency of the communication in the hives (see Table 3). This stemmed from the infrequency of finding nectar in the field, which was due to the random placement of the flowers in the field, overall number of flowers, as well as the limited amount of time to search for nectar. For example, one bee would only have a limited amount of time in the field to find nectar, which would oftentimes be unsuccessful until the game was too close to completion, leaving very little time to use the waggle dance and for others to "listen" to and act on this information before the end of the class period (see Table 3). The subsequent video analyses of this version led us to see a pattern of play that is problematic with the distributed field of flowers (as similarly seen in cycle 1); overall complexity of the task is increased when there are more than 6 or so objects in the field to check. Debrief and reflective conversations, did work to address this complexity, but it felt necessary to simplify the nectar collection task as well. Thus, in subsequent versions of the game, we sought to reduce the overall number of flowers to help provide an easier entry into the game play and help to focus the actors on the behaviors (i.e., the waggle dance) that lead to better understanding of emergence within the system. Here, we might see design takeaways that highlight tensions between physical simulations and computer simulations. The number and type of elements in each might be different and can only be determined through testing.

Table 3: Summary of "waggle dance" communication created by teams in BeeSim v3.0

Condition	**Hive Name**	**Communicate Direction**	**Communicate Distance**	**Communicate Quality/ Amount**	**Communicate Flower Color**
BeeSim 3.0	Team 1	Shake body in the direction of the flower.	Indicate number of steps using fingers.	N/A	Purple: pinch thumb and forefinger Pink: touch face Orange: fist touching chin Yellow: mimic peeling a banana
	Team 2	Numbered flowers one through six from right to left in terms of their placement in the field. Step out the shape of the number.	N/A	N/A	N/A

Cycle 4: "High-tech" condition with simplified layout

In the latest testing of BeeSim, participants used the electronically enhanced components but the gameplay returned to the optimized number and arrangement of flowers from v2.0. Overall findings indicated that performance on pre-to-post measures improved in every case, indicating strong learning gains from participation in this cycle.

While the designs and rules of play were similar to cycle 3, new game designs emerged when the overall number of flowers was reduced, which was kept at 4–6 throughout the testing. Generally, one of the flowers was a distractor that would not produce nectar appealing to honeybees in nature. Additionally, another flower was often set to "empty," and one more was partially filled with nectar. Although the smaller number of flowers meant that participants might be able to check multiple flowers in a relatively short amount of time, with so many of the flowers empty or nearly empty, participants needed to utilize the waggle dance to be most efficient and avoid losing time/energy at empty flowers. The flowers were placed at random locations in the classroom, both to prompt the need for unique waggle dances, and to accommodate immovable classroom furniture.

As a result of this optimized flower arrangement, waggle dances became more efficient during this round of design. Rather than attempting to convey flower color, as had occurred in v3.0, participants focused in on the quality and amount of nectar of the flowers (see Table 4). The faster or slower shaking used by Team 1 mirrored the faster or slower waggling performed by real honeybees. To convey quality, participants needed to attend to an additional piece of information, found in the antennae of the bee puppets. Lights here would flash very quickly for high quality flowers, and more slowly for low quality flowers. Participants in v3.0 were less likely to notice this information as there were many flowers to choose from, and quality became less consequential. This iteration of game play revealed more frequent and more complex communication within the hive sooner in the game play, which allowed for participants to experience and note emergent behaviors in the hive (i.e., that you can more efficiently collect nectar when you communicate where to go to find nectar with your hivemates). This leads to a final design takeaway: it is crucial to check in through the iteration process to ensure core learning goals are not overshadowed by design changes.

Table 4: Summary of "waggle dance" communication created by teams in BeeSim v4.0

Condition	**Hive Name**	**Communicate Direction**	**Communicate Distance**	**Communicate Quality/ Amount**
BeeSim 4.0	Team 1	Shake body in the direction of the flower	Hold hands close together, medium distance, or far apart	Faster shaking to indicate higher quality, slower shaking to indicate lower quality
	Team 2	Shake body in the direction of the flower	Indicate number of steps using fingers	Rub stomach and nod head as if "yummy" to indicate higher quality, give thumb's down to indicate lower quality

Discussion

Through iterative cycles of development, the various versions of BioSim represent a shift in a number of the design features, enabling and constraining the children's activities via the designs and computational affordances of the wearable computers to make visible more aspects of the system. In short, the overall designs of the system were optimized for this age group when the (a) time to discover nectar was constrained by the puppet design and (b) the overall number of flowers in the field was reduced to minimize the number of possibilities for this age group Such findings provide insights into the complexity involved in promoting systems understanding for this age group, and they help us understand the role that spatial design plays in capitalizing on the affordances of learning materials, but they could have gone unnoticed had the research focused only on the summative impact of the intervention.

In sum, these cycles of development revealed how technology could facilitate the implementation of robust game rules, highlighting the importance of communication within the hives. Future participatory simulations designed for young children can build on the design takeaways outlined here. We see them as emerging principles that could guide the design of other types of contexts beyond biological systems and social insects. Furthermore, achieving one of the primary goals of the simulation (i.e., first-person perspectives on the bee's role in the greater system), the technological enhancements made to the BeeSim simulation in the later iteration of the game facilitates changes to the game rules that simulate an experience closer to that of real honeybees, which could be skinned and used in other applications to model parallel systems, such as blood circulation and/or army ants foraging for food. The findings in this paper serve to highlight the importance of individual design elements within a system and how these elements work together to shape the system as a whole.

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