Chapter 11

Designing Complex Systems Curricula for High School Biology: A Decade of Work with the BioGraph Project

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> In ordinary life, we are not aware of the unity of all things but divide the world into separate objects and events. This division is useful and necessary to cope with our everyday environment, but it is not a fundamental feature of reality. It is an abstraction devised by our discriminating and categorizing intellect. To believe that our abstract concepts of separate 'things' and 'events' are realities of nature is an illusion (Capra, 1975; pp. 274–275).
>
> We need to teach our children, our students, and our corporate and political leaders, the fundamental facts of life – that one species' waste is another species' food: that matter cycles continually through the web of life; that the energy driving the ecological cycles flows from the sun; that diversity assures resilience; that life, from its beginning more than 3 billion years ago, did not take over the planet by combat but by networking (Capra & Luisi, 2014, p. 356).

11.1 Developing a Coherent Understanding of Biological Systems

I was first turned on to complex systems ideas through the work of Fritjof Capra, Austrian-American systems researcher, best known for his work in ecoliteracy. The above quotes provide a glimpse into the epistemology that he has espoused for over four decades–that is, despite our predilections toward compartmentalizing phenomena, in reality, the world is a unified whole that is interconnected and interdependent. In order to have a sufficient understanding of how the world works, we need to consider in our knowledge development, how phenomena exist as systems. That is to say, for example, through ecological cycles, which enable constituent parts (or micro-level variables) to operate together to produce holistic systems (or

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macro-level structures). In Capra's brand of systems research, as is the case for me (and other organizations devoted to the study of complex systems, such as the Santa Fe Institute), a critical concept to understand is the notion of micro-level to macro-level emergence. And most complex systems researchers would agree that there is a hidden order that makes complex systems challenging to comprehend because mechanisms that fuel emergence are not readily observable to the naked eye. This has led to, as Kauffman (Kauffman, 1996) writes,

> The past three centuries of science have been predominantly reductionist, attempting to break complex systems into simple parts, and those parts, in turn, into simpler parts. The reductionist program has been spectacularly successful and will continue to be so. But it has often left a vacuum: How do we use the information gleaned about the parts to build up a theory of the whole? The deep difficulty here lies in the fact that the complex whole may exhibit properties that are not readily explained by understanding the parts. The complex whole, in a completely non-mystical sense, can often exhibit collective properties, "emergent" features that are lawful in their own right. (pp. vii, viii).

Some of these emergent features might be the wave-like movement of a flock of birds as they soar through the air, the synchronous flashing of a swarm of fire flies on a summer night, or the seemingly systematic marching of a group of ants lined up in a factory-style formation moving food back to the colony. These patterns that emerge from very simple rules that agents take up, such as the previous ant laying down a pheromone for the next ant to follow, are what drive complex systems researchers' interests in finding the wonderful hidden order that fuels the natural world.

Since the late 1980s, in an attempt to develop national science standards in the United States that culminated in the publication of *Benchmarks for Scientific Literacy* (American Association for the Advancement of Science, 1993), understanding natural and engineered systems has featured prominently in standards for K12 Science Education. The more recent adoption of the Next Generation Sciences Standards (NGSS Lead States, 2013) has also demonstrated the importance of learning about systems, most notably in the seven topics covered in the category of Cross Cutting Concepts, where they all, arguably, represent central systems mechanisms and states, for example through Patterns, Structure and Function and Stability and Change. However, a recent review of twenty years of empirical studies on complex systems learning in science education (Yoon et al., 2018) showed that while there has been a good deal of research on what students know about complex systems and how it can be supported, consensus is still needed in the field to identify essential curriculum content features (Fick et al., 2021). This may be the reason why complex systems curricula have not yet made it into the mainstream of instruction in any depth. Moreover, the same review revealed the need for more research on teacher learning and instructional supports and their relationship to student learning.

There is also the added challenge of developing a coherent scientific systems worldview. For Capra, the importance of such a development is paramount in the study of biology. With a coherent understanding, students would be able to connect separate topics with one another in a way that helps them to explain and predict outcomes of scientific events as well as to solve problems with seemingly disparate phenomena (Fortus & Krajcik, 2012). In terms of developing scientific knowledge, it stands to reason that recognizing relationships and patterns across curricular units would improve students' knowledge economies of scale as more information is added to their cognitive systems. Yet, research demonstrates that students face challenges in developing a coherent understanding of biology for multiple reasons. First, topics covered in standard biology curricula lack any kind of integration (Chiu & Linn, 2011; Chiu & Linn, 2014; Gilbert & Boulter, 2000; Klymkowsky & Cooper, 2012; NRC, 2012). Second, static images and representations of processes in textbooks obscure the dynamic nature of various phenomena (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010). Third, the preponderance of didactic instruction, few inquiry-based experiences, and an emphasis on rote memorization of content in biology classes has added to the issue that students come away from such learning experiences having only learned a set of disconnected facts (Anderson & Schonbom, 2008; Osborne, 2014).

Over the last 10 years, my colleagues and I have worked on an educational research project called BioGraph to develop units for high school biology content that are coherently connected through a complex systems lens. We have worked with teachers in professional development (PD) as first adopters, collaborators, and co-designers to improve the viability of full integration of BioGraph units into the standard high school biology curriculum. Using a graphical blocks-based programming language called StarLogo Nova, we have built agent-based simulations that model essential biology concepts such as protein synthesis and ecological communities that students use with accompanying curricular packets for investigations. A major learning goal is for students to understand that there are unifying characteristics of all biological phenomena that both fuel system dynamics (for example, cycles and perturbations) and define system structures and states (for example, initial conditions; equilibrium) (Yoon et al., 2016). Furthermore, in our PD workshops, teachers improve their own understanding of complex systems applications in science and science education and develop pedagogical content knowledge skills with complex systems curricula in a professional learning community (Yoon, 2018; Yoon, Anderson, et al., 2017a). The overarching research goal that we have sought to investigate is "How and in what ways can complex systems resources be integrated into the high school biology curriculum?"

In the remaining sections of the chapter, I will first detail our approach to designing for student learning (agent-based modeling) in relation to the curriculum and instruction framework that underpins the design of both student-facing and teacher PD activities. I will then discuss our approach to designing for teacher PD (development of social capital). Finally, I will discuss research findings, compiled from several empirical studies working with hundreds of high school students in approximately 30 classrooms that support the design decisions, modifications in the design, and lessons learned toward the goals of achieving high- quality learning and instruction of complex systems resources.

11.2 The BioGraph Curriculum and Instruction Framework

Figure 11.1 shows the curriculum and instruction framework that we have used to inform all project activities. The components point to four distinctive aspects in the development of our BioGraph resources: (a) Curricular relevance: why should it be learned?; (b) Cognitively-rich pedagogies: how does learning happen?; (c) Tools for teaching and learning: what is used to support instruction and learning?; and (d) Content expertise: what is the knowledge to be learned? More details about each of the framework components can be found in previously published work (see for example, Yoon et al., 2016; Yoon, Anderson, et al., 2017a). Here, I briefly describe our motivations in the design of each category.

11.2.1 Curricular Relevance: What Is Being Learned?

From the outset, we were interested in ensuring that the curriculum we developed would be usable by teachers in their high school biology courses and would have utility in supporting students' scientific skills, practices, and habits of scientific inquiry beyond their classroom experiences. When we embarked on the project's design in 2010, we used science education policy documents including local and state standards as well reports from other organizations that had gained some traction at the time in curriculum arenas such as the Partnership for twenty-first Century

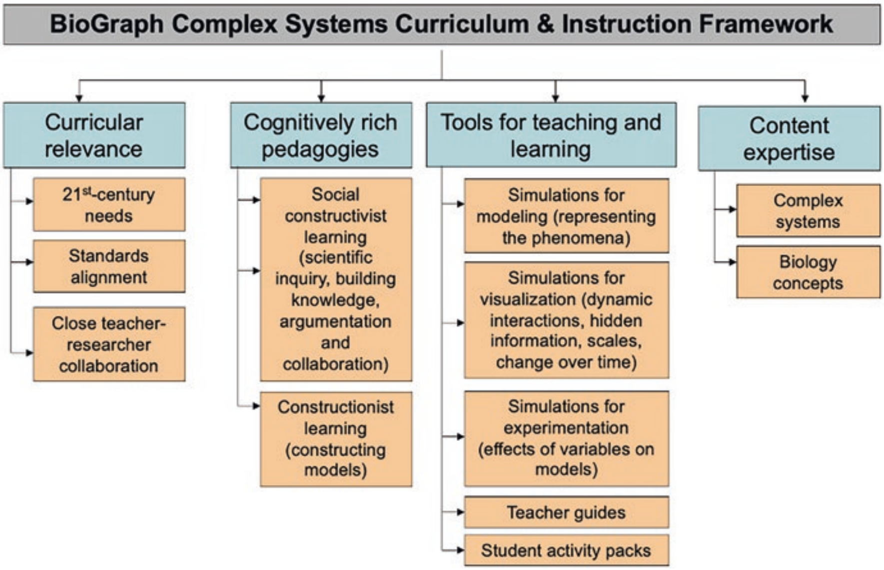


Fig. 11.1 BioGraph complex systems curriculum and instruction framework

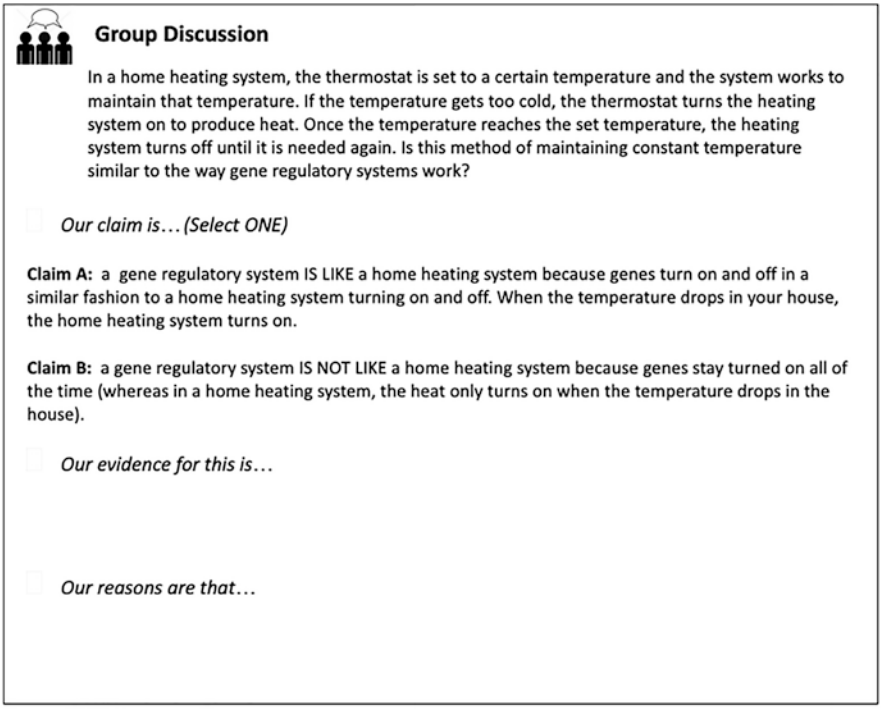
Learning (Partnership for twenty-first Century Skills, 2007) and the President's Council of Advisors on Science and Technology (President's Council of Advisors on Science and Technology, 2010). Emphases from these latter resources stressed critical thinking, collaboration, career skills, and the integration of technology. Just a few years later, with the introduction of the Next Generation Science Standards (NGSS Lead States, 2013), we worked toward providing experiences in three-dimensional learning that combined science and engineering practices and cross-cutting concepts with the biology content standards. It was clear that for curricular relevance to be realized in relation to classrooms in light of these policy mandates, teachers needed to have a key place as partners on the curriculum design team. We worked to improve the curriculum through design cycles with teachers as design collaborators for optimal implementation.

11.2.2 Cognitively-Rich Pedagogies: How Does Learning Happen?

The BioGraph curriculum is premised on two broad theories of learning: social constructivist and constructionist learning. The pedagogy is based in student-centered scientific inquiry exploration. With teachers as facilitators, students in teams of two or three generate hypotheses and questions, perform experiments (by manipulating the model parameters) to verify their hypotheses. They engage in argumentation through prompts that require them to select claims and provide evidence and reasoning to support the claims (see Fig. 11.2). The unifying theme of complex systems anchoring the various biology topics also provides the conceptual scaffold for developing their understanding. Furthermore, students learn how the simulation works through guided tours of the blocks-based coding language and are provided opportunities to modify existing code or construct aspects of the simulation on their own (see expanded explanation below). The idea is that through these hands-on activities, students begin to understand the underlying mechanisms that govern the behavior of system variables to produce the patterns that they see in the phenomenon under study.

11.2.3 Tools for Teaching and Learning: What Is Used to Support Instruction and Learning?

Instruction and learning about complex systems are supported through the StarLogo Nova computational agent-based modeling platform that combines programming based on graphical blocks (Figs. 11.3) with a corresponding simulation interface that allows students to dynamically interact with the programmed behaviors of system variables (Fig. 11.4) Students can simply drag and drop blocks of code, which



Group Discussion

In a home heating system, the thermostat is set to a certain temperature and the system works to maintain that temperature. If the temperature gets too cold, the thermostat turns the heating system on to produce heat. Once the temperature reaches the set temperature, the heating system turns off until it is needed again. Is this method of maintaining constant temperature similar to the way gene regulatory systems work?

☐ *Our claim is… (Select ONE)*

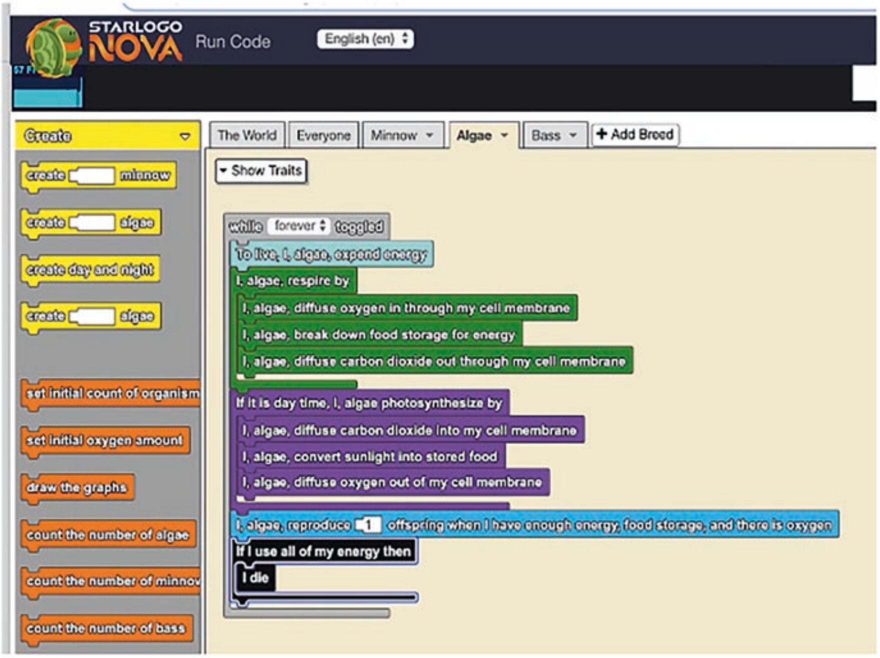
Claim A: a gene regulatory system IS LIKE a home heating system because genes turn on and off in a similar fashion to a home heating system turning on and off. When the temperature drops in your house, the home heating system turns on.

Claim B: a gene regulatory system IS NOT LIKE a home heating system because genes stay turned on all of the time (whereas in a home heating system, the heat only turns on when the temperature drops in the house).

☐ *Our evidence for this is…*

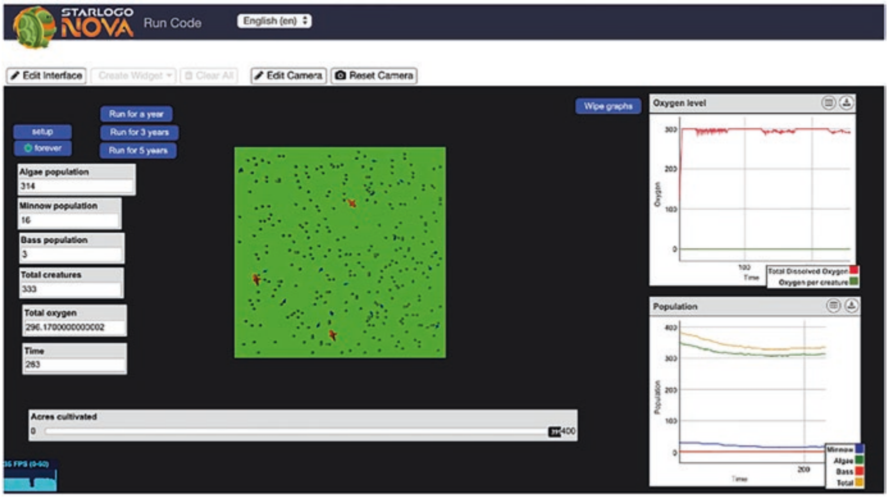
☐ *Our reasons are that…*

Fig. 11.2 Sample argumentation activity



```
while forever toggled
  To live, I, algae, expend energy
  I, algae, respire by
    I, algae, diffuse oxygen in through my cell membrane
    I, algae, break down food storage for energy
    I, algae, diffuse carbon dioxide out through my cell membrane
  If it is day time, I, algae photosynthesize by
    I, algae, diffuse carbon dioxide into my cell membrane
    I, algae, convert sunlight into stored food
    I, algae, diffuse oxygen out of my cell membrane
  I, algae, reproduce 1 offspring when I have enough energy, food storage, and there is oxygen
  If I use all of my energy then
    I die
```

Fig. 11.3 StarLogo Nova blocks-based coding sample



Algae population
314

Minnow population
16

Bass population
3

Total creatures
333

Total oxygen
296.1700000000002

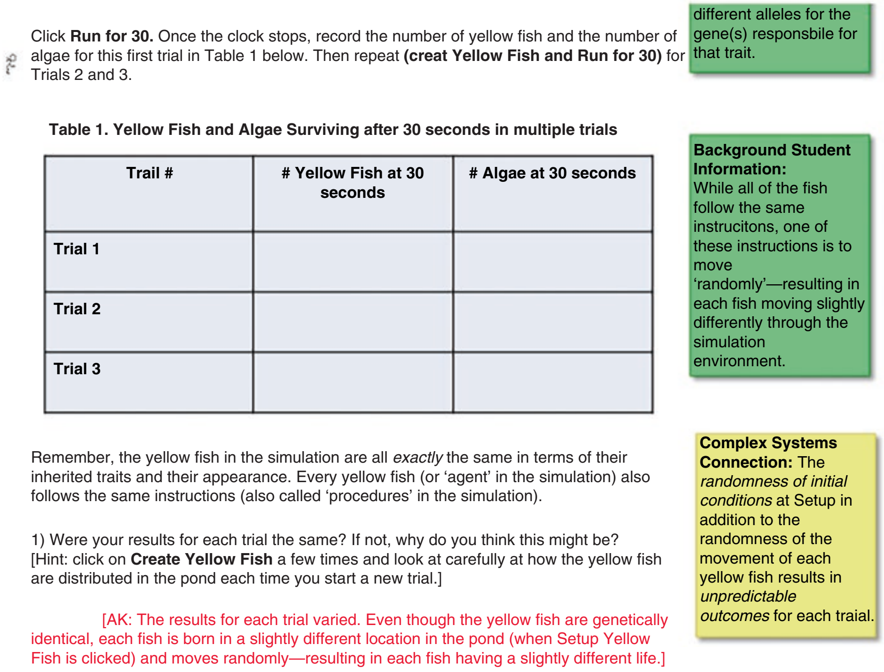
Time
263

Fig. 11.4 StarLogo Nova simulation interface

are organized into categories that neatly stack together to execute commands. Throughout the BioGraph curriculum, students interact with models that visually represent system states and processes at different scales. Teacher guides and student activity packets have been developed to work hand-in-hand with the curriculum. They offer details of the learning goals of the curriculum, steps in the activities, formative questions, and information that tie together complex systems ideas, the biology topic, and how those phenomena are represented in the model (see Fig. 11.5 for teacher guide excerpt). They also make explicit connection to scientific practices such as conducting multiple data collection trials and aggregating data for greater accuracy and precision, controlling and changing variables, and observing visual and graphical patterns as system properties emerge.

11.2.4 Content Expertise: What Is the Knowledge to Be Learned?

The last category builds understanding of complex systems and biology content. We built short units that take two to three classes to complete in five common high school biology topics. These include sugar transport in cells, enzyme interactions, ecosystems, gene regulation and protein synthesis, and the development of genetic traits in evolution. The units can be taught in any order that best fits the school's curricular scope and sequence. In addition to the StarLogo Nova model and accompanying student activity packet for each unit, other resources include freely available videos and news stories that discuss systems ideas in the real world, vocabulary lists that identify common complex system features (for example, self-organization,



different alleles for the gene(s) responsbile for that trait.

Click **Run for 30.** Once the clock stops, record the number of yellow fish and the number of algae for this first trial in Table 1 below. Then repeat **(creat Yellow Fish and Run for 30)** for Trials 2 and 3.

Table 1. Yellow Fish and Algae Surviving after 30 seconds in multiple trials

Trail #	**# Yellow Fish at 30 seconds**	**# Algae at 30 seconds**
Trial 1		
Trial 2		
Trial 3		

Background Student Information: While all of the fish follow the same instrucitons, one of these instructions is to move 'randomly'—resulting in each fish moving slightly differently through the simulation environment.

Remember, the yellow fish in the simulation are all *exactly* the same in terms of their inherited traits and their appearance. Every yellow fish (or 'agent' in the simulation) also follows the same instructions (also called 'procedures' in the simulation).

1) Were your results for each trial the same? If not, why do you think this might be? [Hint: click on **Create Yellow Fish** a few times and look at carefully at how the yellow fish are distributed in the pond each time you start a new trial.]

[AK: The results for each trial varied. Even though the yellow fish are genetically identical, each fish is born in a slightly different location in the pond (when Setup Yellow Fish is clicked) and moves randomly—resulting in each fish having a slightly different life.]

Complex Systems Connection: The *randomness of initial conditions* at Setup in addition to the randomness of the movement of each yellow fish results in *unpredictable outcomes* for each traial.

Fig. 11.5 Sample from biograph teacher guide

feedback loops, and decentralization) and off-computer games that place students themselves in the role of agents in a complex system to see how information travels and gets transformed in the process. These additional resources are meant to demonstrate how complex systems ideas can be found in many different areas of the natural and social worlds such that students can make connections across content domains even outside of biology.

11.3 Designing for Teacher PD

11.3.1 Face-to-Face PD: Exploring Teacher Learning and Community Development

As previously discussed, a central aim of the BioGraph project has been to produce usable curriculum that is readily integrated into standard biology courses. To understand how this could be accomplished, we initially worked with a small group of 10 teachers as collaborators in PD activities to learn about their own content understanding challenges as well as implementation supports needed. Our initial efforts in designing PD experiences focused mainly on developing teachers' content and pedagogical content knowledge, which can be described as human capital (skills, knowledge and dispositions of the individual to accomplish a task). Described in more detail in various project publications (see for example, Yoon, Anderson, et al., 2017a; Yoon, Miller, & Richman, 2020a), the human capital PD design features are anchored in what we know about essential components of high-quality PD as best summarized in Darling-Hammond et al. (2017): (1) a focus on disciplinary content, both the concepts and associated pedagogies; (2) addressing how teachers learn through active learning and sense-making; (3) enabling collaboration among teachers; (4) using models of effective instruction; (5) offering coaching and expert support; (6) dedicated time for feedback and reflection on practice; and (7) sustained duration of PD participation. Similarly, Desimone and colleagues outline a set of core features of effective PD including content focus, active learning, coherence, duration, coaching and mentoring, collective participation, and the consideration of contextual variables (Desimone, 2009; Desimone & Garet, 2015; Garet et al., 2001).

Teachers first learned about BioGraph resources in a one-week intensive summer face-to-face PD workshop that ran for approximately 30 continuous hours and then participated in 10 hours of school year PD on Saturdays. Summer activities consisted of training in complex systems concepts, working in pairs to complete the curricular units as if they were their own students, reflection with each other and the research team examining likely pedagogical challenges such as accessing and working with the computational models, visioning and planning in terms of where the BioGraph resources would fit coherently into their Biology courses, and expert (research team support) to respond to issues of content and pedagogical understanding both during the PD and school year implementation. We considered active learning to be particularly important especially as the BioGraph curriculum is centered on the use of a computational agent-based modeling tool. 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, 2011). To extend the PD experience beyond the initial adoption year, we worked with the same teachers over two years to continually develop their expertise–a time frame that has been shown to improve instruction with technology-enhanced inquiry science programs (Gerard et al., 2011).

In the second year of the PD experience, in addition to developing teacher's individual expertise, we worked more systematically to develop teachers' sense of a community of practice where resources and experiences could be shared between teachers and problems of practice examined and negotiated collectively. We discuss in Yoon, Anderson, et al. (2017a) that teachers wanted more collaborative experiences to learn from peers due to the fact that there are myriad instructional variables to navigate when teaching with our complex systems resources. We describe this second year as a focus on developing teachers' social capital (resources that can be garnered through social relations). Where previously, in our project, teachers were accustomed to accessing expertise from the research team, teachers had become increasingly more adept at using the curriculum in their instruction the second time around and were able to address classroom implementation issues more authentically than the research team although each teacher's experience was slightly different based on their student population. Thus, providing mechanisms for teachers to share their practice was a critical feature in growing the community. Valente (2012) discusses mechanisms that purposefully use networks to influence change in terms of bridging and bonding, that is, bridging between individual differences, and then solidifying those bonds made. We used four social capital categories discussed in Coburn and Russell (2008) and elaborated on in Yoon et al. (b; Yoon, Koehler-Yom, & Yang, 2017b) to inform our community building design. These are attending to:

Tie Quality: How many people teachers talked to in relation to the project implementation and frequency of these interactions.

Trust: How willing teachers were to share information with each other.

Depth of interaction: How related to the project the content of their interactions were especially as they addressed instructional and learning goals.

Access to expertise: How easily teachers were able to access the competencies and resources of other teachers and those found in other teachers' networks.

To improve tie quality, we used a strategy called *seeding interactions*, in which we connected teachers who were able to navigate through the BioGraph resources with relative ease to teachers who appeared to be struggling in their classroom implementation to serve as models and peer supports. During PD workshops, we reserved blocks of time for teachers to demonstrate strategies that they believed were successful in working with students. To develop increased trust among our teacher participants, we considered the important PD characteristic of active learning and sense making. Teachers worked in small teams during workshops on *targeted problems of practice* related to the project that they faced in their classrooms. They then worked together on solutions. The goal was to trigger supportive relational interactions through collective problem solving. In the category of depth of interaction, we grouped teachers who taught in schools that shared common student population characteristics to work on tailoring the curriculum to support increased learning. For example, several teachers in the group worked with large populations of second language learners and they created additional instructions for students to access the information in student activity packets. This *birds of a feather* strategy afforded teachers time to hold conversations that were consequential to the learning that was taking place in their situated contexts. Finally, we used a strategy called *expertise transparency* (Baker-Doyle & Yoon, 2011) to reveal the hidden expertise that resided in project participants, for example by asking teachers to conduct PD sessions in which they lead the other teachers through instructional sequences simultaneously performing a metacognitive think-aloud. For further details about our social capital strategies, see Yoon et al. (2018).

11.3.2 Online Asynchronous PD: Exploring How to Scale BioGraph Resources

Recently over the last few years, we have engaged in design and development of PD experiences to reach broader teaching audiences to scale the BioGraph resources. We decided to leverage existing infrastructures for large-scale dissemination of knowledge through the construction of a massively open online course (MOOC) in edX. In selecting this scale-up asynchronous mechanism, we were motivated by research that discussed a lack of high-quality teacher PD that implicated time and space as issues related to scale. For example, among the highest concerns articulated by teachers for improving practice has been the need for more and flexible time to access and process new information (Merritt, 2016). Other research has highlighted a dearth of access to professional peers and the geographic isolation for teachers (Peltola et al., 2017). This research has indicated that online PD has the potential to supplement local, in-person experiences, where anywhere, anytime access to resources can potentially mitigate time constraints. Some reports have also emerged that suggests online teacher PD experiences (if designed and translated into classroom instruction well) can produce comparable results to face-to-face PD experiences in terms of student learning outcomes (Fishman et al., 2013; Webb et al., 2017).

From our previous work, we understood the importance of building a collaborative community, in which teachers could negotiate issues of practice due to the myriad challenges in integrating computer-supported complex systems curricula into science instruction. This requires teachers to develop adaptive expertise that considers teachers' own knowledge and instructional skills, student learning characteristics, and contextual variables in conjunction with the biology and complex systems content and the technology applications (Yoon et al., 2019). Thus, when investigating the design features necessary to build an online asynchronous course for BioGraph teachers, using social capital strategies became the primary driver (see Yoon, Miller, & Richman, 2020a; Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, & Shim, 2020b; Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, & Marei, 2020c for a more in-depth review of the literature on MOOCs and teacher PD). Table 11.1 summarizes the design choices we made to promote teacher's social capital in our online course. The conceptual framework includes the categories of social capital (Coburn & Russell, 2008) and essential components of high-quality PD (Darling-Hammond et al., 2017). These were embedded in a course with seven online PD modules: (1) Introduction to the course, participants and facilitators; (2) What are complex systems; (3) Why modeling is a core scientific practice; (4) What is scientific argumentation and evidence-based reasoning; (5) How the curricular materials fit into the NGSS; (6) An examination of each of the simulations and corresponding biology units in detail; and (7) Conclusion to the course and framing for implementation. The activities spanned about 30 to 40 hours of participation.

Table 11.1 Design choices for building teachers' online social capital

Social capital category	Teacher PD characteristics	Online design strategies
Tie quality	Collaboration or collective participation Sustained duration	Online profiles to share professional and personal information, e.g., *write a post that describes your background (e.g., how long you have taught, unique skills or knowledge that might interest your classmates). After you have responded, use the forum to connect to a couple of other course participants by clicking "reply" to comment on their posts.* Discussion forum Collaborative prompts to seed interaction, e.g., *share one triumph in creating your model along with one unexpected moment. Then, leave some encouraging comments on other posts!* Six-week PD in edX with follow up Moodle participation
Trust	Feedback and reflection with peers Networked communities	Synchronous meetups (scheduled 3 hour-long meetups for participants to connect course names with a real person) Content and implementation prompts, e.g., requests to share tried and true resources
Depth of interactions	Disciplinary content Active learning and sense making	Demonstration videos and practice with technology Anticipating and discussing problems of practice, e.g., *imagine your own classroom, what challenges do you see happening with your student population around building computational models? Think through some strategies with others* Relationships to standard curriculum, e.g., argumentation Lesson planning with peers on module capstones
Access to expertise	Coaching and expert support	Videos with narration of expert teachers delivering classroom instruction Expert teachers as course facilitators Help forum with technical and pedagogical support from PD development team

11.4 Research Findings

To date, we have conducted 9 research studies that have sought to document the design of BioGraph resources and their impact with students and teachers. A full review of the research methods and findings from each study is beyond the scope of this chapter. However, we have generally found that both student and teacher populations have improved in their learning of complex systems in relation to biology content, and this improved learning has resulted from a change in curricular experiences using the BioGraph resources. Students have especially gained a better understanding of the domain of biology as a coherent set of concepts that can explain the natural world. Teachers have found great utility in these resources that are easily integrated into their standard biology courses and our efforts to move PD from a face-to-face mode to an online asynchronous mode has proven to be successful in terms of a scaling up mechanism that retains high-quality PD characteristics. In this section, I will briefly present selected findings to provide evidence for these claims.

In all of these studies, we have taken a mixed-methods approach to measuring project impact. We draw from multiple data sources that include for teachers, a post PD resource usability survey (rating statements such as, “The PD covered topics relevant to the grades that I teach”); pre- and post-content and pedagogical content knowledge surveys (rating statements such as, “My students use computer models to visualize scientific phenomena”), individual post-implementation interviews, classroom observations, and online PD collaborative discussions. We have collected a similar set of data sources for students that include, pre-post biology and complex systems content knowledge surveys (see the following section for complex systems knowledge survey); pre-post classroom experience surveys; focus group interviews; and video recordings of small group interactions. With respect to our study populations, in earlier design and development studies (Yoon et al., 2016; Yoon, Anderson, et al., 2017a), we worked with a small number of teachers (n = 10) to be able to investigate in some depth the extent to which project simulations and resources were usable in classrooms and produced the desired outcomes of both student and teacher learning. In later studies in which we aimed to scale up the intervention through online PD experiences (Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, & Marei, 2020c) data collection and analyses are based on a larger, more random group of teachers and classrooms. Here are results from selected data sources.

11.4.1 Students Improve in Biology and Complex Systems Understanding

As reported in Yoon, Anderson, et al. (2017a) students improved in their understanding of biology content as measured through 14 multiple choice questions compiled from state and national standardized science exams. Results from a paired t-test with a sample size of 346 students showed significant growth ($p < 0.01$) from pre-survey scores equal to 7.67 (SD = 2.36) to post-survey scores equal to 9.43 (SD = 2.47) with a Cohen’s d effect size of 0.67.

We saw similar results in student’s complex systems understanding. Students responded to the following open-ended question in pre- and post-surveys.

> Imagine a flock of geese arriving in a park in your town or city, where geese haven’t lived before. Describe how the addition of these geese to the park affects the ecosystem over time. Consider both the living and non-living parts of the ecosystem.

Student responses were scored on a scale of 1 (not complex) to 3 (completely complex) for each of four different dimensions of complex systems understanding that included the predictable or random nature of agents in a system; systems processes being static or dynamic; order being centralized or decentralized; and linear versus non-linear emergent effects. Aggregated for a score of 12, a sample size of 361 students showed significant growth ($p < 0.01$) from pre-survey scores equal to 5.80 (SD = 1.23) to post-survey scores equal to 6.79 (SD = 1.29) with a Cohen's d effect size of 0.65. Although this research was a single group non-comparative design, the effect sizes of 0.67 and 0.65 are interpreted as medium effects (Cohen, 1988) and about 3.5 times larger than science learning gains in a whole year of learning as measured by several nationally normed tests (Bloom et al., 2008).

11.4.2 Students Understanding of Biology as a Coherent Set of Ideas Improves

In another study (Park et al., 2017) we sought to determine the extent to which students improved in their understanding of biology as a coherent set of ideas explaining the natural world. Students were asked the following questions in focus group interviews: (1) What do you think biology is? (2) Recall all the units you did using the simulations, which units did you cover and was there anything that these units had in common? (3) How do complex systems fit into biology? A large portion of the student sample articulated that complex systems concepts could be located in many biology ideas. For example, one student stated the following:

> 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.

Here the student explained that multiple concepts in biology could be understood from a complex systems lens. Similarly, another student said:

> 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 explained that all of the units showed how systems have multiple interacting agents, which randomly bump into each other, and depending on the ways in which they interact, different outcomes would occur in the system. Still, another student stated, "Everything is a complex system; if you think about it" (Focus Group ID 6, May 2014). All of these statements revealed that students came to understand biological content more coherently through a complex systems lens.

With respect to how the BioGraph resources supported their understanding, students pointed to the StarLogo Nova simulations and opportunities to modify the code as affordances in their learning experiences. The following quotes illustrate this point:

> 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)

> 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)

It has been clear in all of our studies examining student learning and participation with the BioGraph curriculum that they have gained a great deal in terms of understanding how concepts in biology are connected. Furthermore, in data not presented here, students have articulated enjoyment and interest using the resources, which no doubt has also contributed to their engagement in the project. In the next sections, I discuss findings from teacher data that showed equally successful outcomes.

11.4.3 Teachers Indicate High Usability in their Biology Courses

Results from a PD usability survey (sometimes referred to as a satisfaction survey) administered to teachers at the end of the PD workshop showed high evaluation and usability of the BioGraph resources. Teachers responded to 18 Likert-scale questions (1 = strongly disagree to 5 = strongly agree) in three categories of: overall course satisfaction (for example, *The course covered topics that are relevant to the grade(s) I teach*); module construction and delivery (for example, *The modules actively engaged those in attendance*); and usability of materials in teaching (for example, *The student worksheets given out during the course will be useful in my teaching*). All ratings for both face-to-face workshops (held in 2012 and 2013) and online workshops (held in 2018 and 2019) showed uniformly high ratings ranging from 4.42 to 4.98. Figure 11.6 shows a comparison of ratings across the four years.

What is notable about these numbers is that even as we worked with about 4 times more teachers in 2019 who took the online course, the rates of satisfaction, continued to be high, which bodes well from the perspective of our goals for delivering high-quality PD at larger scales.

11.4.4 Developing Teacher's Social Capital Is Key

Over the years, we have come to understand that developing teacher's social capital may be just as important as developing their human capital. Yoon et al. (2018) demonstrates that teachers in the face-to-face PD wanted to share their experiences with other teachers, characterized their experiences in terms of opportunities rather than

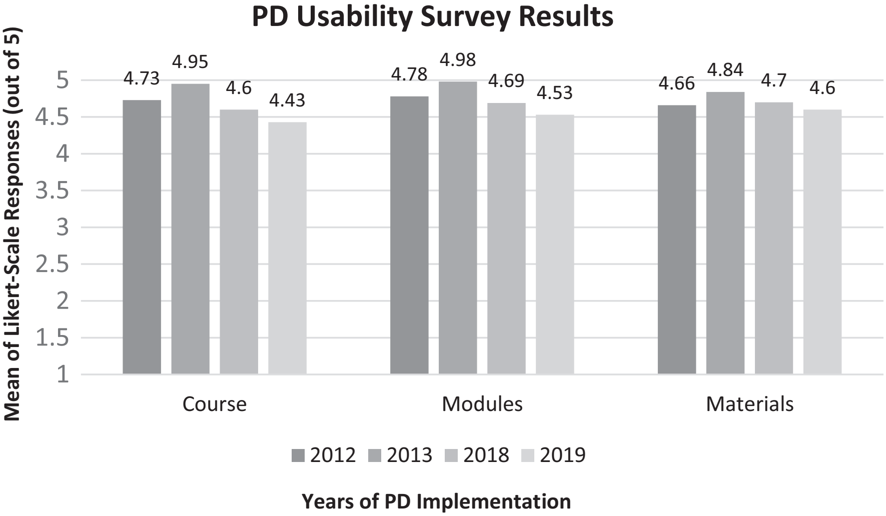


Fig. 11.6 Comparison of teachers' responses to usability of PD resources across 4 years

barriers to implementation, and generally improved in their beliefs about the utility of BioGraph resources to support their instruction. This happened after we launched our social capital PD activities such as seeding interactions and addressing targeted problems of practice. The following comment from one teacher in that study illustrates these ideas:

> I remembered another place where I talked about your simulation[s]. [I talked] with some other biology teachers and certain concepts and I told them that they should check your simulations out because I think they really do a great job…Maybe we were talking about ecosystems or evolution and how there's a real lack of web labs available for us to do and that your simulations…are able to support portions of our curriculum where it's hard for us to find activities to do.

Likewise, teachers' implementation confidence improved dramatically as a result of increased access to peers. Again, the following set of quotes from that study supports this claim.

> Certainly, familiarity was a big thing…I had resources from teachers and online that I didn't have the year before. There were videos that Lisa had put online that I was able to use…I had a lot of things, a whole repertoire of tools that were created [after] the first year that I was able to pull from and more were added. As we went to the PD a lot of teachers shared a lot of what they had created, simple little worksheets. I had all of that in place, all of the very helpful tools that I could use over the course of the year and that made it really easy.

> Again, having that second week of summer PD and really sitting down with the other teachers and figuring out, okay, "When did they incorporate it? What activities did they use? Did they have openers or closers?" So, I think that was the biggest thing; is talking to other teachers and spending that time

> I would say by practice and communicating with the group. That was probably the best set of examples for me. It just helped communicating with the other teachers and communicating with all of you doing the presentations on the complex systems.

Several studies investigating the impact of our social capital design in the online PD mode also shows the importance of sharing and reflecting on practice with others. In Yoon, Miller, Richman, Wendel, Schoenfeld, Anderson, Shim, and Marei (2020c), we saw high degrees of collaborative discourse that resulted from prompts designed to solicit interaction between teachers. In interviews, where we asked teachers to comment explicitly on their experiences in the four social capital categories (namely, tie quality, trust, depth of interactions, and access to expertise), teachers offered many positive comments. For example, in the category of access to expertise, one teacher said:

> I really, really liked watching the online implementations...with watching those videos of classrooms, I got to see what it was going to look like for my students, and I got to think about what I might have to modify for my particular group of kids.

11.5 Benefits of Computer-Supported Complex Systems Curricula and Lessons Learned

With respect to the overarching research goal of this project that I articulated in the introduction, which is “How and in what ways can complex systems resources be integrated into the high school biology curriculum?”, I have illustrated the benefits afforded to student learning about biology content knowledge and their ability to understand the domain in a more coherent way (a need articulated in science education research, such as in Chiu & Linn, 2014) through a computer-supported complex systems approach. This approach addresses further needs in science education research for dynamic visualizations (Hoffler & Leutner, 2007; Plass et al., 2009; Roseman et al., 2010) that allow students to manipulate and modify simulations of biological systems and enables them to compare processes and structures that emerge through agent-based interactions. They also conduct experiments, collect and analyze data, and participate in scientific argumentation in sequenced activities to support their developing knowledge of how complex systems operate.

Over the course of our decade of work, the importance of working with teachers in PD activities as design collaborators must be greatly underscored. In addition to anchoring PD structures in what we know best about how teachers learn and participate in PD (for example, Darling-Hammond et al., 2017; Desimone & Garet, 2015), the following design features of our project have led to usable and impactful curricular and instructional resources:

1. Extensive and repeated training on computers.
2. A minimum of two-years of PD.
3. Focus on developing teachers’ human and social capital.

4. Concerted effort to develop a professional learning community to support teaching beliefs and confidence.
5. Developing high-quality PD at larger scales by utilizing the design features in 1–4 for asynchronous online experiences.

Importantly, this set of design features are critical to the teaching and learning of complex systems resources based upon the use of computational agent-based models that are deployed in real-world classrooms with myriad variables that teachers must negotiate if they are to be successful in supporting student learning.

Lastly, I believe that the BioGraph project instantiates well the complex systems epistemology articulated in Capra's (1975, 2014) quotes at the beginning of this chapter. That is, through curriculum, instruction, and PD activities that highlight the importance of the interconnectedness and interdependence of phenomenon (from micro to macro scales), we will be able to greatly improve teaching and learning in the domain of biology.

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