Design Features for Computer-Supported Complex Systems Learning and Teaching in High School Science Classrooms

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Abstract: While research on teaching and learning about complex systems has achieved solid grounding in the learning sciences, few educational studies have focused on articulating design features for classroom implementation that can serve a modular purpose for building curricular and instructional experiences. Furthermore, despite the fact that several studies describe important roles for teachers in constructing successful classroom learning experiences, only a few of them examine how teachers' instructional practices, knowledge, and beliefs influence student learning outcomes and the extent to which teachers are interested and willing to teach through complex systems approaches. Furthermore, we do not know what supports teachers themselves say that they need to teach about complex systems in their classrooms. In this study, we present a curriculum and instruction framework that outlines how teaching and learning about complex systems in high school science classroom contexts can be done. We articulate the features of the framework and provide examples of how the framework is translated into practice. We follow with evidence from an exploratory study conducted with 10 teachers and over 300 students aimed at understanding change in teachers' instructional practices; the extent to which students learned from the activities; what teachers' perceptions were in terms of utility and usability; and what other supports teachers needed.

Keywords: Innovative Design Approach, Teaching, Science Education, Learning Outcomes

Introduction

The study of complex systems in natural and social sciences has become increasingly essential to understanding disciplinary and interdisciplinary content and practices (The National Academies, 2009). The study of complex systems is also featured prominently in the *Next Generation Science Standards* (NGSS) for K12 science in the U.S. Complex systems can be found in structures and behaviors in all aspects of our world. At the micro scale, an example of a complex system is a single fertilized egg developing to create differentiated cells that eventually become a human form. Macro-scale complex systems include businesses, cities, animal populations, and ecosystems. Although complex systems vary in their physical components, a common feature of all complex systems is the presence of multiple interconnected elements, parts, or individuals that communicate in nonlinear ways. The interactions among the parts form a collective network of relationships that exhibit emergent properties not observable at subsystem levels. When perturbations occur, the network may self-organize in unpredictable ways, allowing new properties to emerge.

While research on teaching and learning about complex systems has achieved solid grounding in the learning sciences (Hmelo-Silver & Kafai, 2011), few educational studies have focused on articulating design features for classroom implementation that can serve a modular purpose for building complex systems curricular and instructional experiences. Furthermore, despite the fact that several studies describe important roles for teachers in constructing successful classroom learning experiences (e.g., Perkins & Grotzer, 2005), only a few of them examine how teachers' instructional practices, knowledge, and beliefs influence student learning outcomes (Yoon et al., 2013; 2015; Randler & Bogner, 2009) and the extent to which teachers are interested and willing to teach through complex systems approaches. Furthermore, we do not know what supports teachers themselves say that they need to teach about complex systems in their classrooms. Addressing these gaps will be critical in the next few years in order to meet NGSS requirements.

In this paper, we respond to these needs by presenting a curriculum and instruction framework that outlines how teaching and learning about complex systems in high school science classroom contexts can be designed and implemented. We articulate the features of the framework and provide examples of how the framework is translated into practice for classroom implementation and for professional development (PD). We follow with evidence from an exploratory study aimed at understanding: 1) To what extent teachers thought the PD was usable; 2) To what extent teachers' instructional practices changed as a result of participating in the PD based on the framework; and 3) To what extent students learned from these curriculum and instruction activities. We also provide information in the discussion about what other supports teachers felt they needed.

Background: Complex systems in science education

Over the last 15 years, about 65 empirical studies have appeared in journal articles on the topic of complex systems in K12 education and of those, a large majority, have been geared toward science learning. Although an extensive review of the focus of these studies is beyond the scope of this paper, there are a number of themes that emerge in the research base such as understanding how students reason about complex systems (Assaraf et al., 2013; Levy & Wilensky, 2008; Grotzer, 2012), pedagogical approaches to supporting learning (Yoon, 2008, Hmelo-Silver et al., 2000), computational tools to build complex systems understanding (Yoon, 2011, Klopfer et al., 2009; Azevedo et al., 2005); and models for curriculum construction (Danish, 2014; Gobert & Clement, 1999). Despite this prevalence, no studies exist that investigate how pedagogical approaches, computational tools, and models for curriculum can work in the situated context of the science classroom where variables such as ability to address content standards are primary concerns for teachers. Likewise, very few studies have examined the role of the teacher in influencing student-learning outcomes. In a quasi-experimental study comparing two different instructional approaches to teaching complex ecological content, one study by Randler and Bogner (2009) showed that the teacher's teaching style had a strong impact on student academic learning. However, this study stands as a rare example of research investigating the teacher's role and incidentally was not the focal goal of the study. In other science education research, we do know that teacher attitudes, beliefs, knowledge, and skills can significantly influence the success of an intervention and even whether an intervention is adopted (Jones & Carter, 2007; Wallace & Kang, 2004). Clearly, more research is needed that includes designs to incorporate classroom and teacher variables to understand how new reform programs like the NGSS can work to improve science education in real classrooms.

To address this need, we constructed a complex systems curriculum and instruction (C&I) framework, in which teacher knowledge of context variables and content standard demands factored prominently in the design along side tools and practices known to improve student complex systems understanding. There are 4 major categories of the framework that are additionally aligned with the literature on needs and best practices for STEM teaching and learning. The first category is *Curricular Relevance,* which focuses on developing 21st century competencies (NRC, 2012), ensuring standards alignment (Desimone, 2009), and collaboration with teachers to promote teacher ownership (Ertmer et al., 2012, Mueller, 2008; Thompson et al., 2013). The second category, *Cognitively-Rich Pedagogies*, involves pedagogies that address situated needs in individual classrooms (Penuel et al., 2011), social construction of knowledge through collaboration and argumentation (Osborne, 2010), and constructionist learning by constructing models (Kafai, 2006). The third category, *Tools for Teaching and Learning*, builds knowledge with computational modeling tools (Epstein, 2008), teacher guides and student packets that provide scaffolds for learning (Quintana et al., 2004), and off-computer participatory simulations to support students' understanding of modeling and complex systems (Colella, et al., 2000). The fourth category, *Content Expertise*, builds deeper content understanding in complex systems (Yoon, 2008), biology (Lewis & Wood-Robinson, 2000), and computational thinking (NRC, 2010).

Based on the framework, our project engages teachers and students in learning experiences that build knowledge of scientific practices, complex systems, and biology using computational models. The project has built instructional sequences for five high school biology units – Genetics, Evolution, Ecology, the Human Body, and Animal Systems. Participants use an agent-based modeling platform called StarLogo Nova that combines graphical blocks-based programming with a 3-D game-like interface. The curricular materials take two or three days to complete. Examples of curricular and instructional activities built on this framework are found in Table 1.

Following the construction of the tools and curricula, we trained teachers in summer and school year PD workshops. We worked closely with teachers to understand implementation challenges and iteratively redesigned project resources to meet their classroom needs. In the next section, we discuss the context of the PD underpinned by the C&I framework, and provide evidence from an exploratory study that illustrates its impact in the classroom.

Table 1: BioGraph C&I framework categories and activities

BioGraph Categories	Activities/Strategies
Curricular relevance	Curricular emphasis on building 21st-century skills in problem solving, critical thinking, and self-directed learning.
	Close alignment with content, practices, and crosscutting themes in the NGSS (e.g., systems).
	Collaboration with teachers as research partners through continual feedback about challenges in classroom implementation and collective problem solving to improve the project and to promote optimal implementation. Peer sharing facilitated through an online database where teachers post lesson plans and comments on implementation details.
Cognitively-rich pedagogies	Consideration of and response to situated teaching contexts such as high ESL populations (e.g., generation of more visual aids to improve cognitive engagement).
	Curriculum and instructional strategies anchored in social constructivist pedagogies (e.g., students working in teams co-constructing ideas through argumentation).
	Using StarLogo blocks-based graphical programming language with a low-level learning threshold, students learn to build simulations to construct understanding of scientific phenomena.
Tools for teaching and learning	Student interaction with models that are visual representations of scientific ideas.
	Visualization of dynamic processes of systems, such as self-organization and emergence, using StarLogo models. Visualization of system states at multiple scales.
	Student experiments using the models, collection and analysis of data, and drawing evidence-based conclusions.
	Easy-to-use teacher guides and student activity packs to promote teacher and student autonomy. Teacher guides for adapting and extending practice.
	Off-computer participatory simulations to engage teachers and students physically in systems that provide additional sensory and cognitive input for learning.
Content Expertise	Popular and academic literature about complex systems for teachers and students. Short movies, PowerPoint presentations, and detailed definition lists to develop systems understanding in the classroom.
	Student interactions with StarLogo models that explore biology content in detail. Some strategically selected content (e.g., evolution) to remediate known robust misconceptions.
	Models set up to allow students to explore the program that executes the model with the goal of developing skills related to computation, such as algorithmic thinking. Some models that require students to manipulate the program and construct their own systems.

Methodology

Context

In order to ensure that the utility of the project's resources could be optimally investigated, we also wanted to take care in constructing PD experiences that would support the efforts. To that end, we designed and conducted the PD following professional judgments about what constitutes state of the art characteristics of high quality PD: (a) aligned content; (b) active learning opportunities; (c) coherence with professional demands; (d) at least 20 hours in duration and spread over a semester; and (e) collective participation of teachers from the same school, grade, or subject (Desimone, 2009; Garet, Porter, Desimone, Birman, & Yoon, 2001). Of these five characteristics, we considered active learning to be particularly important. Due to the well-documented, steep learning curve teachers experience in adopting new technologies in their classroom (Aldunate & Nussbaum, 2013; Ertmer et al., 2012), we emphasized exposure to computers (Mueller et al., 2008) and extensive training on computers (Pierson, 2001). We also incorporated the other characteristics judged to be important for a quality intervention. For example, we achieved coherence with professional demands by providing close teacher-researcher collaboration. We delivered 40 hours of face-to-face PD. We also focused on collective participation by working only with high school biology teachers and, in some cases, working with several teachers from the same school. Figure 3 provides the scope and sequence of professional development activities conducted in the summer 2012 workshop. In this exploratory study, we were interested in understanding what teachers learned and understood about the utility of the activities in terms of classroom practice and whether students' learning improved.

	Monday	Tuesday	Wednesday	Thursday	Friday
8:00 - 8:15	Room Open - Snacks and Coffee				
8:15 - 8:30					
8:30 - 8:45	Welcome and Participatory Sim - Paper Catchers	Welcome and Participatory Sim - Red	Welcome and Participatory Sim - Angles	Welcome and Participatory Sim - Kids as	Welcome and Participatory Sim - Gamblers Dilemma
8:45 - 9:00					
9:00 - 9:15		Why Construct? Why Argue?	Why Model?	Plan Admin Day and Scale Up	
9:15 - 9:30	Complexity Intro Video and Complex Systems Matrix with BioGraph Examples				
9:30 - 9:45					Calendaring Session
9:45 - 10:00		Research Findings			
10:00 - 10:15					
10:15 - 10:30	Differentiation Sessions (Teacher Presenter)				
10:30 - 10:45	BREAK				
10:45 - 11:00	StarLogo Nova - Catching Flies	StarLogo Nova - Ecology Activity	Buffet of Complex Systems Resources/Pedagogy and Lesson Plan Construction	Working Groups - Differentiation and Assessment	Online Resource Forum
11:00 - 11:15					
11:15 - 11:30					
11:30 - 11:45			Argumentation and Collaboration Resources		
11:45 - 12:00					
12:00 - 12:15			Lunch - Radix Demo	Lunch - Stat	
12:15 - 12:30	Lunch	Lunch			Lunch
12:30 - 12:45					
12:45 - 1:00					
1:00 - 1:15	BioGraph Activity & Next Generation Science Standards - Sugar Transport (Argumentation)	Argumentation and Collaboration Resources	BioGraph Activity and Next Generation Science Standards - Enzymes (Argumentation)	BioGraph Activity and Next Generation Science Standards - Evolution (Argumentation)	Sharing of Assessment and Differentiation Work
1:15 - 1:30					
1:30 - 1:45		Student Assessment and Data Collection			
1:45 - 2:00					
2:00 - 2:15					
2:15 - 2:30	Further Complexity	Parallel Session 1 - Assessment (Working Group)/ Parallel Session 2 - Differentiation of Lessons (Working Group)	Model Building/Programming Extensions - Differentiated Session for Teachers	Assessing BioGraph Students' Argumentation Skills	Exit Surveys and Next Steps Check List
2:30 - 2:45					
2:45 - 3:00					Celebration!
3:00 - 3:15					
3:15 - 3:30					
3:30 - 3:45					
3:45 - 4:00	Daily Wrap-Up				

Color Coding Key	
Blue	Pedagogy
Green	Complex Systems
Orange	Argumentation
Purple	Computation Thinking/Modeling
Red	Break/Lunch
Teal	Research
White	Wrap-Up/Celebration

Figure 1. Scope and sequence of professional development activities in the summer workshop

Participants

We recruited 10 teachers from Boston area public schools– seven females and three males. The teachers came from a diverse set of schools. For example, the percent of students who were from minority race/ethnic groups ranged from 3 to 75; the percent who were eligible for free or reduced priced lunch ranged from 11 to 83; and the percent who scored at the proficient or advanced level on the state standardized science test ranged from 54 to 89. On average, the teachers had 7.7 years of teaching experience, with a range of 3 to 18 years. We collected student data from a total of 352 students (mainly comprised of freshman biology students).

Data collection and analysis

We conducted a mixed methods evaluation of the project implementation after the summer 2012 PD workshop and throughout the 2012 and 2013 school year. We collected surveys, interviews, and classroom observations of students and teachers to investigate the research questions. First, to investigate teachers' perceptions of the utility of project resources, we administered an 18-item Likert-scale and 8 short answer usability survey at the end of the summer workshop. Questions probed whether they believed the resources were useful to them, whether they would recommend the workshop to other colleagues, and whether they thought the PD was successful. Simple means are reported to illustrate teachers' perceptions of usability and interest in the project.

To understand how teachers' instructional practices changed, we used two data sources, pre-intervention and post-intervention surveys administered to students, which probed the extent to which they participated in learning through computers and simulations, and student learning using scientific practices that aligned with the project goals. The survey encompassed 44 items on a 5-point Likert-scale that ranged from no participation (1) to a lot of participation (5). A repeated-measures analysis of variance (ANOVA) was applied to the data to understand impact on instructional practices. We also administered year-end interviews with teachers to gather information about their perceptions of the project resources, how their knowledge and skills improved, to determine what aspects did or did not contribute to this improvement, and to understand how to redesign project resources to help teachers further improve. The interviews lasted for 45 minutes and were qualitatively mined by the research team to probe for indicators of project impact.

To determine the extent to which students learned while participating in the project, we administered two surveys to students. The first was a 14-point multiple-choice test that measured biology content related to the project. The second was two open-ended questions that provided scenarios about changes in biological complex systems. Students were asked to rationalize why the changes had occurred. Responses were scored on a scale of 1 (not complex) to 3 (completely complex) in four different categories of complex systems components (e.g., emergence of new properties at different scales). Repeated measures ANOVAs were also conducted on the data. In selected classrooms, student focus group interviews were also held to collect information about what they thought about learning biology through project activities and tools. Although more extensive mining of the interview response data is yet to be completed, we report on initial themes that emerged.

Results

Evidence that the PD was usable by teachers

Responses on all 18 Likert-scale items ranged between 4 (agree) and 5 (strongly agree). For example, teachers felt the workshop topics were relevant to the grades they taught (5); the information presented was useful to them (4.9); the information could be put into practice immediately (4.6); instructional guides were useful to their own learning (4.8); the exposure to agent-based modeling technology was useful to them (4.9); they would be able to use ideas about complex systems in their teaching (4.6); and they planned to share complex systems ideas with their colleagues (4.7). When asked whether they believed the PD was successful (and if so, why), teachers overwhelmingly responded positively referencing aspects of the PD they thought were particularly important in their learning:

> "Ample instructional supplies and resources."
> "Provision for teacher input and collaboration; great materials and instructional team."
> "Practicing each activity and facilitation."
> "I have used many simulations before but they don't drive home the major ideas. The StarLogo lessons, I feel do. Our hands-on activities were extremely helpful."
> "I learned a lot and will be able to confidently implement the program because we ran through and discussed them all, we talked a lot about…complex systems…"

Evidence of teachers' instructional practices and improved knowledge and skills

On the survey that investigated students' classroom experiences in the two main project factors, learning through computers and simulations ($\alpha = .872$), and student learning using scientific practices ($\alpha = .739$), student population responses indicated modest but significant gains in their classroom experiences. On the 5-point scale, responses showed an increase from 3.0 to 3.5 ($p < .001$) for learning through computers and simulations and 3.4 to 3.6 ($p < .001$) for learning using scientific practices. In teacher interviews, teachers felt that these instructional changes did not come at the expense of covering their standard science curricula, as evidenced in the following interview response from one teacher: "I feel like [with] the standards alignment…it was really easy to substitute out something that was old with something that was new. That was very easy."

To understand how teachers' knowledge and skills changed or improved, we asked teachers in the year-end interviews to talk about which of the project's curriculum and instruction components were the most important for their biology students to learn from and which component they used the most in class and why. Teachers said that learning about how to use the visualization tools to help students learn the science content was important. For example, one teacher remarked, "It's really hard for the kids to kind of visualize and understand…but a lot of them kind of had that aha or I get it now moment." Other teachers discussed how their use of scientific practices, such as argumentation, changed. One teacher stated,

> So when they come to me, it's the first time that they see it. And by now, I've got most kids stating a claim, gathering evidence and understanding some difference between evidence and reasoning…and actually the thing that has helped the most this year on it, is that I am requiring all answers to questions that I ask in that framework, even if the framework isn't the greatest for the question, I am actually getting better answers from the students.

Teachers also talked about pedagogical benefits and how the project helped them to work with modeling tools effectively:

> I loved the tools, the StarLogo for modeling and for visualization and simulation. It was fantastic because…a lot of times…if you said here's StarLogo, I wouldn't have had a clue on how to develop any kind of plans or lessons or inquiry based activities. So to have them start off the simulations and then to go backwards and do the modeling…[was great].

Overall, teacher interviews unanimously demonstrated interest in the project for themselves and their students. They identified four main areas of benefit for student learning: (a) student-centered scientific investigations; (b) interaction with computer models; (c) development of evidence-based reasoning skills through argumentation; and (d) multiple resources for developing complex systems understanding (e.g., models).

All 10 teachers have requested opportunities for continued involvement beyond the life of the grant, signaling strong support for the program. More concretely, in their interviews, they identified five affordances of the project related to their own learning and engagement: (a) relevant and multiple resources to engage in real content learning and pedagogical training; (b) access to expert facilitation; (c) peer sharing and collaboration; (d) numerous opportunities to develop teaching skills through hands-on participation and practice; and (e) a sense of identity and community aimed at reforming science education.

Evidence that students showed learning gains in biology and complex systems understanding

For the 14-point biology content test, student scores increased significantly from pre- to post-assessment—from a mean of 6.67 to 8.40 where $F(1, 344) = 32.23$, $p < .001$ and an effect size = .38 (Cohen's d). Students' complex systems understanding measured through the two open-ended questions also showed positive significant growth moving from a mean of 1.48 to 1.61, where $F(1, 350) = 96.03$, $p < .001$ an effect size = .39 (Cohen's d). We do not know how much of this gain would have occurred in the absence of the intervention particularly for the biology content test because we did not have a comparison group. We are also aware that the actual gains in their scores on both measures were relatively small. However, we believe that the moderate significant gains in effect sizes are encouraging results especially for complex systems understanding as the curriculum was new to students and teachers.

From student focus group interviews, several themes emerged that demonstrate the utility of the project activities and curricula to support the development of complex systems understanding. Almost all students mentioned the affordances of interactivity, repeatability, student-centeredness, and visualizations of the simulations. The more interesting ideas in the interviews came in the form of students' abilities to transfer knowledge of complex systems to explain other phenomenon. For example, one student states:

> Well I think they're trying to say everyone or every living thing has a part, and the parts interact as we have like kind of a system. Everyone has their own initiative of what they are trying to accomplish or do, or how they work. Then everything working together creates one thing or not even just one thing. It has a lot of different effects in their own ways.

Here the student makes inferences about the general nature of systems that she gleaned from her participation in the project's collective learning activities. She later states:

> Well every time we did a lab it was like saying - the one about the lactose…you had one part that started something, but connected to another part, and all of these parts connecting made up the system that did one thing. Every part was programmed to move a certain thing or have this one objective, but all combined they did one overall thing that wasn't necessarily what each part did.

This student is articulating the complex systems ideas of emergence, self-organization, and scale, which are essential components of complex systems understanding.

Discussion

Education has become ripe with policy, scholarship, and resources to support the study of complex systems. For example, all seven of the crosscutting concepts in the new NGSS reflect important aspects of complex systems such as *Scale,* and *Structure and Function*. This has raised challenges for educators who must follow the NGSS alongside other contextual and professional demands. Thus, understanding optimal methods for constructing educational experiences is critical. Equally important in this effort is focusing on teacher change, their role in adopting these reforms, and how they can be further supported in the classroom.

Although a good deal of research has been conducted in K12 science education on various complex systems-related topics, surprisingly few frameworks and studies have considered teaching contexts and teachers. In this paper, we introduced a framework for teaching and learning about complex systems that addressed needs in designing approaches for classroom implementation and teacher change in addition to designing activities for student learning. Working closely in PD activities with our teachers, we gathered information about whether their instructional practices changed and investigated reasons for how and why they changed. The results indicated that teachers used more computers and simulations and also increased the use of scientific practices in their instruction. They identified several affordances of the project's design in supporting their own learning, which included relevant and multiple resources, peer sharing, and hands-on participation and practice. Student learning in both biology and complex systems content significantly improved and teachers collectively said that project resources were useful to them in their classroom practice. However, in interviews, teachers said that they themselves learned about complex systems but acknowledged that they needed more time to learn how to reinforce the ideas in their lessons. Teachers discussed a similar need for more time to become pedagogically confident about programming the StarLogo simulations and, for some teachers, fully implementing the argumentation process. We continued to work with teachers to develop more resources to help them teach in these three areas. Teachers also shared their teaching strategies with each other in Saturday PD sessions during the school year. Teachers told us that these opportunities to continue practicing integrating the ideas into their instruction, to access more resources, and to learn from other teachers were invaluable to their growth.

As we move forward in adopting and translating the NGSS into classroom experiences, the teacher's knowledge, skills, and attitudes will be crucial to successful implementation. Working as research and design collaborators with us, teachers provide invaluable feedback about their perceptions of the utility of the resources and the value added to instruction. Importantly, they provide essential information about how to improve the design based on their professional and contextual expertise, which we must incorporate into future implementation iterations if reforms are to take a hold in the science classroom. We believe that the significance of this study lies not only in articulating design features that work in concert with each other to improve student learning and teacher instructional outcomes but also in examining teachers as the recipients of these complex systems reforms which research has yet to seriously investigate apart from one or two studies (e.g., Randler & Bogner, 2009).

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