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Life in the Hive: Supporting Inquiry into Complexity Within the Zone of Proximal Development

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Abstract Research into students' understanding of complex systems typically ignores young children because of misinterpretations of young children's competencies. Furthermore, studies that do recognize young children's competencies tend to focus on what children can do in isolation. As an alternative, we propose an approach to designing for young children that is grounded in the notion of the Zone of Proximal Development (Vygotsky 1978) and leverages Activity Theory to design learning environments. In order to highlight the benefits of this approach, we describe our process for using Activity Theory to inform the design of new software and curricula in a way that is productive for young children to learn concepts that we might have previously considered to be "developmentally inappropriate". As an illuminative example, we then present a discussion of the design of the BeeSign simulation software and accompanying curriculum which specifically designed from an Activity Theory perspective to engage young children in learning about complex systems (Danish 2009a, b). Furthermore, to illustrate the benefits of this approach, we will present findings from a new study where 40 first- and second-grade students participated in the BeeSign curriculum to learn about how honeybees collect nectar from a complex systems perspective. We conclude with some practical suggestions for how such an approach to using Activity Theory for research and design might be adopted by other science educators and designers.

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Introduction

While we rarely label it as such, the world we live in is a complex system. It is made up of many inter-related and inter-dependent elements ranging from the atoms that make up the objects that we interact with to the organs that make up our bodies and the other people who shape our communities. Increasingly, scientists discuss these relations in terms of their properties as complex systems and as a result, science educators seek to help students understand complex-systems concepts (Sabelli 2006). Unfortunately students and adults alike find complex-systems related concepts to be difficult to learn (Hmelo-Silver and Azevedo 2006; Jacobson and Wilensky 2006). For this reason, and because researchers may assume that young students lack the cognitive and meta-cognitive skills necessary to understand complexity (Hmelo-Silver and Azevedo 2006), young children are traditionally—and, we will argue, unnecessarily—left out of learning about complexity.

It has been suggested that much of the existing literature on young children's understanding of science, and the curricula that results from this literature, is grounded in misinterpretations or misapplication of early research regarding young children's developmental constraints (Metz 1995, 1997). As a result, Metz suggests that we revisit our current assumptions regarding young children's capabilities. While we agree that current assumptions need to be questioned and that young children are actually far more capable than the current literature and practice would suggest. One reason for this is that many studies have focused on the individual child rather than what the child is capable of within a properly designed activity system. Therefore, we suggest a shift in analytic focus from the developmental constraints of young children to the promise of activity systems in which young children engage. This shift in mindset has the potential to dramatically alter our vision of the kinds of science young children are capable of grasping. Specifically, we propose using Activity Theory (Engeström 1990b, 1999; Kaptelinin and Nardi 2006) as an analytic framework for both designing and interpreting young children's science activities. We propose an approach grounded in the notion of the Zone of Proximal Development (Vygotsky 1978) which highlights the difference between what a child can do on their own and what they are capable of accomplishing with the help of a more capable other. In order to highlight the benefits of this Activity Theoretic approach, we describe our process for using Activity Theory to inform the design of new software and curricula in a way that is productive for young children to learn concepts that we might have previously considered to be "developmentally inappropriate". As an illustrative example, we present a discussion of the design of the BeeSign simulation software and accompanying curriculum that was designed from an Activity Theory perspective to engage young children in learning about complex systems (Danish 2009a, b). To illustrate the benefits of this approach, we present findings from a new study where 40 first- and second-grade students participated in the BeeSign curriculum to learn about how honeybees collect nectar. We conclude with some practical suggestions for how such an approach to using Activity Theory for research and design might be adopted by other science educators and designers.

What Makes Complex Systems So Complex?

The term "complex systems" is used to describe collections of inter-dependent and inter-related elements where the collection, or system, has properties that emerge from both the individual elements and their relationship to each other (Jacobson and Wilensky 2006). In the case of honeybees collecting nectar, we can view the honeybees within a hive, the hive itself, and the flowers that the bees visit to collect nectar as a system.[1] Honeybees collect nectar from these flowers, converting it into honey within the hive. As scout bees discover good sources of nectar, they return to the hive where they perform a "bee dance" that indicates the direction and distance to the source of nectar. Other bees observe this dance and then set out in search of the identified flowers. The result is not only an incredibly efficient nectar collection operation, but also a highly adaptive one with honeybees ceasing to visit flowers that are no-longer effective nectar sources, shifting rapidly to new abundant supplies.

What makes this a complex system is not just that it consists of different elements (i.e., the bees, hive, and flowers), but also the inter-relatedness between these elements, and the different levels of analysis at which it operates (Hmelo-Silver and Azevedo 2006). The different levels of the system are also the first place where we see a clear distinction between experts and novices. Novices tend to view a system such as this in terms of its superficial structures (e.g., the honeybee body parts) and behaviors (e.g., bees dance) instead of the functions of these behaviors and structures that experts note (e.g., the dance leads to faster nectar collection) (Hmelo-Silver and Azevedo 2006; Hmelo-Silver et al. 2007; Hmelo-Silver and Pfeffer 2004). One reason for why the functions are so elusive may be that these functions typically require an examination of the emergent properties of the system as a whole, rather than the local behaviors. One goal of the BeeSign curriculum was to help move young students from superficial descriptions of the system of honeybees collecting nectar to a more nuanced understanding of the functions that these different behaviors served.

An alternative approach to examining complex systems in education has been to focus on the process through which properties of the system "emerge" from the behaviors or properties of the individual elements (Jacobson and Wilensky 2006; Wilensky and Resnick 1999; Wilensky and Stroup 2000). In the case of honeybees collecting nectar, for example, we wanted the students to understand the way that the hive as a whole is efficient at collecting nectar despite the fact that individual bees engage in behaviors that may not appear to be immediately effective such as spending time dancing (instead of collecting more nectar). Prior research has consistently shown that this kind of emergent property is quite challenging for adolescents and adults to understand, particularly because it requires the ability to shift one's perspective back and forth between "levels" of analysis, represented here by the individual bees and the hive as a whole (Hmelo-Silver and Azevedo 2006; Wilensky and Resnick 1999).

Another common misconception arises as individuals often resolve this tension between individual entities and the emergent properties of a system by assuming a "centralized mindset" (Resnick 1996; Resnick et al. 1990). A "centralized" explanation for the honeybees collecting nectar would erroneously suggest that one central entity—typically thought to be the queen bee from our prior data collection efforts (Danish 2009a, b)—has knowledge of the entire system and is therefore able to direct the other bees

[1] We present a somewhat simplified description of this system here for the sake of brevity. For additional details we recommend Seeley's (1995) excellent description of the social organization of the honeybee hive.

to the flowers that have nectar. In actuality, honeybees are quite de-centralized. The apparent organization of the hive emerges from the simple fact that when bees dance, more bees know to visit a source of nectar. The better the source, the more bees that will continue to dance, leading to increasing numbers of bees which will visit the nectar source. If the source disappears, fewer bees will dance, resulting in a shift to other sources of nectar. With such an elegant solution in place, there is no need for centralization. Given one's experiences with centralized control, it is incredibly challenging for adults and adolescents to understand these principles (Resnick 1999; Wilensky and Resnick 1999), leading many educators to mistakenly believe that it's untenable to teach complex systems to young children (Hmelo-Silver and Azevedo 2006).

BeeSign was designed, therefore, to see if children as young as kindergarten could come to learn about honeybees collecting nectar in terms of the functional, emergent, and decentralized explanations for how honeybees effectively collect nectar (Danish 2009a, b). In the initial BeeSign study (Danish 2009a, b, under review) it was demonstrated, using open-ended pre- and post-test interviews, that young children could engage with complex systems concepts when learning about honeybees. The present study builds upon these prior findings with a more detailed interview protocol which highlighted students' understanding of the honeybee hive at the oft-elusive aggregate level.

Activity Theory: Designing for Collective Learning in the ZPD

Perhaps the most familiar concept from Activity Theory is Vygotsky's notion of the Zone of Proximal Development (ZPD) (Chaiklin 2003; Griffin and Cole 1984; Vygotsky 1978). The ZPD describes the space between what a child can accomplish on their own (their current developmental level), and what they are capable of with the help of a more capable other (the level of potential or proximal development). In this space, argues Vygotsky (1978), learning is most effective. Rather than asking children to engage with ideas that are already familiar to them, children are challenged to engage in new, more advanced ways of thinking, albeit with support. If successful, learning in the ZPD, at the edge of one's competence, can then result in the appropriation on the part of the child of new psychological tools.

A common misinterpretation of the ZPD is to assume that it is simply a property of the individual child in question—that the child has an "upper bound" as it were on their capabilities. Rather, the ZPD should be viewed as a property of the child in interaction with their context, including other people and the tools at their disposal (Chaiklin 2003). Intuitively, this is simply a paraphrasing of the common-sense notion that some forms of help are better than others. The question then becomes how to conceptualize and design productive forms of help—those that will lead to effective learning.

To help answer this question, we turn to Activity Theory in order to systematically consider those features of the students' context that are likely to mediate their interaction with complex systems concepts. By Activity Theory, we refer to those theorists within the sociocultural tradition, whose analytic focus has been activity systems as opposed to individuals engaging in mediated action, or inter-connections between activity systems to describe the encompassed and encompassing levels of analysis that others have studied respectively (c.f., Cole and Engeström 1993; Engeström 1990b, 1999; Roth 2007; Wertsch 1981). Activity can be defined in brief as the organization of individuals (referred to as the community) around a shared object or set of goals for their activity. The community and shared object are crucial in distinguishing between activity, and simple actions by individuals (which are shaped by, and shape the activity systems in which they occur) (Cole 1996). For this reason, we find it useful to begin our design and interpretation of activity systems specifying the object of activity.

In the case of the BeeSign curriculum, this meant designing for a shared object of activity for the students. We might presume that the students come to the classroom with an object of having fun, and, in some cases, pleasing the teachers. However, we wanted to add to this the object of "understanding how bees get food." Therefore, we designed our curriculum to bring this question to the attention of the students, to inspire them to want to resolve this question, and then to help them discover the tools to do so. We accomplished this largely by asking students what they knew about bees, and how they thought bees collected food. Furthermore, we strove to create opportunities in which a student would encounter a "double-bind" or contradiction between the individual's current developmental level, the demands and possibilities of the social environment and the individual's needs (Chaiklin 2003; Engeström 1987). Helping students to resolve these double-binds involves the creation of new tools (both material and psychological), which the student then appropriates or learns and takes up in use. For example, students typically began by believing that the dance would not support faster nectar collection. Seeing this contradicted by BeeSign appeared to help motivate them to try and explain why.

An important notion in Activity Theory is that the subject's interaction with respect to the object of their activity is mediated (Wertsch 1981) by tools, the community, the rules of the community, and a distribution of labor amongst the members of the community (Engeström 1987). Figure 1 uses an activity triangle to illustrate these meditational relations. While a full discussion of the notion of

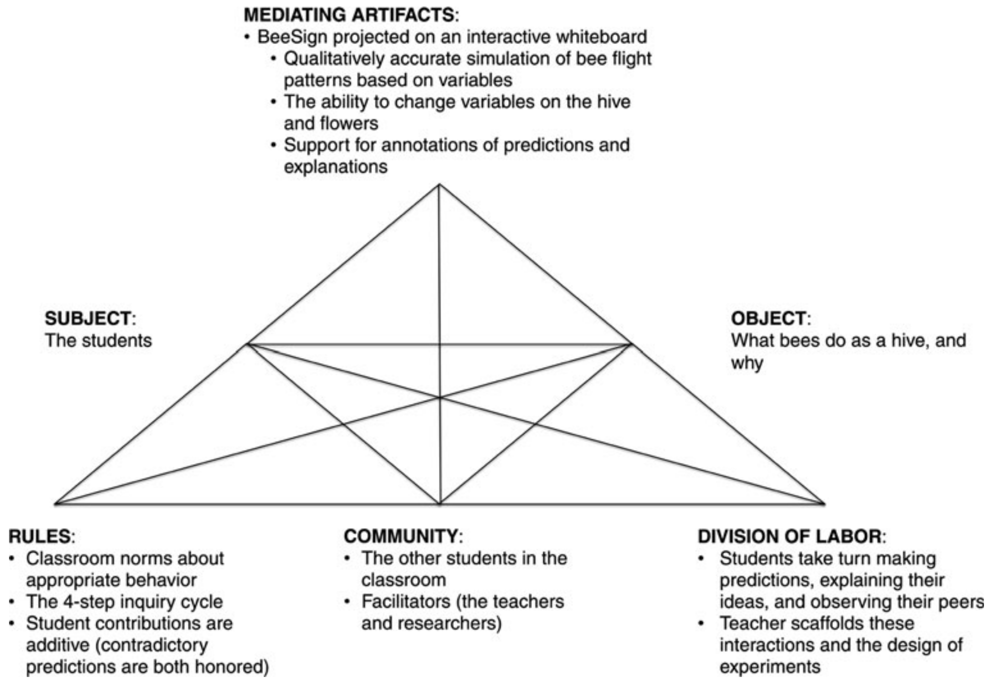

Fig. 1 The BeeSign activity system summarized, adapted from Engestrom 1990

mediation is beyond the scope of this paper, mediation represents a relationship between the individual (or subject) and the object of their activity that simultaneously defines and transforms their relationship with object. For example, the students in the present study were presented with many ideas about bees using the BeeSign software (the mediator). In this sense, they might not even have thought about the question of "how honeybees collect nectar" as a problem without the software (it helped to define their object). At the same time, the design of BeeSign makes certain patterns in honeybee flight visible to the students (it changed their relationship with the object). A further important aspect of this mediation is that all of the ongoing mediation is defined in relation to the other forms of mediation (Engeström 1990a, 1999; Roth 2007; Witte and Haas 2005). For example, we typically only had one student at a time come up to the board to draw a prediction on the projected BeeSign screen. Thus the division of labor was such that one student directly engaged with the software while the others viewed the students' contribution, changing their working conception of the software and the ideas that it represented, which they could then respond to.

The relational nature of activity makes it challenging to design for mediated activity because each aspect of the system is defined in part by the others, thereby creating a conundrum of where to begin one's analysis (Witte and Haas 2005). We have found that this tension is resolved by engaging in iterative cycles of design that are organized around specific instructional goals which each represent an aspect of the overarching object. In this process we simply define an instructional goal (e.g., help students to see the patterns in bee flight) and then iterate between proposed designs of the tool (BeeSign), the division of labor (e.g., only one student at a time can label the interactive whiteboard), and the rules (e.g., students are expected to attend to their peers). With specific learning goals in mind, it is possible to continually vet these relational means against each other as well as the overarching object of activity. We will outline the key goals that we strove to satisfy in the design of BeeSign below.

The Question of Unit of Analysis

Activity Theory guided us in thinking about the activity system in which young children were exploring the question of how honeybees collect nectar. The students' actions within this activity system, we argue, represent their potential within a Zone of Proximal Development. However, as educators, our interest does not end at the ZPD, and neither does an Activity Theoretic analysis. The power of the ZPD as Vygotsky (1978) defined it is that learning within the ZPD is in advance of a child's developmental ability and as a result has the potential to drive their development. Vygotsky also suggested that learning occurs as children appropriate new psychological tools, transforming them from the inter-personal plane of mediated social interaction to the intra-personal plane (in the mind). Therefore, if the children were truly in the ZPD as they engaged in our designed activity systems, they would also likely develop and appropriate individual intuitions.

As a result, our research was guided by two complementary questions that attempt to capture this relationship between the collective activity during the curriculum intervention and the individual reasoning that students were asked to engage in during the interviews. First, we asked whether we had in fact created a ZPD where students were able to productively engage with complex-systems concepts in the designed activity system. Second, we asked whether students had in fact appropriated these new concepts and could continue to offer similar explanations when asked to do so in an individual context (interviews) away from the social support structures provided by the activity system.

Methods

Research Context and Participants

This project took place with 40 first and second grade (ages 6–9) students in a mixed-age classroom in a public elementary school located in central Indiana. The majority of students at the school were White (90%) with only 17% of the students receiving free or reduced lunch.

The Complex Systems Unit on Bees

Before the start of our study, the classroom teachers made books about bees available to the children to read in their free time. These books included science illustrations pointing out the structures of the bees (e.g., the bee's head, thorax and abdomen) as well as other facts about how beehives operate. At the start of the current study, we administered pre-interviews with the students to establish what they already knew about honeybees and the process through which they collect nectar. While several students were able to learn a great deal about bees from their informal reading, as pre- and post- test results show, these opportunities did not, on their own, result in the children learning about the behavior of the hive at an aggregate level.

The Bee Curriculum

The students engaged in the bee curriculum in place of their regularly scheduled science activities. The curriculum consisted of roughly 1-h sessions that took place 2–3 days per week for a total of 18 sessions. The curriculum included a range of activities such as individual drawings, creation of skits, engaging in the BeeSim participatory simulation (Peppler et al. 2010), and playing a custom board game that we designed specifically for this study. Each of these activities was designed to help the students engage with different aspects of the honeybee system. For example, students' drawings were expected to help them think about the bee's anatomic structure, and the participatory simulation was intended to help them think about the inherent challenge in searching for nectar and the benefit of the bee dance in simplifying this search. The focus of the present analysis is on the role of BeeSign in supporting students' engagement with the hive behaviors at the aggregate level with a focus on emergence as it is the most elusive and challenging. BeeSign activities took place across a total of 6 days of the curriculum (Days 3/4, 11/12, 16/17), supporting three separate rounds of 45 min of small group inquiry (10–12 students per group).

The BeeSign Software

BeeSign[2] is a computer simulation of honeybees collecting nectar. There are two honeybee hives displayed on-screen in two side-by-side simulation windows (see Fig. 2). Students are able to change the variables affecting either the hives (e.g., do the bees dance to communicate nectar collection or simply remember where they have been before) or the flowers (do the flowers contain a lot of nectar; are they located near the hive). They can also determine what information is displayed on-screen (amount of nectar/quality of nectar) and how it is displayed (e.g., choosing a number, visual meter, or both). The students can then view the simulation in action using simple DVD-style controls to play or rewind the simulation. BeeSign was designed to be projected on an interactive whiteboard (see Fig. 3) so a group of 5–10 students could interact with it in collaboration with a facilitator (typically one of the researchers).

The current version of BeeSign included several new features that were added as a result of the initial study. Two specific features stand out. First was the inclusion of the ability to "zoom out", scaling the hives and flowers down so that students could view them as if from a further distance, which has the added benefit of making the benefits of the dance far more pronounced because it is now possible to position flowers much further from the hives. We also added a new "game" feature that allowed us to hide the labels on the beehives and then randomly determine whether or not the bees within would dance to communicate nectar source. Students then competed to be the first to notice whether or not the hive was "dancing" or not as a way of helping them to focus on the way that the dance related to the pattern in bee flight and speed of nectar collection.

As noted above, our design followed an iterative cycle of identifying our overarching goals and then specifying those mediators intended to meet those goals. To illustrate this process and identify the two main principles that we examine in the analysis section below we now present these overarching goals. Note that our assumption is that the subject (individual students) and community (their peers and the facilitator) did not change and that their

[2] BeeSign can also be seen at http://www.joshuadanish.com/beesign.

Fig. 2 The BeeSign Interface depicting the difference in bee flight patterns between a hive where the bees are dancing (*right*) and a hive where the bees simply remember the location of a flower (*left*)

Fig. 3 A student explains their prediction in BeeSign

relationship with the community is captured in the rules and division of labor.

Goal 1: Help Students Engage in Cycles of Inquiry

We developed a 4-step cycle of inquiry to be scaffolded by a teacher or facilitator working with a group of 5–10 students while using BeeSign on an interactive whiteboard. We based our model of inquiry upon the definition of inquiry within the national science standards which states "Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results" (NRC 1996, p. 23). Our 4-step version of an inquiry cycle using BeeSign included: (1) asking students to articulate their predictions, (2) running short experiments to observe the outcomes of the simulation, (3) describing observations of these outcomes, and (4) interpreting these findings and suggesting new questions to repeat the cycle. Therefore, specific aspects of the activity system were designed to accomplish each of these, with the activity triangle (see Fig. 1) serving as a reminder of the need to account for students' mediation via the mediating artifact (BeeSign), as well as by the rules and division of labor (see Table 1).

Goal 2: Help Students See the Patterns in Bee Flight

In order for students to successfully reach conclusions about the honeybees, they need to be able to identify and describe the resulting patterns of honeybee flight. Real bees

Table 1 The 4-step inquiry cycle used with BeeSign

Step in the inquiry cycle	Tool features	Division of labor	Rules
1. Make predictions	BeeSign supports drawing tools so that students can not only label their predictions for all to see, they can distinguish them (using color) and hide them temporarily while conducting the experiment	Student can see their peer's predictions and add to them. The facilitator can ask guiding questions	Students don't always get to make a prediction. Students are expected to attend to their peer's predictions. New predictions do not replace old predictions (multiple predictions remain visible for comparison
2. Observe the outcomes	BeeSign was designed to show clear, obvious patterns resulting from the honeybee dance (see below). This was further supported by the ability to control the scale of the simulation and the speed	Students were sometimes asked to attend to specific features (e.g., one student might observe the dancing hive closely while another student observes the competing hive). Students could also participate by pressing the play and pause buttons. Finally, regardless of what they were asked to do (or not) the students often called out their observations as the simulation ran, often directing their peer's attention to specific features	Students were expected to attend to the ongoing simulations
3. Describe the outcomes	The drawing tool supports students in reviewing their predictions or creating new visual documentation of their observations. Also, students can repeat the experiment as often as needed and the bees will always fly in the same pattern	The facilitator selects students to share their observations and/or modify the predictions. The facilitator can also highlight the match (or mis-match) between predictions and outcome as needed. The students observe their peer's responses	Students are expected to only speak one at a time and to listen attentively to their peers. Students were also expected to explain their reasoning. Additional explanations were expected to be unique and build upon or extend prior explanations
4. Interpreting the findings	By supporting students in conducting additional cycles of inquiry, BeeSign was intended to help students see the role of the bee dance in supporting effective nectar collection	The facilitator asks guiding questions and suggests follow-up studies. The students posit variables (such as the bee dance or the quality of nectar in the flowers) that can explain the difference in outcome between the two hives	One variable at a time is typically changed in order to systematically control the experiments

may have erratic flight patterns, need to avoid environmental obstacles, and occasionally do not find a nectar source. However, all of this additional "noise" might easily distract students from the underlying pattern in how the dance leads the bees to more consistently find the flowers containing nectar. Therefore, BeeSign was designed to support students in viewing and identifying qualitatively accurate patterns in how the bees fly and how quickly they collect nectar. These flight patterns are, in BeeSign, quite striking (see Fig. 2), often leading students to refer to the bees in flight as forming a "chain." This design choice was intended to build upon young children's strength in recognizing simple visual patterns, and avoid any potential difficulty they might have in recognizing patterns in a noisier environment.

We also wanted to ensure students went beyond recognizing the superficial patterns of bee behavior to describe the mechanisms that lead to these patterns. Therefore, BeeSign was designed to help students see certain aspects of the phenomenon, as described above, which helped to highlight the underlying mechanisms and import of the honeybee dance (e.g., the tool is designed to highlight the speed of nectar collection using a visual nectar meter). However, this is nothing new—the design of simulations and microworlds typically involves careful selection of the variables to display and the format of their display (White 1993). We also aimed to design a sequence of activities that the teacher might guide the students through, highlighting specific patterns and supporting students by asking specific questions at opportune moments. For example, to help students reflect upon the importance of rapid nectar collection, BeeSign includes a feature that simulates "winter." The sky darkens and the bees no-longer forage for food. However, as the students quickly realize, the bees do continue to consume the food in their hives, meaning that the bees with a larger nectar store are more likely to survive winter.

Data Sources and Analytical Techniques

In the current study, we used pre- and post- interviews and video data to inform our understanding of how young children develop ideas about the aggregate and emergent properties of complex systems.

Pre- and Post-Interviews

Pre- and post-interviews were conducted with the students on a 1–1 basis. Interviews were videotaped and lasted approximately 20 min, consisting of 31 questions. The present analysis focuses on a sub-scale of 6 questions designed to assess the student's understanding of the aggregate functions of bees. As noted above, the functional level of a system is the most elusive for children (Hmelo-Silver et al. 2007). Similarly, other approaches to complex systems (Resnick 1996; Wilensky and Reisman 2006) tend to highlight the challenges that students face in shifting from the local behaviors to their implications for more aggregate outcomes.

The questions that solicited students' aggregate level understanding included: (1) Using this diagram [picture of two hives with bees flying to collect nectar], can you tell which hive has the bees that dance and which one doesn't based on how they were flying? (2) Which hive would get nectar faster, the one with the dancing, or the one that doesn't dance? [and if so] How come? (3) Which hive is dancing? (4) How can you tell? Why does that mean they are dancing? (5) Which hive would get nectar faster? (6) Is it important for the hive to collect nectar quickly [and if so] how come? These questions were designed to elicit information about inferences students could make about flight patterns and determine if students understood that the bee dance directly impacted the colony's ability to coordinate their search for nectar as well as the aggregate impact of this behavior over time.

Interviews were transcribed and coded by a primary coder as either correct or incorrect. Inter-rater reliability with a second coder for 30% of the data was 92%. Percentages of correct answers were then generated to account for cases where an interviewer did not ask a question (typically when a prior question obviated the need). We then used a paired-samples t-test to determine whether or not the change from pre- to post-interview was significant.

Video Recordings of Classroom Discussions

All the student interactions with the BeeSign software were video recorded and then transcribed. The transcription was then parceled into interactional units that were defined by student responses to the prompts that the facilitator made (clarifying questions were considered to be within the initial interactional unit). Inaudible responses were removed from analysis. In sum, 656 unique interactions were identified across all days of the BeeSign curriculum.

We then analyzed the video in iterative cycles as proposed by Erickson (2006) to develop hypotheses about how the BeeSign interface supported students' activity and learning. These hypotheses were then revised through repeated viewing of the video and discussion amongst the research team. The transcriptions of the videos were done with attention to (a) the selected features of BeeSign, (b) the facilitators' speech and interaction with the BeeSign platform (e.g., choosing volunteers, running a simulation, revealing the nectar meters), (c) the students' speech and gestures (e.g., moving their arms in the patterned directions they predicted bees would fly), and (d) interactions with the BeeSign platform (e.g., drawing a prediction, pressing winter, etc.). The resulting coding scheme, which was not mutually exclusive, is summarized in Table 2.

Our second design goal was to support students in noticing patterns in honeybee flight. We generated a second set of codes, summarized in Table 3, which identified whether students were discussing (a) the aggregate flight pattern, (b) the aggregate speed of nectar collection, and/or (c) winter survival. Finally, we were interested in whether or not the students identified and described the honeybee dance accurately as the mechanism leading to the patterns noted above. Instances where students identified the dance as a mechanism were therefore identified and coded as either accurate or inaccurate (see Table 4).

Results

We now briefly report the interview results followed by the analyses of the students' interactions while using BeeSign.

Interview Results

The percentage of student responses that were coded as correct on the aggregate knowledge sub-scale of the interviews increased from an average of 25% answers correct on the pre-test (SD = 0.19) to an average of 70% correct on the post-test (SD = 0.28). This increase was significant $t(36) = 2.03$, $p < 0.000$ (two-tailed), suggesting that the children in this study gained in their overall understanding of the aggregate mechanisms of beehive behavior. Table 5 is an example of one students' change in understanding to illustrate how our codes were applied and what implications this might have for students' understanding (the student in question was a 2nd grade girl). In general, the students appeared to shift dramatically in their thinking, and to demonstrate a rich understanding of the mechanisms through which honeybees collect nectar.

BeeSign Sessions

We next sought to determine how the students developed these understandings. The primary context in which the

Table 2 Forms of facilitator prompts

	Notice	Prediction	Observation	Explanation
Description	(Prompts students to) Attend to the features of the simulation such as the location of flowers or the split screen.	(prompts to) Guess how the simulated event will play out.	(prompts to) Describe how the simulated event did play out.	(prompts to) Posit a mechanism or variable that explains why the event will or did turn out that way.
Examples	"What do you notice first of all about what's up here?"	"what will happen when bees come out of the hive?"	"What did they do when they first came out of the hive?"	"Why were the bees flying around like that?"
	"there's a sun."			
	"I see a flower"	"which one do you think is going to be faster?"	"Can anyone tell me what happened?"	[after a prediction is made] "interesting, why do you think it is going to be faster?"
	"So what's going on here [after adding an extra flower]?"			
	"there's two flowers"			"so why is it important that bees collect nectar"

Table 3 Aggregate patterns within the science content

	Flight pattern	Nectar collection rate	Surviving the winter
Description	Includes discussion of where the bees are flying	Includes discussion of the amount of nectar bees/hive are collecting from flowers.	Includes discussion of how bees need to collect enough nectar to stay alive during the winter time.
Examples	"they're going back to the flower and keep bringing it back"	Student explains "it gets them more nectar" to facilitator's question "what does the dance do for the bees"	"it helps them collect nectar for the winter"
	"[they're] going out of the hive in all different directions"	"they're eating up all the nectar and [the meter] is going down"	"they need [nectar] because they can't go out and collect it during the winter time"
	"um they come out of the hive, go to that flower and then go back to that hive"	"[they're getting nectar] a lot faster"	Student observes "they're starving" during the beesign winter time. Another student observes "they're eating the nectar for the winter time"

Table 4 Student discussions of mechanism

	Mechanism: bee dance	Mechanism: other
Description	Bees communicate the location of nectar with one another to find food. This dancing behavior can, in turn, explain the honeybee flight pattern, the quick collection rate of nectar, and how bees are able to survive winter (see the aggregate patterns from Table 2)	Other relevant variables to how honeybees collect nectar include (a) nectar quantity of flowers (b) proximity of flowers to hive and (c) the quality of nectar. In addition, students gave a variety of erroneous mechanisms (a sampling of which are below)
Examples	Correct: "I think they could be doing a dance to show each other it was the flower over there."	Incorrect explanation of speed of nectar collection: "Maybe bees in that hive are really slow and bees in that hive are really fast"
		Incorrect explanation of flight pattern: "[it goes to the sun] to see if there's a whole field of flowers"
		Correct explanation of flower preference "the flower is closer to the hive"

aggregate outcomes were studied and discussed was BeeSign. The BeeSign data also demonstrated that, in many cases, students held misconceptions at the beginning of one session and then shifted to the normative conception at the end of a single day's session with BeeSign, suggesting that their learning occurred during the session. We present an analysis of the students' interactions with BeeSign, following the order of the goals described above, to further articulate the role that BeeSign had in supporting students' learning.

Goal 1: Help Students Engage in Cycles of Inquiry

A high-level examination of the data reveals that the two facilitators (the first and second author) did in fact stick to the planned script of 4-step inquiry cycles. We further

Table 5 A representative set of interview responses

Aggregate interview questions	Pre-interview response	Post-interview response	Notes
1. Can you tell which hive has the bees that dance and which one doesn't based on how they were flying?	Well because honeybees like to move more but the bumblebees barely move	Yes. So say this is the one. So you would see it probably going back and forth [*finger gesturing in a straight line*] but only like a few bees maybe trying to go out to see if there may be another flower out there…[The non-dancing bees] probably would go because they would just go scattering out like so [*gesturing in all different directions*]. [Like] if you dropped some marbles they would just go all in different directions	This student appears to move from a conception of the bees moving more (likely as a result of the word dancing) to a nuanced and predictive description of how the dance will create a pattern in the bee flight. In addition to the obvious aspect of the pattern (the straight line of bees vs. the scattered bees), this student also remembered the more subtle pattern that honeybees will occasionally search for new nectar sources even when there is a known source
2. Which hive would get nectar faster, the one with the dancing, or the one that doesn't dance? How come?	Dancing. Because they can move faster and they move more so it makes them go faster so they're warmer	Dancing. Well, if you dance it tells more bees because most bees in the hive don't know where nectar is. For the ones that don't dance it takes a little while longer to figure out where a flower is. So if this was a line and a bunch of bees were going everywhere and that was a red flower usually they don't really go in the direction of the flower if they dance. So if one was going and the other one was going and one was going there and only one was going over there they would just go back and forth. So probably by an hour they would have 12% of honey. But if that flower had a lot of really good nectar and a lot of nectar so they would probably have 30 but this one, since that has good nectar, they would probably have 120 by now	The student's response on the post-test is particularly compelling because the student is able to trace the causal chain from the dance (within the hive) to the fact that the bees would more easily find a nectar source, which results in the speed of nectar collection
3. Which hive is dancing?	[Student points incorrectly to picture 'B' which displays bees that are not dancing]	A [pointing to the dancing hive]	
4. How can you tell? (Why does that mean they are dancing?)	Because they're all moving in different ways but this one is just like a line of one going back and one going out	Since most bees are not going all different directions they're all going to the same place. There's no bees all around here. They're all going to that flower and basically only one bee is going to that flower so that would probably be the one that's dancing	Notice how the student's response from the pre- to post- literally reverses itself. This is a clear indication both of the kinds of misconceptions students typically bring to complex-systems contexts and how they are amenable to change
5. Which hive would get nectar faster?	Dancing	Dancing	
6. Is it important for the hive to collect nectar quickly? How come?	[No response.]	Yes, because they don't have that much time since they're that small and the world is that big it takes a little while to get to a flower and back. So they want to try and get it as fast as possible because when it at least gets to Fall they can't fly that much or in April because it rains. For them the raindrops are about this big [*gesturing a large sphere*]	The student moves from not believing that speed of nectar collection matters to a nuanced understanding of the benefits of faster nectar collection as it relates to the survival of bees in times of inclement weather

examined the type of inquiry prompted by the facilitator and the type of student response. Not surprisingly, the two were closely linked; if facilitators prompted students to explain, describe, notice or predict an outcome, the student responses were often in kind (see Table 6). For example, see Excerpt 1. This is the first prompt that occurred in the use of BeeSign. As typically happened, the facilitator's request for simple observations resulted in exactly that. On rare occasions, as the curriculum progressed, students would leap ahead and offer predictions in place of noticing (e.g., responding by saying that not only have they noticed a flower, but that they expect the bees will go to that flower rather quickly).

So, young children are able to respond accurately to these types of inquiry requests, and will, when presented with these ideas and information that highlights them. However, they don't appear to respond with this type of information when they are not prompted directly (e.g., students rarely provided an explanation regarding the reasons behind an observation when they were not directly prompted for it). For example, Excerpt 2 depicts a scenario in which a student has observed that the bees are able to find a flower rather quickly. It is only after the facilitator specifically queries the students for an explanation that a student responds with an (erroneous) explanation for how this might have happened. With continued prompting another student then offers a more normative explanation in line 3. These examples demonstrate the importance of the framing of teacher prompts in shaping classroom inquiry and revealing student competencies.

Additionally, the type of facilitator prompts tended to shift over the course of the study. During the first two sessions of the BeeSign curriculum, facilitators tended to ask for more explanation and prediction. In the last BeeSign session, facilitators shifted to asking for more description and noticing of patterns. This tended to coincide both with the evolving understanding of the students as well as the game features that were engaged only on the third BeeSign session. Student responses followed similar patterns but during the third session they continued to offer explanations and predictions even when facilitators stopped asking students for these specific prompts, which is an indicator that students were internalizing these types of inquiry practices when they were producing them when unprompted by the classroom instructor.

Table 6 Proportion of student response types by facilitator prompt type

	Facilitator prompt			
	Notice	Predict	Describe	Explain
Student response				
Notice	75/86	1/142	0/142	0/158
Predict	2/86	135/143	0/142	25/158
Describe	1/86	2/142	134/142	18/158
Explain	0/86	31/142	22/142	139/158

Goal 2: Help Students See Patterns in Flight, Nectar Collection, and Winter Survival

We further probed how the BeeSign features appeared to support different kinds of aggregate patterns that children notice. To do this we looked at the key design features of BeeSign (i.e., the split screen comparison, the nectar meter, and the winter functions) and further examined the relationships between the BeeSign features and the patterns that the students were noticing in the discussion (i.e., the flight patterns, the nectar rate of collection, and the decrease in nectar storage when bees are surviving winter or adverse weather). While we hypothesized that we would see developmental shifts over time, particularly during the first session, it appears that the features of BeeSign made the aggregate patterns immediately obvious to the students, which resulted in high levels of these observations immediately at the start of the curriculum with relatively little change over time. This can be explained by the interface being designed to promote these understandings. In general, students tended to note the flight pattern about three times more than the other patterns. This may be because the split comparison feature was almost always used.

Excerpt 3 depicts an example in which the nectar meter was first introduced. The facilitator asks the students to predict whether the two hives (one with a flower close to it, and one with a flower far from it) will gain nectar at the same rate. The student appears to hesitate for a moment before stating that no, they will go up at a different rate. As the excerpt continues (line 5 and 6) we see another example of how the facilitator's prompt is crucial in soliciting the students' explanation for this (one of the hives is positioned with flowers that are farther away, which the student believes will lead to slower nectar collection). By the study's end, students regularly commented upon or claimed to know which hive was dancing based upon the speed of nectar collection, demonstrating an increasingly nuanced understanding of the relationship between the bee dance and nectar collection efficacy.

Moreover, certain features of BeeSign appeared to prompt certain types of pattern recognition. For example, the split comparison prompted students to notice flight patterns, having the nectar meters turned on prompted students to note the nectar rate of collection, and the winter function tended to encourage the kids to talk about the need for bees to survive winter and the resulting decrease in the nectar supply. Additionally, students tended to note these types of aggregate patterns before the emergence of talk

Excerpt 1 Noticing prompts noticing

1.	Facilitator	What do you see. This is a special computer program called BeeSign, what do you see over here?
2.	Student	I see a flower, a honeyco, honey, well a thingy a thingy

Excerpt 2 The facilitator prompt leads to a shift from description to explanation

1.	Facilitator	They all starting going really quickly to the flower. How did they figure that out? Any ideas?
2.	Student 1	Because they saw like the other bees, some other bees, were going then more bees starting going there maybe
		[The facilitator continues to solicit alternative ideas ultimately leading to the following response]
3.	Student 2	I think that… they… bees… might like (inaudible) The bees that went up and the bees that went down…they might like kinda feel their antennas and feel the ground and they will probably know that there's not a flower and then the bees that are going to the flower that we can see … they would probably do a little dance or do a signal for them to come to the flower that they found because they actually found the flower

Excerpt 3 The nectar meter helps the students notice the implications of the bee dance

1.	Facilitator	Now, what we are going to do is when the hives get nectar this [the nectar meter] shows how much nectar is in the hive [sets up simulation] so what is going to happen when we press play?
2.	Student	It is going to get higher and higher…
		[brief interruption]
3.	Facilitator	Is it going to happen at the same speed for both hives?
4.	Student	Well, no?
5.	Facilitator	Raise your hand if you think yes. Nobody thinks yes. Why no?
6.	Student	That one is closer and that one is farther away from the flower.

about the mechanism behind these patterns (i.e., the bee dance).

However, the BeeSign curriculum was designed to go beyond these potentially superficial pattern-recognizing exercises. At the core of the BeeSign curriculum is a drive to help students to understand the mechanisms driving the emergent properties of the hive. Under closer examination, students increasingly noted the bee dance as the mechanism driving the other patterns that they were seeing in the BeeSign simulation such as the organization of the bees flight and the increased nectar collection by the hive that danced when contrasted with one that did not. In the first BeeSign session students noted the bee dance accurately a total of 13 times (in 5.1% of the classroom interactions on that day). In session 2, accurate mentions of the bee dance increased slightly to 18 mentions (9.2% of the interactions on that day). During the third and final session, however, there was a more substantial jump to 32 mentions of the bee dance (which was 16.2% of the day's interactions). In order to compare the gains from session 1 ($M = 0.051$, $SD = .22$) to session 3 ($M = 0.162$, $SD = .37$), we used a paired samples t-test. This increase was significant $t(469) = 1.97$, $p < 0.001$ (two-tailed) and indicated that the number of times students made reference to the bee dance mechanism significantly increased in Day 3, echoing the findings from the interviews. Excerpt 4 illustrates both an initial misconception about the bee dance (that bees followed each other instead of communicating via the dance) and a more normative conception (that the dance is the reason multiple bees visit the same flower) demonstrated by two different students during the first BeeSign session. By the final session, the majority of the students were consistently demonstrating the normative view that the bee dance is the mechanism leading to the observed flight pattern of the majority of the bees visiting the flower known to be a good source of nectar.

We further probed to determine if there were particular prompts by the facilitators and/or features of BeeSign that appeared to be driving students to discuss the bee dance as the mechanism driving the behaviors of the hive (see Tables 7 and 8). In terms of facilitator prompts, a large number of the students mentioning the bee dance mechanism (75%) were the result of students responding to requests for explanation from the facilitator. We interpret this to suggest that many of the students who understood the bee dance mechanism did not explicitly discuss it until prompted by the facilitator. Next, we examined whether there was a relationship between the BeeSign features and students citing the bee dance as the guiding mechanism. Of the five features we looked at (i.e., game conditions, split comparison, nectar meter visibility, winter, and zoom), the proportion of interactions in which a student offered a mechanism description was highest for split comparison, nectar visibility, and game conditions (see Table 8). The split comparison finding may be misleading given that the split screen comparison was active the majority of the time.

Excerpt 4 An early misconception

1.	Facilitator	So why are they all going to the same flower now. What happened at the hive?
2.	Student	Well they're going back to the flower and keep bringing it back. One of them found the flower so the others are following it. […]
3.	Facilitator	What else could be happening?
4.	Student 2	I think they could be doing a dance to show each other that it was only the flower over there

Table 7 Proportion of facilitator prompts leading to a description of mechanism

Notice	Predict	Describe	Explain
1/64	11/64	13/64	48/64

Table 8 Proportion of times a feature was active when a mechanism description was given

Game	Split	Nectar	Winter	Zoom
27/64	54/64	35/64	3/64	9/64

However, we think the nectar visibility and game conditions may have coincided with more elaborate descriptions, resulting in the discussion of the mechanisms. This suggests that the facilitator prompt type and features of the software are closely linked to whether students are able to accurately cite the mechanisms driving the aggregate behaviors of the hive.

Discussion

Our analyses demonstrate that, through their interaction within the BeeSign activity system, first and second-grade students were able to engage with honeybees collecting nectar as a complex system at the ever-elusive aggregate level. These analyses extend prior work to demonstrate that students not only described the aggregate level patterns in how bees fly and collect nectar, but also articulated a number of accurate descriptions of the mechanism through which the bee dance leads to effective nectar collection. Furthermore, we have demonstrated that these discussions occurred in an activity that was within the students' Zone of Proximal development. Interaction within the ZPD, we have argued also lead the students to appropriate a conceptual understanding of these principals, which they were then able to apply in an individual interview setting.

At the heart of the design process that made this transformation possible lies a very simple assumption—that young children can engage in rich, complex science when the activity system supports it. To this end we have proposed a process that involves focusing on the activity system, and in particular the mediating role of the artifacts, rules, and division of labor in students activity. We believe that such a focus enabled us to engage in principled design, helping us to identify and design with those key mediators in mind. This approach does not guarantee success, and we believe that our own designs can continue to improve. Nonetheless, this approach was successful in resolving the issue that often arises in designs or analyses that attempt to leverage Activity Theory—given that everything is mediated, where does one start (Witte and Haas 2005)? Furthermore, this activity focused design generated what Sandoval (2004) has referred to as an embodied conjecture—a clearly articulated set of testable design principals. More specifically, we have been able to verify that the designed features of the activity system coincided with our hypotheses about how they might support student learning.

We propose the following process for using Activity Theory in creating similar designs. First, identify the object of students' activity. If the students are not already engaged with this object, design activities to bring it to their attention. We have found that leading students to questions that represent a double-bind, or untenable breakdown between their current understanding and an observation, is a productive approach to driving scientific activity. This follows similar approaches to problem based learning throughout the literature. Where our approach differs, however, is in how we suggest one approach the design of the activities once they have identified learning goals in the pursuit of the object.

Central to our proposed design approach is a very simple heuristic: once you have identified a learning goal, brainstorm the mediators that might support students in achieving their learning goal. As you identify a target mediator, note whether it is a tool, rule, or division of labor. Whichever it is, make note of the other two in relation to the identified mediator. This approach, we believe, circumvents the "chicken and egg" problem that often arises from attempting to begin one's work with a specific mediator. Similarly, it allowed us to side step a problem we have previously encountered wherein systematic approaches to design sometimes appear to conflict with one's natural tendency to flow from idea to idea. At the same time, the need to regularly and systematically work from each mediator to the other two is a key element to maintain a principled design approach. Furthermore, this design approach results in a carefully articulated embodied conjecture, which can then be used to support systematic verification of one's design choices and assumptions.

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