Teaching Characteristics of Complex Systems in K-12 Education: Lessons Learned

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Abstract

This paper describes lessons learned while completing a pilot project initiated by Professor Jay Forrester through the Creative Learning Exchange. The goal of the Characteristics of Complex Systems Project (CCSP) is to create online curriculum materials for K-12 students and interested adults that will illustrate the characteristics of complex systems first enunciated by Forrester (1969) and appearing repeatedly in the systems thinking/system dynamics literature since then.

The pilot project was designed to address the characteristic "The cause of the problem is within the system" through the creation of a family of models that share the generic 2nd order negative feedback loop that generates oscillation. By utilizing the online simulations and attendant lessons, students encounter this particular characteristic in various formats and subject areas. Through repeated exposure to models and materials that incorporate instructional scaffolding principles[1](Wood et al. 1976), students learn to recognize the perceived problematic behavior exhibited is a consequence of the internal system structure.

Introduction

The vision of the CCSP is the widespread internalization of the characteristics of complex systems, such that citizens become consumers of models addressing social policy and social system design. Citizens should understand the nature of complex social systems – why do such systems resist policy changes? Why are short-term and long-term responses to corrective action often at odds with each other? How can leverage be applied to bring about desirable change in social systems? An abstract level of understanding with regards to social systems will help prepare future citizens to actively shape their society (Forrester 2009).

The challenge of this project is to create readily accessible and interesting materials for a K-12 audience that not only fit the current curriculum standards of this country, but simultaneously teach a perspective that most teachers and school administrators do not yet include – seeing the world through the lens of complex systems. Teachers have more pressing requirements to meet. An iceberg visual[2] illustrates the approach utilized for this project.

The top of the iceberg features the "event" perspective. Events are viewed as individual incidences of a particular phenomenon and are rarely placed in context with the systems in which they are a part. In the K-12 environment, this is manifested through learning about facts in various subject areas. Biology class

[1] Instructional scaffolds are temporary support structures teachers use to assist students in mastering new tasks and concepts they could not initially achieve on their own.

[2] Iceberg Visual shown in Figure 1 is available on the Creative Learning Exchange website at http://www.clexchange.org/curriculum/complexsystems/oscillation/complexsystems_iceberg.asp

teaches about topics in biology; it may not be viewed as an opportunity to learn about similarities between biological and social systems.

A family of models illustrating the same behavior pattern invites the investigation of such similarities. Ideally students are exposed to more than one model in the family so they can more easily move down the iceberg to the "Patterns of Behavior" level. Each lesson showcases the pattern and the underlying structure that produces it. Repetition is the key to reaching the bottom of the iceberg. For that reason, the family of models covers five topic areas and three age groups (Level A – ages 5+, Level B – ages 9+ and Level C – ages 13+) to ensure access to these ideas throughout the K-12 spectrum. For example, students could conceivably encounter the Level A "playground dynamics" simulation as 5th-grade students and then be introduced to "predator-prey dynamics" as 8th- grade students. In a 12th-grade economics class they could apply their understanding of oscillation to the phenomenon of commodity cycles. The required timeframe to reach an abstract level of understanding concerning the Systems Principle, "The cause of the problem is within the system," is necessarily long. Ideally, many talented people will contribute to the body of materials so that the teaching of all Dr. Forrester's characteristics of complex systems can be integrated into the K-12 environment.

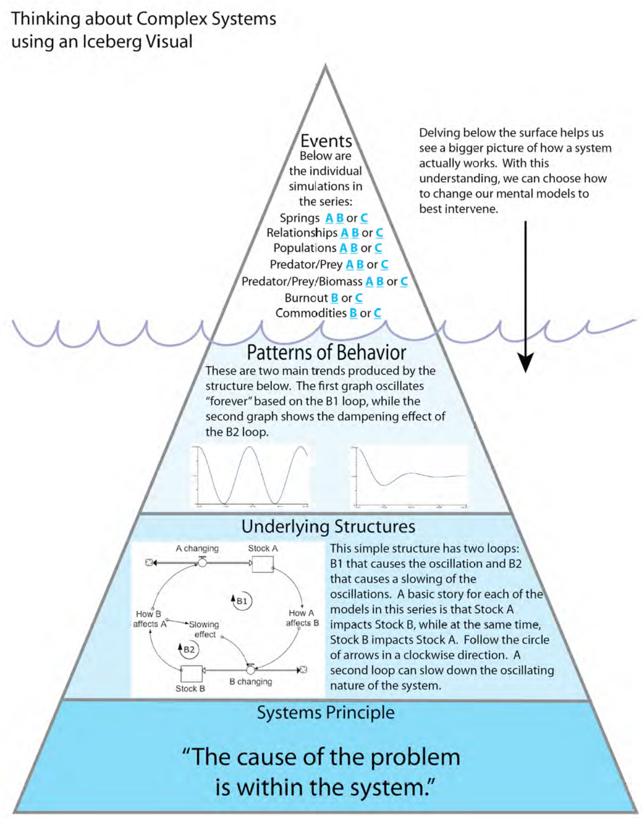

Figure 1: Thinking about complex systems using an iceberg visual.

This paper relates the participants' experiences and lessons learned that were acquired through the completion of this pilot project. This information may be useful in other contexts where the focus is on learning through the use of simulation rather than learning skills to build simulation models.

Project Participants and Their Roles

The pilot project was completed with collaboration between many individuals. Jennifer Andersen served as the primary modeler for the project and created simulation interfaces and model background documentation for the high school audience. Anne LaVigne created simulation interfaces for middle school and elementary audiences as well as lesson plans and classroom handouts for all three audiences. Michael Radzicki assisted Jennifer as senior modeler on an as-needed basis. Lees Stuntz served as project coordinator and gave frequent input in the areas of scope, sequence, design and content. George Richardson helped to bridge the educational and system dynamics worlds by bringing his extensive experience with both to bear on the materials produced. He joined many conference calls.

In addition, the expertise of a number of individuals affiliated with the CLE, Andrea Miller, Jan Bramhall, Marcy Kenah and Bunny Lawton, were instrumental in editing and publishing all the simulations and accompanying materials.

Planned versus Actual Deliverables

The pilot project proposal suggested the creation of simulations in five topic areas. After a review of the existing literature on oscillatory systems, topics identified with connections to K-12 curricular standards were:

- Love-hate relationships
- Predator-prey cycles
- Burnout cycles
- Commodity cycles
- Weight cycling/Yo-Yo dieting

Except for weight cycling, one or more existing models were identified for each of these topics. This project plan would have resulted in **five simulations** (models plus interfaces) with **five sets of lessons and handouts** for teachers. Actual deliverables of the pilot project are outlined in the table below.

Simulation Models	Interfaces Age 5+ Age 8+ Age 13+	Teacher Lesson and Handouts Age 5+ Age 8+ Age 13+	Background Documents Age 5+ Age 8+ Age 13+
1. Spring Dynamics	● ● ●	● ● ●	●
2. Love-Hate Relationships	● ● ●	● ● ●	●
3. Logistic Growth	● ● ●	● ● ●	●
4. Predator-Prey Cycles	● ● ●	● ● ●	●
5. Predator-Prey-Biomass Cycles[3]	● ● ●	● ● ●	●
6. Burnout Cycles	● ●	● ●	●
7. Commodity Cycles	● ●	● ●	●
7 Simulation Models	**19 Interfaces**	**19 Sets of lessons & handouts**	**7 Background documents**

[3] Simulations 5, 6 and 7 are role-playing simulations. The interfaces and accompanying materials are more complex than simulations 1 – 4.

Using principles of backwards design (Wiggins, McTighe, 2005) the simulations and accompanying materials were developed with the end in mind. That is, defining what students should know and be able to do by the end of a lesson/unit along with desired enduring understandings was a critical step during the development process. The identified characteristic (cause of the problem is within the system) was the guiding concept to foster a particular enduring understanding for students. In addition, current K-12 standards were identified to align with both the context and the characteristic for levels A, B, and C. The simulation itself along with wrap-around materials (introductions, debriefs, and assessments) supported students in achieving the desired learning goals.

Assessment strategies varied from one lesson to the next, but with increasing content complexity (simulations 5, 6, and 7), students can take on more realistic roles, playing out scenarios to demonstrate an understanding of how policy levers create or do not create desired results. Students summarized their learning using a variety of methods including creating a stock/flow map, a written essay, a report to a fictional supervisor, and a newspaper article. These summative assessments, some with accompanying leveled rubrics, helped determine to what degree students achieved the stated learning objectives identified during the initial phase of development.

As part of the development and refinement process, lessons and assessments were implemented at elementary, middle, and high school levels in multiple school and district settings. These teachers and their students provided important feedback for refining the lessons and simulations eventually published on the CLE site

A Summary of Lessons Learned

At the outset of the pilot project the team did not have a clear picture of how a model-based curriculum to teach K-12 students that the "cause of the problem is in the system" should look, nor how many simulations would be enough to ensure transfer of learning to new situations. There are now 19 simulations available in a total of five topic areas. Depending on the age group, these materials provide five to seven opportunities to engage this complex system characteristic. During the course of two years of development time, several notable challenges arose, leading to valuable lessons learned thus informing best practices for future projects.

Challenges	Lessons Learned	Resulting Best Practices
I. Changes to the Scope: Translating an idea for K-12 from something an SD modeler would appreciate into something a K-12 teacher will use. (See section below.)	Teachers are not aware of the need for children to learn about the Characteristics of Complex Systems. They need multiple paths of approach and good supporting materials to help them get to this insight.	• Allow the needs of the K-12 environment to inform how the SD model will be used. (For example, predator-prey became three models/lessons, added a spring model, and created role-playing simulations.) • Slice the K-12 spectrum into manageable groups (three age groups) and develop supporting materials accordingly. • Be flexible in certain aspects of

		modeling to make the end product more accessible to a non-modeling audience (variable names changed to suit the age of the audience, for example).
II. Process: The iterative nature of the work. (See section below.)	Allow sufficient time to iterate as necessary, but also look for ways to streamline processes.	• Follow an agreed-upon process to develop simulations without excessive iteration. • Create templates whenever possible (interfaces, lessons, handouts, background documents). • Review interface content early and often by sharing with others; late changes trigger the rework cycle.
III. Alpha-testing our materials: Incorporating feedback from teachers and others about the simulations and accompanying materials. (See section below.)	Recognize the need to gather user feedback, but consider these comments holistically rather than one-by-one.	• Provide the necessary context for teachers to understand and use the simulations and materials (CLE web materials and background documents). • Work with a small group of teachers for initial review and testing. • Allow extensive classroom testing to inform future changes to the simulations. • Recognize that teachers are on a learning journey; encourage them to move forward by incorporating good modeling practice.
IV. Collaboration: Collaborating as a team over physical distance.	Do not underestimate the time and energy needed for long-distance collaborative project work.	• Schedule frequent conference calls (every month became every two weeks). • Utilize technology – video conferencing allows everyone to see the same computer screen.

More Detail about Lessons Learned

This section of the document elaborates on points I – III from the table above.

I. Changes to the Scope

The Addition of Age-Appropriate Interfaces

Early in the project it became clear that the original project plan, as articulated in the proposal, would not lead to the creation of complex systems materials that would serve the needs of the entire K-12 spectrum. For example, while the proposal suggested the creation of simulations and materials within five topic areas, it was heavily biased toward older (high school level) students. How the simulations and materials would be used toward younger students was not articulated. A resulting conclusion was that certain topics, such as predator-prey cycles and love-hate relationships, would be relevant to even the youngest audience members (perhaps as young as five years old) while others, such as commodity cycles, would not.

The team chose three target age groups (5+, 8+ and 13+) and decided that each group would need an individualized, but standard interface (using the same template for each simulation in the group). Each template features age-appropriate text, pictures, simulation exercises and debrief explanations, along with age-appropriate materials such as lesson plans for teachers and handouts for students. For example, the menu systems for each age group were designed to appeal to the maturities of the audiences. Very young students (Level A) learning to read and manipulate a mouse benefit from simple text, illustrative symbols and large buttons. Level B students use a button-with-text menu system and Level C students use a hyperlink menu system.

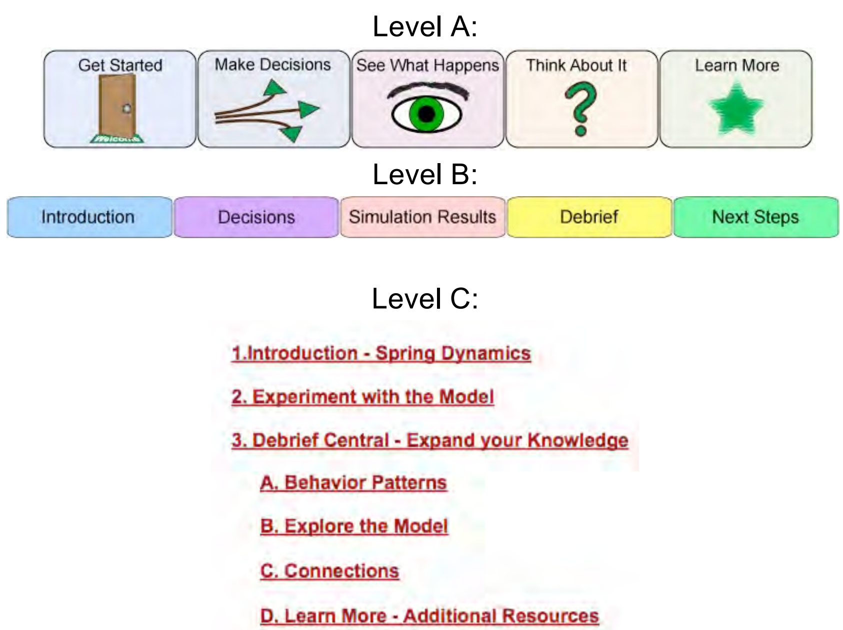

Figure 2: From the top, Level A, Level B and Level C standard menu systems are shown.

In addition, the models themselves needed modification. For example, variable names were altered to suit the audience's level of understanding, and in some cases, the context of the model was significantly changed. For example, love-hate relationships for the oldest students became playground ups and downs for the youngest. Please see Figure 3 for a view of these models.

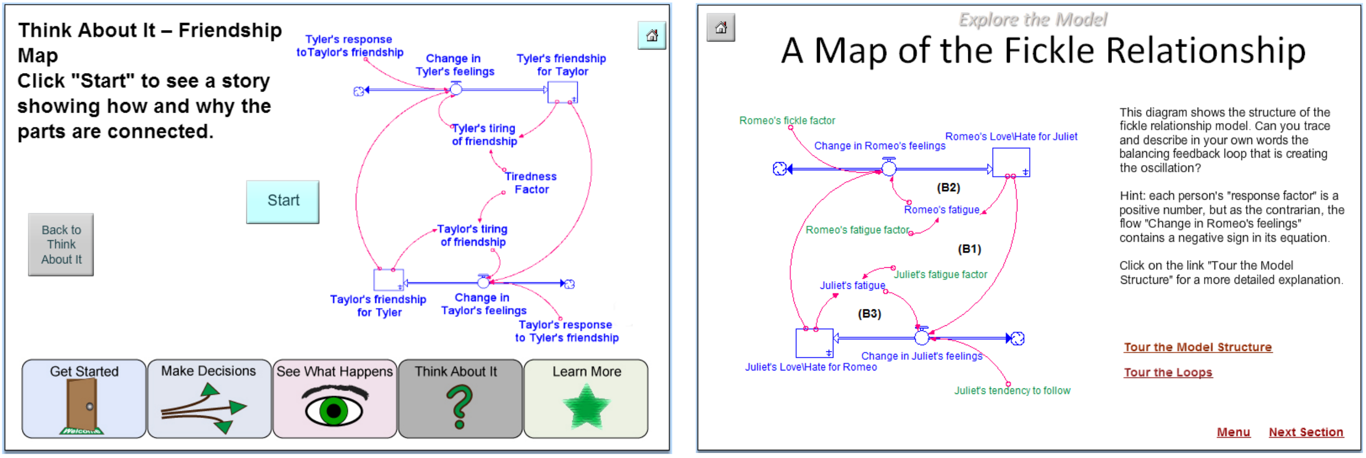

Figure 3: The left side features the Level A "playground dynamics" model that was recast from the original "love-hate relationships" model intended for Level C students.

Changes to the List of Simulation Models

The Addition of the Spring Model

The family of models needed to progress in some fashion in order to encourage the investigation of the whole series. Learning about one topic area – predator-prey cycles – was unlikely to make a lasting impression regarding the complex system characteristic that ***the cause of the problem is within the system***. A simple position-momentum model of a spring was added to the series as an introduction to the idea of oscillation as a behavior pattern. For all age groups, this simulation is adaptable to experimentation with physical springs. It emphasizes the idea that springs are a function of their structure (the material of which they are made as well as their shape) and that once set into motion, they oscillate because of these characteristics. The other simulations refer to this introductory lesson and emphasize that just as a spring behaves according to its structure, so do predator-prey relationships, burnout cycles, and so on.

Three Simulations for Predator-Prey

To encourage the investigation of more than one model of the series, predator-prey cycles became three separate simulations. The first is a logistic growth simulation that illustrates why a one-stock model cannot oscillate. The second simulation adds the predator population to generate the cycles and also shows that eliminating predators takes one back to the structure of the logistic growth model. The third simulation expands these ideas by adding a food supply for the prey. Students in the role of Wildlife Manager can investigate real-life implications of the elimination of predators on a managed prey population as they strive to satisfy diverse interest groups. Please see Figure 4 for the progression of model structure for these three simulations.

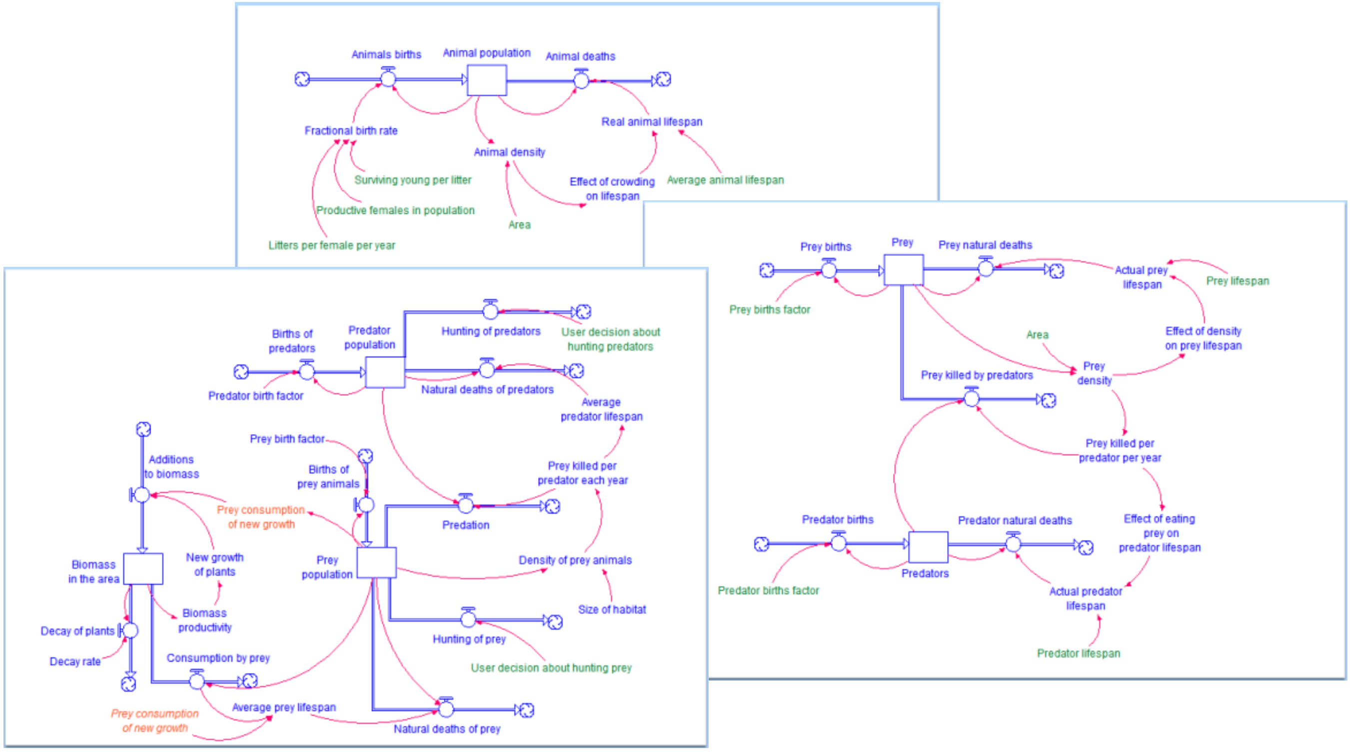

Figure 4: Clockwise from the top, logistic growth, predator-prey and predator-prey-biomass models are shown as a progression of structures from simple to more complicated.

Several reasons are pertinent for creating this mini-series of predator-prey models. Knowing that the topic of predator-prey relationships is highly relevant within K-12 educational standards, it was important to create a comprehensive set of materials. A math teacher seeking a concrete example of logistic growth could become interested in the series just as easily as a biology teacher seeking an example of trophic interactions. The predator-prey models helped to create a soft transition from the tangibility of the spring model to the relatively abstract ideas of the more advanced simulations (burnout and commodity cycles). Lastly it provided a fun way to introduce role-playing to the family of models as a whole (predator-prey-biomass is a role-playing simulation).

Three Role-Playing Simulations

One important aspect of the pilot project was to provide a platform for students to explore complex issues while taking on a role and completing a summative project to illustrate their understanding. Inspired by project-based learning, students can "become" project manager, national park advisor, architect, business owner, consultant, and so on. This naturally leads to the need for a more complex model in which students can experiment with different intervention plans. In this series, students step into the roles of Wildlife Manager (managing the prey population of the predator-prey-biomass model), Peer Coach (advising fellow students regarding burnout cycles) and local newspaper journalist (investigating hog farming for the commodity market versus raising heritage breeds of hogs for a more specialized market). In order to create these types of experiences with simulation models, students need to have a role and a goal for success within the simulation. As the roles and goals are identified, that informs the model structure, the interface look and feel, and the needed support materials for teachers and students.

II. Process

Through trial-and-error, a process of simulation development to organize the work more efficiently emerged:

1. For each simulation to be developed, define learning goals (based on national K-12 standards and system dynamics principles) for each age group and determine how students will demonstrate understanding.
2. Create an overall vision of the experience the students will have, including defining any and all roles for a role-playing experience.
3. Develop the model and interface for the oldest students (C-level), based on the predefined learning goals, before the other two age groups. The interface does not have to be finished to the point of final editing, but the content should be settled before attempting the B- and A-level interfaces.
4. B- and A-level interfaces can be developed concurrently based on the predefined learning goals. *The content of these interfaces may be adapted from the C-level interfaces but will be significantly different (level of interactivity, text, pictures, etc.).*
5. Lessons and background documents can be developed concurrently with the design of the interfaces.
6. Use the first simulation to set the overall design of the interface for each age group (a template). Interfaces should be different between age groups to make them age-appropriate, but must be consistent within the age group for the entire series.
7. Iterate (adjusting the model, interface, and/or lesson) as needed throughout the design process.

III. Alpha-testing our Materials

Incorporating Feedback

The team was fortunate in being able to elicit feedback on the simulations and materials from many talented people across the spectrum of needed skills. Two experts in system dynamics, George Richardson and Mike Radzicki contributed to adherence to good modeling practices. Diana Fisher and Jeff Potash lent their experience both as educators and modelers for a K-12 audience. In addition, a number of dedicated teachers reviewed and in some cases tested the materials in their classrooms before final publication. Feedback from all sources was reviewed; what could not be incorporated in the pilot project has been noted to inform future work. In addition, a feedback form is accessible from the CLE web pages devoted to these materials, to continue to collect suggestions for future improvements.

Empowering Teachers and Other Users

The materials and supporting web resources are designed to be stand-alone for teachers and other users who have limited experience with the concepts of stocks and flows. To this end, web content showcases the entire set of lessons on the Creative Learning Exchange website (including material on the characteristics of complex systems) and created seven background documents, one for each of the simulation models, to aid teachers in experimenting with the models, understanding the structure of the models and interpreting model behavior for a variety of simulation runs. Taken together, this complex systems curriculum allows entry from various topic areas and provides a means for moving from less-complex to more-complex interaction. Students who complete a number of simulations will be exposed to the idea that the oscillatory (problematic) behavior pattern arises due to system structure and not the influence of unseen, exogenous forces.

Conclusion: Continue to Create Appealing and Accessible Simulations and Materials

For future materials to teach the characteristics of complex systems, the following are recommended considerations for development and implementation:

1. Have separate materials for novice users and experienced users. The concepts of system dynamics are often overwhelming for novices. Further consideration is needed for how to introduce the concepts without turning people away. The simulations developed for the pilot project are generally intended for people who have some experience with concepts such as stocks, flows and feedback loops. Key questions include, "To what degree is the stock/flow piece too much for people, especially novice users?" and, "What is needed to increase understanding of system structure and behavior without overwhelming teachers and students?"
2. Include the storytelling feature only in the downloadable STELLA file, along with a simple interface with suggested experiments to run. The online Forio version would be left less technical, only explaining a conceptual view of the model rather than delving into stocks and flows.
3. Increase the level of visual interactivity through video, animations, etc. One idea is to create "facilitator" videos featuring someone who guides users through the different parts of the simulation.
4. As much as possible, continue to create role-playing simulations, for the reasons discussed earlier in the document. Investigate whether developing materials that move from stand-alone, role-playing experiences to seeing the general patterns and generic system dynamics structures is feasible and/or useful. The advantage is that simulations in which teachers have already shown an interest in using can be a hook to having their students delve deeper into seeing the same phenomenon over multiple instances.

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