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Integrating the Dimensions of NGSS within a Collaborative Board Game about Honey Bees

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Abstract

The current reform in U.S. science education calls for the integration of three dimensions of science learning in classroom teaching and learning: Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. While the Next Generation Science Standards provide flexibility in how curriculum and instruction are structured to meet learning goals, there are few examples of existing curricula that portray the integration of these dimensions as “three-dimensional learning.” Here, we describe a collaborative board game about honey bees that incorporates scientific evidence on how genetic and environmental factors influence variations of traits and social behavior and requires students to collaboratively examine and use a system model. Furthermore, we show how students used and evaluated the game as a model in authentic classroom settings.

Keywords

NGSS; three-dimensional learning; game-based learning; honey bees; modeling

Introduction to Curriculum & Game

The current reform in science and engineering education, the *Next Generation Science Standards* (NGSS), based on *A Framework for K–12 Science Education* (National Research Council [NRC], 2012), identifies three dimensions or aspects that are integral to science education: Science and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. Each of these dimensions are expected to be woven together into curricula, instruction, and assessments to create *three-dimensional learning* (NRC, 2014). In other words, as students explore core ideas in science, they should do so while engaging in the practices and making connections to concepts common to all scientific disciplines.

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The writers of the NGSS are explicit in the intent that the standards “do not dictate curriculum” nor “the manner or methods by which the standards are taught” (NGSS Lead States, 2013, p. xiv). Thus, specific curriculum and instruction are left to be determined by districts, schools, and teachers. However, this means that those attempting to align their curriculum and instruction to the NGSS may still struggle with integrating the various dimensions of the standards. As K–12 science education moves toward adopting and implementing the NGSS, teachers and educators will need high-quality NGSS-aligned materials that are engaging and student-driven to use as a resource.

Here, we describe an example activity that incorporates three-dimensional learning in an engaging board game within a curriculum unit for students at a range of levels (with appropriate supports or adaptations) in grades 9–12. First, we introduce the curriculum unit that explores the biology of honey bee behavior – a timely and relevant topic because of the importance of pollinators in agricultural and ecological issues such as sustainability. Then we introduce a board game called “Swarm! The Honey Bee Game” that allows students to manipulate a model of various influences on bee behavior and the resulting impact on colony growth, which culminates in the successful reproduction of the hive in an event called “swarming.” Finally, we describe the gameplay and its connections to three-dimensional learning.

A Curriculum about Honey Bees

Imagine a hive of honey bees, humming with activity. The size of a honey bee colony naturally fluctuates throughout the year, and a healthy colony can contain >60,000 individual bees at its peak population. Within the hive, the vast majority are worker bees – sterile females that perform many different tasks throughout their lives. The worker bee’s role depends mostly on her age: younger bees typically clean the hive, care for larvae (nurse bees), and build the hive (comb builder bees); older bees may protect the hive (guard bees), remove sick or dead bees from the hive (undertaker bees), or collect nectar (forager bees). In addition to the worker bees, there are a few hundred to a few thousand drones (male bees) whose only purpose is to go on mating flights with a virgin queen bee from another hive. Finally, there is a single fertile queen bee, the mother of all the worker bees, who are sisters and half-sisters. After mating with several drones at the beginning of her life, the queen’s only role is to lay eggs. Contrary to the allusion to monarchy embodied by her name, the queen does not lead the colony, nor does she direct the behaviors of other bees (Winston, 1987).

If they do not have a leader, how do all those bees communicate, organize, and coordinate their behaviors to cool or warm up the hive, find new sources of food, or separate and form new colonies? Do genetic differences lead to differences in bee behavior? To what extent are bee behaviors influenced by the environment? By studying model organisms like honey bees, scientists have determined that “nature” (genetics) and “nurture” (environment) are

both important influences on traits like social behavior (Robinson, 2004; Robinson et al., 2008).

Such research inspired the authors, through Project NEURON at the University of Illinois at Urbana-Champaign, to create a curriculum unit about honey bees for high school biology teachers. Honey bees are a familiar and socially relevant context for student learning because they are commonly seen in nature and are pollinators of ecological and agricultural importance. Students investigate the driving question “What makes honey bees work together?” and explore how genetics and the environment affect individual and group behaviors of bees within their social colonies. Furthermore, students learn how scientists utilize honey bees as a model organism to study behavior, genetics, and neuroscience – among other topics.

Students play “Swarm!” in the second of four lessons in the unit. In the first lesson and prior to playing the game, students learn about different roles and behaviors of bees within the hive. In the third and fourth lessons, following the game, students design experiments to test how collective behaviors can influence the environment through a digital simulation and analyze data to explore the genetic basis for the evolution of such behaviors.

A Game about Honey Bees

Games, many of which contain simulations and models, have been identified as an area of interest in science education research (NRC, 2011). “Role-playing games” (Gaydos & Squire, 2012) or “participatory simulations” (Colella, 2000) engage students in model-related thinking as they adopt identities within meaningful contexts. These types of activities may also be particularly helpful for students who struggle within traditional classroom formats (Barab & Dede, 2007; Marino et al., 2012). Furthermore, collaborative board games have been shown to engage players in computational thinking (Berland & Lee, 2011), identified as a scientific practice within the NGSS.

“Swarm!” was designed for the high school biology classroom to support three-dimensional learning. Here, we describe the game briefly to provide a context for the subsequent discussion; detailed descriptions of gameplay and rules are available for free with the associated game materials and curriculum on the Project NEURON website (<http://neuron.illinois.edu/>). The goal of the game is for the honey bee colony (represented by the whole class) to “swarm” by sufficiently feeding and maintaining its population. In nature, swarming is the process by which the queen and several thousand worker bees leave the hive to create a new colony.

Before starting the game, students are placed in small groups of three to five members to facilitate collaboration and gameplay. Throughout the game, students perform some actions as a whole class (a colony represented by 10–30 students) and other actions individually or within their small groups. Students are guided in the game by the teacher and an illustrated QuickRules document (Figure 1), which illustrates game setup and the steps of each round.

At setup, students roll a die to determine the initial ages and roles of the worker bees within the colony. Each student starts with four worker bees, represented by four tiddly-winks (or

other marker) on the student's individual board. The board illustrates the possible paths of a honey bee as she progresses through her life (Figure 2). Students manage their bees as they age, progress through nursing and foraging behaviors, and die.

Each round, students must consider adjusting their bees' behaviors to balance the colony's production of brood and honey. Nurses contribute points to the Brood Score, and foragers contribute points to the Honey Score. These points are summed within groups and reported to the teacher, who records the total points for the entire class in a digital spreadsheet designed to organize data and calculate scores. Students are permitted (and encouraged) to discuss within and between their small groups about individual and collective strategies.

If the colony earns a high-enough Honey Score, an indicator that enough food was produced to support the colony, they receive a Honey Bonus. Likewise, a sufficiently high Brood Score rewards the class with a Brood Bonus and also allows students to add new bees to their boards, replacing bees that have died. When the class collaborates successfully to earn seven or more of each bonus within 10 rounds, the colony "swarms" and the class wins the game.

Incorporating Three-Dimensional Learning

The "Swarm!" activity integrates the three dimensions of Disciplinary Core Ideas, Science and Engineering Practices, and Crosscutting Concepts. Table 1 shows the components of the three dimensions that are most prominent in the game and aspects of the game that align to these components.

Connections to Disciplinary Core Ideas

"What makes honey bees work together?" is the name and driving question of the curriculum unit surrounding the game. In the game's context, the question specifically explores how the behaviors of individual honey bees are balanced and coordinated within the system of the colony. Researchers have found that a combination of genetic and environmental factors, mediated through social interactions, determine the behaviors and roles of worker bees. Thus, the game aligns most closely to the core ideas of "Social Interactions and Group Behavior" and "Variation of Traits" (including genetics and environmental influences) within the Life Science discipline.

LS2.D: Social Interactions & Group Behavior

A prominent form of communication in insect colonies occurs through trophallaxis, or the passing of food or liquid mouth-to-mouth between individuals. Older forager bees produce a pheromone that delays maturation in younger nurse bees; this pheromone is passed to hive bees when they receive nectar collected by foragers (Huang & Robinson, 1999). Thus, when a hive is starving, it is primarily a lack of foragers that prompts nurse bees to become precocious foragers, not assessments of food stored within the hive (Schulz et al., 1998). Furthermore, genetic differences can modulate production of, or sensitivity to, this and other pheromones to create behavioral variation among individual bees; the influence of genetics on behavior is discussed further in the next section.

A major component of the “Swarm!” game is that students are able to collaborate with each other to succeed in the game as an entire class. Although game rules do not dictate methods of collaboration, game testing showed that students consistently communicated directly with each other within their small groups and, in some cases, between groups. Conversation between groups in the game serves as a representation of the complex communication that takes place within animal societies.

LS3.B: Variation of Traits: Genetic Factors

In nature, worker bees have a typical life span of approximately six weeks as adults, and during that time they perform many different tasks, depending mostly on age. When a worker bee emerges (“ecloses”) from her cell as a fully formed adult, she will first perform tasks inside the hive such as caring for brood or “nursing” (Winston, 1987). After about three weeks, she switches to tasks outside the hive such as foraging; the occurrence of such behaviors in the last portion of a worker’s life may have evolved that way because of associated risks and increased mortality (O’Donnell & Jeanne, 1994). Scientists have identified groups of gene candidates associated with the transition from internal to external hive tasks (Whitfield et al., 2006; Zayed et al., 2012), but a complete functional understanding of how specific genes influence behavior is still unknown.

In the game, the developmental progression (and associated tasks) of worker bees is demonstrated as students “age” their bees once per round by moving each bee one space forward along the path with solid arrows on the board (Figure 2). The typical path starts at Brood (one round) and continues to Young Nurse (three rounds), Mature Nurse (indefinite rounds), and Forager (three rounds) before ending at Death.

The process of changing from a nurse to a forager is accompanied by many physiological changes, driven by genetics, in the worker bee’s body. For instance, nurse bees have large hypopharyngeal glands that produce proteins beneficial to the brood they feed, whereas these same glands in foragers are smaller and include enzymes for converting nectar to honey (reviewed in Winston, 1987). Other changes in foragers include reduced body fat (Toth & Robinson, 2005), modified wing muscles for flight (Harrison, 1986), and neural changes in preparation for and in response to increased visual and olfactory experience, in order to navigate outside the hive (Withers et al., 1993, 1995; Farris et al., 2001). Although genes provide the “instructions” for how to undergo the process of changing from a nurse to a forager bee, the exact timing of the age at which a nurse changes roles to a forager is mediated by environmental factors.

LS3.B: Variation of Traits: Environmental Factors

Environmental factors that determine variation of traits can include factors both outside the hive and inside it. Outside the hive, the colony may be affected by weather, season, disease, predators, and humans. These types of events are represented by Environment Event cards in the game, which are randomly selected by the teacher each round. Each card is based on a theoretically feasible event and may have a positive, negative, or neutral effect. Some examples are shown in Table 2. (The game also includes a sheet of blank cards, so classes

can add their own events if desired – another way in which students can manipulate the model.)

Although environmental events external to the hive are more obvious in the game model, there are other, more subtle influences from the environment within the hive. The composition of the roles and ages of bees in the colony can affect the roles of other bees, especially young bees. If there are not enough nurse bees in the hive, some foragers will become “reverted nurses” and care for the brood; if a colony is starved, some nurse bees convert prematurely into “precocious foragers” (for details, see below). In nature, this process is mediated by pheromones that are communicated throughout the hive via social interaction. In the game, this communication process is modeled through the flow of colony information from teacher to students and explicit student group discussions. For example, during the “Change bee roles” step, students collectively decide within their small groups if bees should revert to Nurses or convert to Foragers prematurely; and during the “Record reasoning” step, students write down which factors influenced their decisions (see illustration of general gameplay in Figure 1).

Connections to Crosscutting Concepts

The Crosscutting Concepts are overarching ideas that exist across all disciplines of science. While these concepts are often implicit within science instruction, drawing attention to them can help students develop a comprehensive and meaningful view of science and engineering (NRC, 2012). Although the game touches on many concepts, it connects to the concepts of “Cause and Effect” and “Systems and System Models” most strongly.

Cause & Effect

Cause and effect is examined in many different aspects of the game. When students are deciding whether or not to change the roles of their honey bees, they explore possible patterns across the rounds of the game and examine what causes their scores to go up or down. In a broader sense, they are determining what causes honey and brood production to increase or decrease within a hive, and they are predicting the effect that changing or not changing the roles of their honey bees will have on the system, testing those predictions (either individually or as a group) by changing the roles of their honey bees, and observing the outcomes at the colony level in the next round.

As students reflect on the game, it is important for them to recognize how cause and effect differs between nature and the game. In the game, students make decisions about how bees will behave. In real life, honey bees do not take directions from a leader, nor do they have a formalized quantitative framework (such as points or scores) to direct or coordinate their behavior. Therefore, what affects the individual path of a honey bee and the roles that she performs throughout her life? What exactly causes her to change from one role to another? As described previously, current scientific knowledge suggests that a combination of genetic factors, environmental effects, and social interactions within the colony influences the brain of an individual honey bee to cause behavioral changes.

Systems & System Models

Hives, like other systems in nature, are very complex. It is helpful, when studying a system, to define its boundaries and initial conditions. Limiting, defining, and analyzing a system as a *system model* is particularly helpful for scientists trying to understand the parts of the system and their relative influence on the system as a whole (and vice versa). In this case, students' experiences playing the game can give them an appreciation for the complexities of a system. The qualities and uses of a model, as well as core content knowledge about the honey bee hive as a system, are communicated to students as they participate in the activity.

Connections to Science & Engineering Practices

The main practice addressed in "Swarm!" is Developing and Using Models (a detailed description of the practice from the NGSS Appendices is provided in Figure 3). The writers of the *Framework* and the NGSS encourage a conceptual shift in the definition of a model from the physical replicas used in traditional classrooms to a definition that encompasses the many different types of models used by scientists. These authentic types of models include "diagrams, physical replicas, mathematical representations, analogies, and computer simulations" (NGSS Lead States, 2013, p. 52).

As described previously, role-playing games and participatory simulations contain models and can be meaningful contexts in which students engage in model-related thinking. Although "Swarm!" and the surrounding activity touch on several components of what models are and how they are used by scientists, we will concentrate on illustrating the (a) limitations and approximations of the model, (b) features that are based on scientific evidence, and (c) how students use the game to generate data and make predictions. We also share summaries of data collected from authentic classroom settings in which (d) students evaluate the game as a model.

Limitations of the Model: Assumptions, Focus & Obscurity

As stated in the NGSS, models "bring certain features into focus while obscuring others" (Appendices, p. 52). The features brought into focus in "Swarm!" are the nurse bees' role in nurturing the colony's population and the forager bees' role in gathering and providing food for the hive; other worker-bee tasks, such as guarding, undertaking, or comb building, are not represented. Including only two specific worker-bee roles, nursing and foraging, allows students to more easily focus on the environmental and genetic cues that influence particular bee behaviors.

In order to focus on the roles of the worker bees, the reproductive roles of the colony are obscured. Male drones are not represented in the game, and neither is the queen. It is assumed that the queen lays eggs at a constant rate and that the number of bees raised successfully to adulthood is only affected by the number and ability of the nurse bees. In nature, brood production depends on additional factors such as colony size and health, season, and nutrition (Harbo, 1986).

Approximations Based on Scientific Evidence

While guiding the class through the game, the teacher uses a spreadsheet to calculate the scores and determine whether the colony reaches its goals of making enough honey and caring for its brood. Each bee in the colony produces points that contribute to the Honey Score and Brood Score. If one or both of those scores is high enough, the colony receives bonuses that are necessary for winning the game.

In each round of the game, if students succeed in obtaining a Brood Score greater ≥ 2 , they earn a Brood Bonus and get to add more bees to their boards. However, if the Brood Score is < 2 , then there is no bonus, and no new bees are added in that round.

The Brood Score is calculated within the teacher's Excel sheet as

$$\text{Brood Score} = \frac{\sum(\text{Nurse Bee Points})}{\sum(\text{Forager Bee Points})}$$

This simplified model is based on scientific evidence that suggests that the “ideal” ratio of nurse to forager bees is approximately 3:1 nurses to foragers (or 25% foragers). In scientific manipulations of colonies, if there are too many foragers and not enough bees performing nursing tasks, some foragers will revert to nurses until an ideal nurse-to-forager ratio is obtained (Robinson et al., 1992). In the game, this can be simulated if the failure to obtain a Brood Bonus prompts students to change the roles of Mature Foragers to Reverted Nurses.

If students earn a Honey Score that is 90% or more, they earn a Honey Bonus that round. The Honey Score is reported as the percentage of the maximum amount of honey possible (based on the work of forager bees):

$$\text{Honey Score} = 100 \times \frac{4 \times \sum(\text{Forager Bee Points})}{(2 \text{ Bee Points}) \times (\text{N of students}) \times (\text{N bees per student})}$$

The denominator is the maximum possible Forager Bee Points that the colony can earn, based on the initial bee population. Forager bees can earn a maximum of 2 points each, and the initial bee population is the number of students in the class multiplied by 4, the default starting number of bees per student. The value of Forager Bee Points in the numerator is doubled to ensure that the 3:1 ratio of nurses to foragers can be viable without the colony starving; since the “ideal” portion of foragers in the hive is 25%, this ensures that the Honey Score will be 100% at that ideal.

The game mechanic of the Honey Score is also modeled on scientific evidence. When an actual honey bee colony is starved, nurse bees will become new or “precocious” foragers (Schulz et al., 1998). In the game, the failure to receive a Honey Bonus may prompt students to change the roles of Young Nurses to Precocious Foragers.

The consequences of bees changing roles outside the typical life progression of brood–nurse–forager is also based on scientific evidence in real colonies. Nurses who change roles prematurely and become “precocious foragers” are not as efficient in gathering food

resources (Perry et al., 2015), and large numbers of foragers who become “reverted nurses” are associated with higher brood mortality in the colony (Robinson et al., 1992; Toth & Robinson, 2005). In the game, this is reflected in the fact that Precocious Foragers and Reverted Nurses earn half as many points as their respective counterparts, Foragers and Nurses.

Generating Data & Making Predictions

A key part of the game occurs at the end of every round, when students have the option of changing the roles of their bees in order to increase their chances of receiving Honey or Brood Bonuses in the next round. Failure to earn a Honey Bonus in the previous round may be an indicator that honey production is low because there are not enough foragers in the colony; likewise, failure to earn a Brood Bonus may be an indicator that there are not enough nurses. Creating a balance between honey production and brood production may be achieved by changing the roles of bees from nurse to forager or vice versa. However, this strategic advantage must be weighed against the fact that Precocious Foragers and Reverted Nurses contribute fewer points to the Honey and Brood Scores.

Students wrestle with these decisions as they discuss within their small groups, recording their decision and reasoning every round on a provided student sheet. Thus, students analyze data (Honey Scores and Brood Scores), make predictions of the influences of honey and brood production (relative contributions of points), and manipulate the model (change roles of their bees) – key aspects of the scientific practice of developing and using models.

Student Evaluation of the Model

In this section, we offer evidence from authentic classroom settings to show how students evaluated the game as a model. During iterative development, the “What makes honey bees work together?” curriculum unit and game were tested by several teachers, one of whom taught at a public high school with ~1000 students, 64% of whom were identified as low income. This teacher implemented the curriculum in three AP Biology courses across two semesters: the first semester had two classrooms of 19 and 10 students, and the second semester had one class of 25 students. After playing the game, students responded to surveys with open-ended questions that asked students to evaluate various aspects of the game as a model, such as the accuracies and limitations of the model. The survey questions were developed from the discussion questions provided to teachers within the lesson plan of the curriculum materials available on the Project NEURON website (<http://neuron.illinois.edu>). A total of 35 surveys were collected from students who provided assent and consent (18 the first semester and 17 the second semester).

We found that students were able to use their existing knowledge of honey bees from the unit to evaluate the game as a model. In reflecting on how the goals of the game represent honey bee behaviors, most responses stated that it accurately modeled the evolutionary drive of honey bees to survive (61%) and reproduce (35%). Some students also included how the roles of the bees (19%) and the balance of these roles (16%) were modeled. Students also identified limitations of the model; responses included the absence of the queen (25%), the number of bees represented in the hive (21%), approximations in how scores were calculated

or used (14%), and the absence of drones (11%). These values help give a sense of students' most common ideas about the game and conceptualization of actual bee hives. For example, more students noted the absence of the queen bee over the absence of the drones. Although both queens and drones are important for reproduction, students may be more familiar with the queen bee and therefore quickly identify her absence as a limitation of the model.

Students were also able to recognize the core disciplinary ideas integrated within the game, but this also seemed to be somewhat mitigated by explicitness in gameplay. For example, when evaluating how environmental influences of behavior were modeled in the game, 56% of responses said that the environmental event cards influenced their decisions, especially in how events affected bee behaviors (50%) and the balance of tasks (44%). In addition, many students recognized that bee behaviors were influenced by genetics (48%), especially in terms of age (24%) and how bees could change roles (24%). However, a small number of students also mistakenly thought that the die rolling during game setup (to establish the initial condition of the hive) represented the influence of genetics (17%). Although the reasons for this misconception are currently unknown, it may be because students perceive genetics primarily as a "predetermined" cause that affects traits before birth, and are not as aware of how genetics could affect behaviors throughout life. We plan to continue exploring these student perceptions in future research, especially how implementation of the game may contribute to these perceptions or be used as a method of uncovering these misconceptions. For instance, an introduction of genetic influences on behavior before the game may mitigate student misconceptions on the purpose of the die roll during setup.

In future iterations of this game, we are planning to formalize the discussion and evaluation of games as models by developing a rubric for the task. We are also designing extension activities to challenge students in their use of the game as a model. For example, students could compare the game to scientific models in primary research literature; Khoury et al.'s (2011) model of colony population dynamics or Russell et al.'s (2013) model on colony growth and failure include much of the same scientific evidence found in "Swarm! The Honey Bee Game." Students could also estimate or modify the underlying equations that drive the model within the teacher's spreadsheet. Both of these extension activities would integrate more in-depth elements of the "Developing and Using Models" practice at the high school level, which includes comparing multiple models of the same system and utilizing mathematical models, and also connect to the "Mathematics and Computational Thinking" practice from the NGSS.

Conclusions

As states continue to adopt the NGSS, districts and teachers will need to find creative ways to engage their students in learning that integrates multiple dimensions of the NGSS. We examined how a collaborative board game that simulates worker bees within a colony could be used to address integrated Scientific and Engineering Practices, Crosscutting Concepts, and Disciplinary Core Ideas. We found that the game incorporates many aspects of the scientific practice of developing and using models, including assumptions and focusing on or obscuring aspects of reality, limitations and approximations based on scientific evidence, and student evaluation of the game as a model. Furthermore, the mechanics of the game

create a context to explore scientific ideas such as cause and effect, and systems and system models, within the context of the genetic and environmental influences of behavior, which are mediated through social interactions within the colony.

Data from a survey of students in classrooms that piloted the game suggest that students are able to evaluate the game as a model by identifying strengths and limitations, and making connections to core biology ideas and crosscutting concepts based on their current understanding of bees. Thus, games and simulations, especially if they are collaborative, are a promising way to engage students in three-dimensional learning as they communicate their understandings and strategies.

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Figure 1.

The QuickRules document guides each group of students, showing (a) conditions for winning the game, (b) rules and progression for setting up the game, (c) general progression of steps for each round, and (d) a key for which actions are performed as a whole class or within their small groups.

Figure 2.

A game board for an individual student, showing the age progression and associated tasks that are possible for their bees. The space that a game marker rests on represents a bee and her current role, which depends largely on her age: **(a)** The yellow space at the top is for “brood” or a new bee, **(b)** green spaces with “larva symbols” indicate a bee with Nurse roles, **(c)** blue spaces with “honey dipper symbols” indicate bees with Forager roles, and **(d)** black spaces at the far right indicate that the bee is dead. The symbols on the board also indicate

the relative number of how many Nurse Bee Points (larva symbol) and Forager Bee Points (honey dipper symbol) each bee will contribute to the Brood and Honey Scores, respectively.

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Models include diagrams, physical replicas, mathematical representations, analogies, and computer simulations. Although models do not correspond exactly to the real world, they bring certain features into focus while obscuring others. All models contain approximations and assumptions that limit the range of validity and predictive power, so it is important for students to recognize their limitations.

In science, models are used to represent a system (or parts of a system) under study, to aid in the development of questions and explanations, to generate data that can be used to make predictions, and to communicate ideas to others. Students can be expected to evaluate and refine models through an iterative cycle of comparing their predictions with the real world and then adjusting them to gain insights into the phenomenon being modeled. As such, models are based on evidence. When new evidence is uncovered that the models cannot explain, models are modified. (NGSS, volume 2: Appendices, p. 52)

Figure 3.

The detailed description of the scientific practice “Developing and Using Models” (NGSS Lead States, 2013). Underlined phrases highlight the aspects of models focused on in this article’s discussion of the game in three-dimensional learning.

Table 1

Components of each of the three dimensions in the *Next Generation Science Standards* (NGSS) for grades 9–12 (NGSS Lead States, 2013, vol. 2: Appendices) and their integration within specific components of “Swarm! The Honey Bee Game.”

Components of the Three Dimensions in the NGSS	Aspects of the Game That Align to the NGSS Component
Disciplinary Core Idea LS2.D: Social interactions and group behavior (Grades 9–12): “Group behavior has evolved because membership can increase the chances of survival for individuals and their genetic relatives.” (p. 44)	Students communicate verbally with each other within their small groups and occasionally between groups. Communication is indirectly rewarded in the game because it increases the chance that students will be able to coordinate their efforts and win the game.
Disciplinary Core Idea LS3.B: Variation of Traits (Grades 9–12): “The variation and distribution of traits in a population depend on genetic and environmental factors.” (p. 44)	Genetic factors: Once per round, students “age” their bees by moving each bee one space forward on the game board, modeling age-associated behavioral changes in bees.
	Environmental factors: Environment Event cards introduce random events that have a positive, negative, or neutral effect on gameplay once per round; students may also change their bees’ behavior depending on the internal hive environment (e.g., student decides to revert foragers to nurses because of large numbers of foragers in the class’s colony).
Crosscutting Concept Cause and effect (Grades 9–12): “[Students] suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems ... They recognize changes in systems may have various causes that may not have equal effects.” (p. 83)	Students explore cause-and-effect relationships primarily between the roles of nurse and forager bees and (a) the related Honey and Brood Scores (modeled honey production and brood care) and (b) environmental events and genetic factors (e.g. limited life span of honey bees).
Crosscutting Concept Systems and system models (Grades 9–12): “[Students] use models ... to simulate ... interactions within and between systems at different scales. They also use models and simulations to predict the behavior of a system and recognize that these predication have limited precisions and reliability due to the assumptions and approximations inherent in the models.” (p. 85)	The game model is based on a honey bee colony system, including worker bees, resources, and external environment. Student gameplay models interactions between behaviors of worker bees within a hive. During gameplay, they make predictions about how their actions as an individual, small group, or class might affect the class score each round and adjust their reasoning based on the results of their tested predictions. Students are asked to evaluate the assumptions and approximations (affordances and limitations) of the game as a model.
Science and Engineering Practice Developing and Using Models (Grades 9–12): “Modeling in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables in the natural and designed world(s).” (p. 53)	The post-game discussion (debrief) encourages students to determine the assumptions and limitations of the game as a model. For example, the game focuses on the behaviors of worker bees (especially nurse and forager bees) but not bees in reproductive roles (drones or the queen). Within the main text, we describe the evidence-supported mathematical models underlying the game simulation. Throughout the game, students generate data (scores), make predictions, and manipulate the model through their role playing.

Table 2

Examples of “Environment Events” within “Swarm! The Honey Bee Game” and their effects on the game mechanics.

Environment Event	Effect on Game Mechanics
“Clover is in bloom, and nectar is plentiful.”	“Add 20 points to the Honey Score this round!”
“The brood are diseased because of an infestation of mites.”	“You do not receive a Brood Bonus this round, regardless of the Brood Score.”
“An assistant beekeeper adds a small feeder with extra honey and pollen to the hive.”	“Each Reverted Nurse produces 2 Nurse Bee Points [instead of 1] next round.”
“A pesticide is accidentally sprayed on blooming wildflowers and is eaten by Forager bees.”	“All Foragers move forward an extra cell during the ‘Age Bees’ step.”
“Some drones do not return from a mating event.”	“The Honey Score and Brood Score are not affected.”