Learning Biology Coherently Through Complex Systems, Scientific Practices, and Agent-Based Simulations

Miyoung Park, Emma Anderson, and Susan A. Yoon
parkmi@gse.upenn.edu, ejanderso@gmail.com, yoonsa@upenn.edu
University of Pennsylvania

Abstract: The Next Generation Science Standards (NGSS) calls for greater coherence in how science is taught and learned in K-12 classrooms. Research on biology classrooms has shown that different units are often taught in a disconnected way, with little focus on unifying themes (e.g., systems) that connect various concepts together in the study of biology. In this study, we hypothesized that a curricular model based on scientific practices and agent-based simulations to teach biology through a complex systems lens would support students' coherent understanding of biology. We investigated the extent to which and ways our curriculum supported students' biology coherence. Units covered topics of diffusion, ecology, enzymes, evolution, genetics, and modeling. Fifty-four students were randomly selected for focus group interviews from a larger study of 463 students. Findings provide promising evidence that students developed a coherent understanding of biology.

Keywords: Biology Teaching, Complex Systems, Modeling, Simulations, Scientific Practices, Integrated Knowledge, Curricular Coherence, NGSS

Introduction

The Next Generation Science Standards (NGSS) in the United States has required a shift in how science is taught and learned in K-12 classrooms. There exists a greater focus on cross-cutting themes such as systems thinking and modeling in order for students to have a deep and more connected understanding between various concepts that are taught (NRC, 2012). Too often, long lists of disconnected facts are taught to students with a focus on breadth, rather than on the overall coherence of how students understand science. This type of approach is alienating to students and also leaves them with fragments of knowledge that provides no sense of the creative achievements of science, logic and consistency in science, and the universality of science (NRC, 2012). Some science education researchers have suggested that, in order to be a scientifically literate adult, knowledge of relationships among ideas is key—understanding the ways important ideas fit together (Roseman, Stern, & Koppal, 2010).

A coherent understanding of biology is defined by an integrated understanding of the various units that comprise the study of biology. This means that students are able to connect separate topics with one another in a way that helps them to better understand biological phenomena (Fortus & Krajcik, 2012). Additionally, an understanding of the relationships and patterns across units enables learners to explain and predict phenomena as well as solve problems (Fortus & Krajcik, 2012). Yet, there are challenges that students face in developing a coherent understanding of biology. First, there exists a lack of integration across topics in science (Chiu & Linn, 2011; Chiu & Linn, 2014; Gilbert & Boulter, 2000; Klymkowsky & Cooper, 2012; NRC, 2012). Second, static images and the ways processes are presented in textbooks make it difficult for students to see the dynamic nature of various phenomena, which make it hard for students to learn biology coherently (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010). Third, science is often taught in a didactic manner, requiring students to learn concepts through rote memorization, which adds to the issue that students often learn long lists of disconnected facts (Anderson & Schonbom, 2008; Osborne, 2014).

We developed a curriculum intervention, which was designed to address these challenges that students face in learning biology coherently. This curriculum supported students' connected understanding of biology through complex systems as an integrated theme, use of dynamic visualizations, and student investigations of scientific practices related to inquiry and argumentation. The research questions that guide our study are: (1) To what extent did the curriculum help students to learn biology coherently?; and (2) How did the curricular model support student understanding?

In the following section we discuss the curricular design choices and provide evidence from the literature that demonstrates how, in combination, these choices may address the curricular coherence problem.

Conceptual framework

The study's conceptual framework is underpinned by three current research areas in science education that include learning about complex systems, instructional use of agent-based simulations, and scientific practices that more closely represent how science is done in the real world. Each unit in our curriculum was taught through a complex systems lens in order to respond to the lack of integration across topics in science (Chiu & Linn, 2011; Chiu & Linn, 2014; Gilbert & Boulter, 2000; Klymkowsky & Cooper, 2012; NRC, 2012). Agent-based simulations are an integral part of our curriculum because they address the disparate and static manner in which textbooks present phenomena (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010). To address the prevalence of didactic instruction and rote memorization strategies in science class, we integrated key scientific practices that encouraged students to actively construct knowledge (Anderson & Schonbom, 2008; Osborne, 2014). We expand on each of these literature bases in the following section.

Complex systems

Systems and system models have value for integrating and unifying concepts (Pratt, 2012). Yet, students often have misconceptions about systems, believing, among other things, that they are controlled by a central agent and intentionally designed with certain functions (Taber & Garcia-Franco, 2010). Learning about complex systems is important as students develop understandings about the variability and unpredictability of systems (Osborne, 2014). Complex systems are characterized by multiple interrelated parts that form non-linear relationships, which exhibit emergent properties. Because of this non-linearity, small changes can have large consequences (Yoon, 2008; Yoon, 2011). Curriculum developed through a complex systems lens can cut through various domains and concepts in science (Yoon, 2011; Grotzer et al., 2015; Wilensky & Rand, 2015). Although other studies have examined aspects and challenges of students' complex systems understanding (Ben-Zvi Assaraf & Orion, 2010; Ben-Zvi Assaraf & Orpaz, 2010; Chi et al., 2012; Grotzer et al., 2015), we do not know of any studies that looked purposely at how computational thinking through complex systems can contribute to developing a coherent understanding of biology.

Agent-based simulations

The second aspect of our conceptual framework and curriculum involves the use of agent-based simulations. Learning through simulations and modeling can lead to greater understanding of scientific phenomena through scaffolding student meaning-making (Smetana & Bell, 2012). Visualizing patterns is better accomplished through computer simulations than through static images or descriptions found in textbooks (Yoon et al., 2013). Chiu and Linn (2014) demonstrated that dynamic visualizations helped increase connections among students' ideas about chemical reactions compared to typical instruction. Beyond the simulations themselves, agent-based modeling allows the student to connect micro and macro aspects of scientific phenomena. By tinkering with the programming, students can explore questions, which reveal the implications of their ideas, while simulating new ideas (Wilensky et al., 2014). Agent-based simulations enable students to understand how processes work together in emergent ways. In this study, we are interested in what ways this support enables students to learn about biological complex systems in a dynamic way for coherent understanding.

Scientific practices

As students engage in scientific practices, they are involved in the very practices that are essential for a deeper, more nuanced understanding of science (NRC, 2012). The NGSS identifies eight scientific practices for K-12 classrooms: asking questions, developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations, engaging in argument from evidence, and obtaining, evaluating and communicating information (NRC, 2012). In one study, the importance of students' designing, conducting, and critiquing experiments was highlighted to promote a coherent understanding of science (Chang & Linn, 2013). Students are being pushed to move beyond rote demonstration of scientific content to developing, using, and engaging in constructing knowledge to make sense of the world (Berland et al., 2015).

Methods

Context

This study is part of a larger project in which a series of units were developed to support improved understanding of biology through a complex systems approach in the following topics: diffusion, ecology, enzymes, evolution, genetics, and modeling. Each unit takes 2-3 days of instruction to implement in a classroom. The units can be implemented in any order the teacher believes will best suit the curriculum in their classroom. Along with the curricular units, teachers were also provided with off computer tasks that could be used to introduce or reinforce complex systems ideas.

Each unit consisted of a simulation and student packet, which scaffolded students' learning about complex systems, scientific practices, along with biology content knowledge. Each of the curricular units was intentionally constructed with complex systems components to enable students to understand multiple different biological phenomena through a complex systems perspective. For example, in the unit on evolution, complex systems was first emphasized in the packet introduction. It highlighted how genetic drift is due to random chance survival. Additionally, the units on diffusion, ecology, enzymes, and genetics also all emphasized randomness as a key component in understanding biological phenomena.

In terms of scientific practices, students were asked to make hypotheses, collect data, create and interpret graphs, compare results, answer argumentation questions, etc. In addition, several units required students to read or manipulate the simulation's code. For example, students were asked to go 'under the hood' to explore how fish move. Figure 1 provides an example of instruction and questions students are given in order to interpret the code.

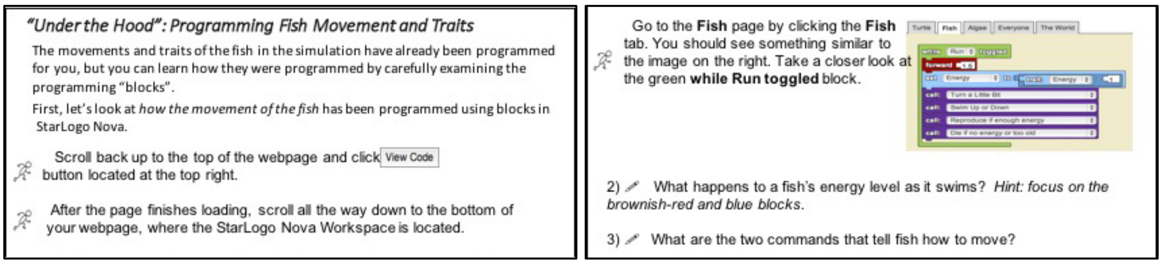

Figure 1. Instructions for viewing the code and questions that ask students to interpret the code for the simulations.

All of the units ask students to respond to argumentation prompts that require students to state a claim, and provide evidence and reasoning to support their claim. For example, in one argumentation prompt, through group discussion, students needed to figure out if the simulation has shown them genetic drift or natural selection and why, with the following sentence starters: "Our claim is…", "Our evidence for this is…", and "Our reasons are that…"

Participants

The larger study involved 463 students in grades 9 through 12 from seven different schools in the northeastern United States during the academic year 2013-2014. We collected demographic information about this larger group. For school-level data, the seven schools ranged from having 11.4% to 83% of students on free or reduced-price lunch. The schools also ranged from 3.4% to 79.1% non-white students, and ranged from 54% to 89% of students above proficient in the state standardized exam. For this smaller study, we randomly selected 54 students in grades 9-11 to conduct 12 focus group interviews at the end of the academic year to understand in more detail how and what students learned.

Data sources

We conducted 12 focus group interviews with 4-5 students in each. The combined interview time was 3 hours and 15 minutes. Students were asked the following questions: (1) What do you think biology is? (2) Recall all the units you did using the simulations, which units did you cover? Was there anything that these units had in common? What were these common characteristics? (3) How do complex systems fit into biology? (4) Can you please define what science is?

Data analysis

The interview transcripts were mined for the three different conceptual framework components. For complex systems, a coding scheme emerged through the data analysis, which included any student response that showed an overarching theme of complex systems thinking which could include nested levels, interdependence, and complex systems mechanisms such as randomness, feedback, cascading or nonlinear actions etc. The other two aspects were coded using previously vetted and validated coding schemes. For agent-based simulations, a coding scheme was used from Yoon and Wang (2014), which included affordances of a phenomenon being visible, dynamic, details, interactive, and scaffolding. For instances of students engaging in scientific practices, a coding scheme was used from the NGSS scientific practices (Pratt, 2012). Table 1 shows the coding scheme for complex systems, agent-based simulations, and scientific practices, with a description of each code and an example and explanation for each of the codes.

If the researchers disagreed on a code, the researchers discussed until they came to consensus on a single code for that particular response. Each student was only coded once for each category. For example, if a student made three different responses that could be coded as understanding the umbrella theme of complex systems, that student was only coded once for that code.

Table 1: Coding Scheme

	Code Description	Exemplar Coded Response
Complex Systems	**Umbrella theme of complex systems** Student articulates an overarching theme of complex systems thinking.	***Example***: *"I feel like the complex systems govern kind of the overarching patterns that we see from stuff that's really, really tiny like the organelles in your cell. Like ribosomes and enzymes functioning and in each of those cells go by another and form organs, each of those organs form complex systems, to form your body. Each individual body forms complex systems within a population and it just builds, and builds, and builds."* **Explanation**: Here the student shows how multiple concepts in biology can be understood from a complex systems lens.
Agent-based Simulations	**Visible** Allows users to see things that are normally invisible.	***Example:*** *"I think it was especially good for visualizing the randomness aspect of a lot of this. You kind of hear that it moves randomly, but you don't quite register it until you see all these things bouncing all over the place. Then you are like, oh that's how they ended up over there. They weren't just making their way for the gap, they just sort of bounced."* **Explanation:** Here the student is articulating that it wasn't until she saw the visualization that she could truly understand that the agents were moving randomly, revealing normally invisible information.
	Dynamic Displays the phenomenon in motion, showing changes over time	***Example:*** *"So you got to see how over time they changed."* **Explanation:** Here the student articulates the importance of seeing the dynamic nature of the phenomenon.
	Details Provides scientific details of the phenomenon.	***Example:*** *"Yeah, it gave you like a visual of what was actually happening."* **Explanation:** Student is articulating how actually seeing a phenomenon helped him to better understand biology.
	Interactive Enables the user to interact with the device.	***Example:*** *"I think that was definitely the most helpful part; being able to change something in the situation."* **Explanation:** Here the student articulates how changing a variable in the phenomenon, helped her learn biology better.
	Scaffolding Provides structure that focuses the users' attention on relevant information.	***Example:*** *"I think the fact that everything was going on at once made it a lot clearer that a single action has more than one consequence. It's not just a chain reaction of events. It's all of this stuff is more or less happening at once, in various stages, and intersecting and bumping into each other. It's harder to convey that on paper. You have to use a ton of arrows. You usually just simplify it to one example of each aspect and that's really not how stuff worked in real life."* **Explanation:** By being able to show multiple things happening at once the simulation was able to focus the students' attention to the fact that a single action has more than one reaction—in a way that a textbook diagram cannot show.
Scientific Practices	**Asking questions and defining problems** Students should be able to ask questions of each other about the texts they read, the features of the phenomena they observe, and the conclusions they draw from their models or scientific investigations. Asking questions and defining problems progresses to formulating, refining, and evaluating empirically testable questions and designing problems using models and simulations.	***Example:*** *"I may not directly find out what I want but I feel like I'm finding out new things I didn't know before and answering problems that I would have never [gotten] to."* **Explanation:** Here the student articulates how he answered problems by asking questions that he may have otherwise never considered, which helped him understand a phenomenon better.
	Developing and using models	***Example:*** *"I've seen a flock of birds outside before but when*

	Modeling can begin with students' models progressing from concrete "pictures" and/or physical scale models (e.g., a toy car) to more abstract representations of relevant relationships in later grades, such as a diagram representing forces on a particular object in a system. It includes using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.	*you look at the programming specifically, you can see the rules that they're following whereas if you looked at it outside, you wouldn't see those rules really showing."* **Explanation:** Here the student articulates how seeing the rules in the code that modeled a real-life phenomenon enabled her to better understand what was happening.
	Planning and carrying out investigations Students should have opportunities to plan and carry out several different kinds of investigations. At all levels, they should engage in investigations that range from those structured by the teacher - in order to expose an issue or question that they would be unlikely to explore on their own (e.g., measuring specific properties of materials) - to those that emerge from students' own questions. Planning and carrying out investigations include investigations that provide evidence for and test conceptual, mathematical, physical, and empirical models.	***Example:*** *"We just made changes in the simulation but it gave us the basis of what it means to make your own hypothesis."* **Explanation***:* Here the student shows how developing a hypothesis was helpful.
	Analyzing and interpreting data Because raw data as such have little meaning, a major practice of scientists is to organize and interpret data through tabulating, graphing, or statistical analysis. Such analysis can bring out the meaning of data—and their relevance—so that they may be used as evidence. Analyzing data includes introducing more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data.	***Example:*** *"Sometimes we did [compare] data with other groups so we got to changes to see if all complex systems are the same [or] if all were different. From mostly what we did I can remember for the most part, most group[s] kind of got the same results; they weren't the same exact results."* **Explanation***:* Here the student shows how, through data collection and analysis of the data, they were able to see the larger patterns across complex systems in biology, and the non-static nature of science, that science does not have one set answer.
	Using mathematics and computational thinking Mathematical and computational thinking includes using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.	***Example:*** *"I've seen a flock of birds outside before but when you look at the programming specifically, you can see the rules that they're following whereas if you looked at it outside, you wouldn't see those rules really showing."* **Explanation:** Here the student shows how using a computational simulation with specific rules enabled them to see something they would otherwise not have been able to see and understand.
	Constructing explanations and designing solutions The goal of science is the construction of theories that provide explanatory accounts of the world. A theory becomes accepted when it has multiple lines of empirical evidence and greater explanatory power than previous theories. Constructing explanations and designing solutions includes explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.	**Example***: "Yeah because we [did] observations, charts and graphs. And we also had to do that summarizing thing."* **Explanation:** Here the student is expressing how, in the unit, she had to summarize her findings—therefore she was constructing an explanation.
	Engaging in argument from evidence The study of science and engineering should produce a sense of the process of argument necessary for advancing and defending a new idea or an explanation of a phenomenon and the norms for conducting such arguments. In that spirit, students should argue for the explanations they construct, defend their interpretations of the associated data, and advocate for the designs they propose. Engaging in argument from evidence includes using appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about the natural and designed world(s). Arguments may also come from current scientific or historical episodes in science.	***Example:*** *"…yeah and like the evidence, reasoning, claim thing."* **Explanation:** The student is explaining how she had to answer questions using evidence, reason, and claims, the scaffolding design in the project helped students answer argumentation questions.
	Obtaining, evaluating, and communicating information Any education in science and engineering needs to develop students' ability to read and produce domain-specific text.	***Example:*** *"And we had to like kind of hypothesize a lot and like explain why this happens and why everything comes on."* **Explanation:** The student is expressing how her group had to

	As such, every science or engineering lesson is in part a language lesson, particularly reading and producing the genres of texts that are intrinsic to science and engineering. This includes evaluating the validity and reliability of the claims, methods, and designs.	communicate why her group had gotten the results to their experiments.

Results

To investigate our research questions, we looked at the total number of responses per coded category, which is shown in Figure 2. In total, there were 114 unique codable responses. The most frequent categories included detail (21 responses) in agent-based simulations, umbrella theme of complex systems (18 responses), and planning and carrying out investigations (14 responses) in scientific practices.

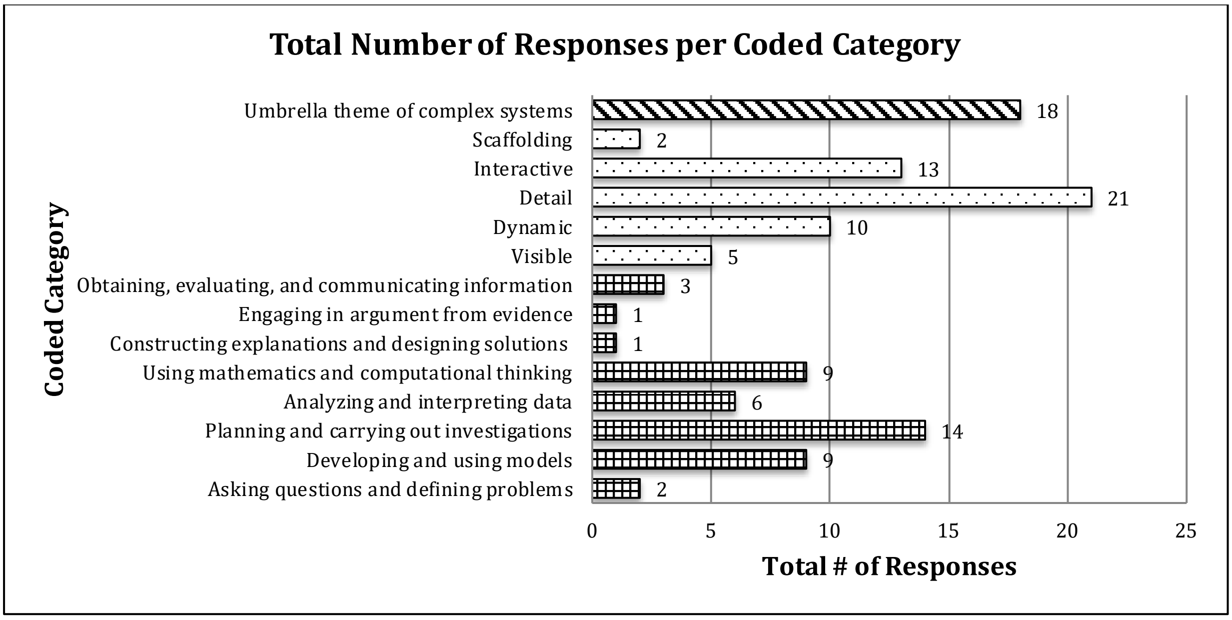

Figure 2. A bar graph representing the total number of responses per coded category.

To answer our first research question, we found that 33% of students in our sample (18 students) articulated an umbrella theme of complex systems in understanding biology. For example, one student stated:

> *I mean all [of the units] just had like -- It wasn't just sun hits plant, plant goes, yay. It was like the protein goes over here. Then the RNA reacts like this, and this hooks onto here, but if it hits here, then it does this. If it goes over there, then it does that. There were multiple factors all running around doing their own things and depending on how they interacted, when they bumped into each other mostly, the step would interact differently. Stuff would happen. They were all like that.* (Focus Group ID 6, May 2014)

In the above quote, the student explains that all of the units showed how systems have multiple intersecting agents, who randomly bump into each other, and depending on the ways in which they interact, different outcomes would occur in the system. The student shows a sophisticated understanding of complex systems and how this is a tying theme across the units. Another student simply states, *"Everything is a complex system; if you think about it."* (Focus Group ID 6, May 2014). This statement reveals this student sees complex systems everywhere—understanding that complex systems are pervasive.

To investigate the second research question, we analyzed students' statements to understand the ways in which the most frequently identified supports helped students learn biology in a coherent way. Amongst the student responses related to the simulations, 41% identified detail as an important affordance of the simulations. For example, a student states, *"The biggest thing that helps me understand biology was how everything in the simulation has a set of rules that it follows and how things move about randomly in complex systems. It's hard to get that from a diagram that your teacher might draw on the board or something like that."* (Focus Group ID 9, May 2014). Here, we observe that seeing the detail in the simulation enabled the student to understand randomness in complex systems. This was important because his understanding of a complex system came through an affordance of the simulation, which ultimately contributed to his coherent understanding of biology. Amongst the student responses related to scientific practices, 31% identified planning and carrying out investigations as important. A student articulates that playing with the code of the simulations itself helped the student understand the simulation model, "*I like using the coding; when you use the coding to change the program… Because I could control what everything was doing and I saw like how when you took the tumble blocks in and out, I saw like [how] things worked. Like I could just know what they were suppose [sic] to do.*" (Focus Group ID 5, May 2014). The student points out that being able to manipulate the code allowed her to understand how the agents function within the model (planning and carrying out an investigation), giving her a greater understanding of the complex system.

Discussion and significance of the study

We conducted this study in response to the need for students to have a coherent understanding of biology (NRC, 2012; Roseman et al., 2010). Our curriculum was designed with complex systems, agent-based simulations, and scientific practices to address the challenges that students face in developing this coherent understanding. In the results, we identified that there were particular aspects of the agent-based simulations and scientific practices that had been designed into the curriculum that enabled students to learn biology through complex systems, which in turn helped them learn biology in a coherent manner. Developing a coherent understanding of biology using standard curriculum is challenging to do, and here we found that a third of our students were able to very clearly articulate a systems understanding that brought multiple units of biology together. This study was completed in five units that took about ten days of instruction. It was a small portion of the curriculum, and yet we see promising evidence that a third of the students had a clear understanding of complex systems unifying the various topics in biology. From earlier studies we know that students do understand complex systems (Yoon et al., 2015)—what we see in this study is that understanding complex systems, which was enabled through the details in simulations and students' planning and carrying out their own investigations, may have contributed to their coherent understanding of biology for at least a third of the students.

Agent-based simulations let students see details in processes. Scientific practices enabled students to understand how models function and what is actually happening in the phenomena. These scaffolds work together to help students learn biology coherently. Moreover, this study extends the literature that suggests ways in which supports may help students to better understand scientific phenomena (Berland et al., 2015; Osborne, 2014; Wilensky et al., 2014). This is important as we consider the design of future biology curriculum and the ways we can incorporate complex systems as a unifying theme for various units, with the supports of simulations and scientific practices. The results of this study are encouraging and give us reason to believe that follow-up curricula that demonstrate how biology is interconnected through a systems lens would support pattern recognition across content domains. In the future, an experimental randomized controlled study of this curriculum would validate these findings, since a limitation of the current study is the lack of a control group. Additionally, further study of classroom observations and teacher interviews may reveal additional mechanisms through which students developed a coherent understanding of biology.

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