Teaching Characteristics of Complex Systems in K-12 Education

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Abstract

This poster session will describe the progress of a pilot project initiated by Professor Jay Forrester through the Creative Learning Exchange. The parent project goal 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.

This initial pilot project addresses the characteristic "The cause of problems is within the system" through the creation of a family of models that share the generic 2nd order negative feedback loop that generates oscillation. Students will encounter these models in various formats and subject areas and will have the opportunity to experiment with non-oscillating test inputs. Through repeated exposure to models and materials that reflect instructional scaffolding principles[1], a framework will be created that will teach them to recognize that the perceived problematic behavior exhibited is a consequence of the internal system structure.

The vision of the parent project is the widespread internalization of the characteristics of complex systems, such that citizens become consumers of models addressing social policy and social system design. The required timeframe is necessarily long; ideally, many talented people will contribute to the body of materials.

Perception of a Need

Over the past 50 years, the field of system dynamics has captured minds around the world, in every major field of study. The latest version of the system dynamics bibliography contains over 9,000 entries (System Dynamics Society, 2010); it is reasonable to assume that it reflects only a fraction of the entire stock of system dynamics models in existence. Similarly, the Creative Learning Exchange website (http://www.clexchange.org/) is just one example showing the interest and activity surrounding system dynamics modeling in K-12 education. At first glance, it appears that the power of exponential growth – the churning wheels of models being produced

[1] Instructional scaffolding involves providing support to students when they are learning new concepts or tasks. Support can take many forms and is gradually removed as students become more proficient. It is often used to support problem-based learning (PBL), where students work together in small groups to research and analyze problems and suggest possible solutions (http://en.wikipedia.org/wiki/Instructional_scaffolding).

by and for educators – will eventually diffuse knowledge of complex systems to every K-12 student in America.

Such an assumption, however, may be incorrect. While it is likely that many well-made models are being used in K-12 education, and also likely that educators with a sound understanding of system dynamics principles are teaching students about the characteristics of complex systems, can we conclude that we are on the way to creating a population of "systems citizens?"[2] In other words, will systems citizens emerge simply from using system dynamics models in K-12 education?

Professor Forrester maintains that students "can miss most learning for the 21st century" in the absence of correct guidance (Forrester, 2009). He has requested proposals to fill this perceived need in K-12 education. A coordinated, sustained effort that focuses on using system dynamics modeling as a tool to teach students (and others) to understand complex systems will, if executed thoughtfully, accelerate the learning curve and ensure progress towards this goal. Specifically, the request from Professor Forrester was to create a cohesive set of generic models, using examples from multiple disciplines, to teach the characteristics of complex systems. The list below is based on the ideas that first appeared in Chapter 6 of Urban Dynamics (Forrester, 1969).

1. Cause and effect are not closely related in time or space
2. Action is often ineffective due to application of low-leverage policies (treating the symptoms, not the problem)
3. High-leverage policies are difficult to apply correctly
4. The cause of the problem is within the system
5. Collapsing goals results in a downward spiral
6. Conflicts arise between short-term and long-term goals
7. Burdens are shifted to the intervener

In schools where system dynamics is taught, students are exposed to the idea that behavior arises from the structure of the system; redesigning structure is therefore necessary to make lasting improvements to behavior. They learn to recognize stocks and flows and that change occurs when flows are accumulated in stocks. This is successfully being taught in K-12 settings. This project will build on current success by providing models and supporting lessons with the focus on insight instead of modeling skills. Modeling skills are not ignored, however. Those who aspire to deeper understanding of the models will be able to investigate entire sequences that show the build-up from simple to more complicated structures (the idea behind instructional scaffolding).

[2] The Creative Learning Exchange was founded "to encourage the development of systems citizens who use systems thinking and system dynamics to meet the interconnected challenges that face them at personal, community, and global levels;" see http://www.clexchange.org/.

Professor Forrester has provided the analogy that one can live in a house and use it effectively without understanding how it has been built and without having the skills to build it oneself. Computer models can be used as tools to understand complex systems without having to learn how to model. Those who learn how to model will be rewarded with *greater* understanding than those who do not, but the premise of this project is that insight can be transferred through the *use* of models.

Consumption of Computer Models for Social Policy

The global society we live in today is dependent on computerized models of physical, biological and social processes. Many people recognize the value of physical models. Design of objects such as cars, airplanes, bridges and road networks starts with a model, often a CAD model, long before actual production begins. Less obvious may be the spread of computer models in the medical field. Models now represent organs of the body with such detail and authenticity that surgeons practice difficult procedures using virtual reality simulation before operating on human patients (“Virtual Surgery”, 2010).

The area where the use of computer models may be most difficult for the general public to recognize is in the social sciences. According to the National Academies website, formal computer models are used to inform public policy at the national level in the United States. A study by the Commission on Behavioral and Social Sciences and Education found that “… the policy community in Washington takes for granted that neither the administration nor Congress will consider legislation to alter any of the nation's expenditure programs or the tax code without looking closely at ''the numbers." Often, these numbers are the product of team efforts to apply formal computerized modeling techniques and large-scale databases to the task of estimating the impact of alternative policies. The kinds of formal models that are used for policy analysis … vary widely. They include large-scale macroeconomic models, single-equation time series models, cell-based models of population groups, econometric models of individual behavior, and large-scale microsimulation models...” (Citro and Hanushek, 1991, p.1).

The study further states that “Despite the widespread use of formal models to provide information to the legislative debate, neither the policy analysis tools employed nor the estimates they produce have been subject to much explicit evaluation of their utility or accuracy” (Citro and Hanushek, 1991, p.2). The study calls for emphasis on validation and also for improved communication of the results to decision makers. In contrast, the vision encapsulated in this project is one in which citizens themselves are both interested in and capable of examination of the models and underlying methodologies that inform the policies shaping their society. Citizens will ask more informed questions of their leaders and demand more thoughtful policy responses to the issues and challenges of their times. They will become model consumers, comfortable with using, questioning, adopting and rejecting models of social systems.

Professor Forrester's early experience in building system dynamics models to address specific, persistent problems in managerial systems (Forrester, 1961) eventually resulted in a description of the "nature of complex systems" in Urban Dynamics (Forrester, 1969). The characteristics first described over 40 years ago have changed little since then and form the basis for the list presented earlier. They can be likened to Newton's Laws of Motion. They provide a framework from which to better our understanding of our world. We are all taught the laws of motion in school but in general, would claim an implicit rather than explicit knowledge of them. We do not, for example, calculate our momentum and stopping distances at various speeds before driving a car to the store. We do, however, possess an *awareness* of how our momentum affects our stopping distance. When more exact information is needed, we can be as precise as needed using Newton's equations. Similarly, if ordinary citizens have an intuitive feel for the phenomenon of "shifting the burden" or "worse before better" will they make better decisions in their personal lives? Could they transfer such knowledge from one area of relevance to another?

This explanation implies that teaching characteristics of complex systems means teaching about social systems. Without delving into the realm of "what makes a system complex?" we are indeed operating within a hierarchy to achieve our goals. The top of the hierarchy is to gain understanding about the nature of complex systems – why do complex systems resist policy changes? Why are short-term and long-term responses to corrective action often at odds with each other? Getting to an abstract level of understanding in dealing with social systems requires grounding in a wide array of concrete, even simple, examples. This will be explained in terms of the structure of the project.

The Pilot Project

Our approach to Professor Forrester's initial call for project proposals was to suggest a pilot project. Starting with a pilot project is analogous to creating a system dynamics model – we want to reduce future financial risk and increase our understanding of the project's challenges by performing key tasks on a smaller, well-defined scale.

One of our first tasks was to request input from teachers experienced in using system dynamics in the classroom to narrow the topics listed above to a single characteristic as a logical place to start. The consensus among this group was to begin with the fourth characteristic: "The cause of the problem is within the system." The deliverables of the pilot project will be a family of models and surrounding curriculum materials that clearly illustrate this characteristic.

The unifying behavior pattern chosen for the family of models is oscillation. The models will cover a number of disciplines so that the generic structure causing oscillation is presented repeatedly and in different contexts. Where appropriate, the models will be knocked out of a state of equilibrium with exogenous input (step, pulse and random input will be used). The exercises surrounding the models will emphasize the point that the forces buffeting the system from the outside are not oscillating and are thus not the cause of the system's behavior. Together, a family of models will illustrate the necessity of closed-loop thinking and endogenous cause and effect more powerfully than a single model.[3]

Oscillation

Open-loop thinking would suggest that oscillation is caused by an oscillating external input. The Beer Game famously illustrates that the problem behavior, oscillating orders of beer in a simplified supply chain, is created by the structure of the system itself. The "external input" in this example (often the target of blame in real-life supply chains), purchases of beer by the customer from the retailer, is simply a step increase. Through playing the Beer Game, many people with no prior knowledge of system dynamics have been introduced to the idea that oscillation is actually caused by delay in a negative feedback loop and their own tendencies to over-order. They are taught that their initial assumption, that customer orders fluctuate wildly and cause the rest of the supply chain to follow suit, is incorrect. Customer orders, except for the single step to a higher level, are constant.

There are many examples of oscillating systems that we experience and read about in the media without necessarily recognizing them as such:

- Predator-prey cycles – a few years ago hunting was good; where did the animals go?
- Personal relationships – why does this argument resurface?
- Mechanical systems – how many people would even recognize that a swinging pendulum is an oscillating system? Or a mass on a spring?
- Burnout – why do I work until exhaustion, recover, and then repeat the process?
- Employment cycles – why are there suddenly many jobs available, and then hardly any five years later?
- Financial cycles – why does the value of my portfolio fluctuate instead of just growing like I want it to (and need it to if I am ever to retire)?
- Real estate cycles – why is my house worth less now than it was when I bought it a few years ago?

[3] Much literature is available about the science of learning. We will undoubtedly add to the existing body of knowledge concerning how K-12 students learn through interacting with models and how to facilitate the transfer of knowledge from one situation to another.

Throughout our lives, through the media and even educational institutions, we hear many explanations for oscillation that are incorrect.[4] Blame is placed outside the perceived realm of influence and the focus is then on reacting to the external force(s) to mitigate the problem behavior. The gift a systems education provides is the ability to look within the system to make relevant and lasting changes. Perhaps more importantly, it also illustrates the futility of implementing solutions that address symptoms rather than structural changes.

Relevance to K-12 Audience

The pilot project materials are being created with input from K-12 teachers and will reflect the desire to influence K-12 education.[5] The chosen subject areas are fitting for this audience:

1. Movement of a spring
2. Predator-prey interactions
3. Relationship/playground dynamics
4. Burnout
5. Weight cycling
6. Commodity production

In the pilot project proposal, we suggested limiting the family of models to five topic areas; numbers 2 through 6 above were distilled from several iterations with a group of interested teachers as topic areas that compliment national curriculum standards. The cleanest possible family of models would have been one model for each topic area, each neatly and interchangeably fitting the 2-stock generic structure commonly known for generating oscillation. It became readily apparent that we would deviate from this ideal. Upon reflection about how teachers often introduce a new topic, we added a model of a spring to allow for physical experimentation and to bridge the conceptual divide between physical systems and their abstract representation in computer models. This will be particularly helpful for young children. We are also exploring the possibility of adding a seventh topic area, that of forest fire suppression and the resulting higher incidence of larger, more intense fires that seem to result from this policy. As often as possible, the audience will be invited to apply knowledge gained to new situations. For example, flood suppression is a logical and relevant counterpart to the forest fire example, and supplementary materials will be included to help transfer understanding to new situations.

Knowing that our materials will be used first in a classroom setting, we have broken full models into sequences of models that start as simple models and build to the 2nd order negative loop

[4] Despite the success of the Beer Game, the field of supply chain management defines the "bullwhip effect" as being "unplanned demand oscillations" caused by customers, promotions, suppliers, etc. See http://www.datalliance.com/donovan.pdf for one example.

[5] In the fullness of time, the wider audience of this project is everyone over the age of 5.

that is the main feedback loop common throughout the family. To make sure our models also build to a relevant real-life example, we have also included at least one 3-stock model, adding “food” to the traditional predator-prey model. This created the opportunity for two separate 2-stock sequences that build into a more complex, yet understandable, 3-stock oscillating structure.

This brings us back to the idea of hierarchical learning and how the project is structured. On the most basic level, the subject matter presented in each topic area is the straightforward, most concrete learning opportunity. Teachers may select the level of complexity from the sequence with which they are comfortable and proceed with deeper learning by advancing to the next lesson. If we have chosen topics of relevance to our audience, we will draw from a wide audience of teachers looking for innovative ways to teach interesting subject matter that fits with national curriculum standards. This point cannot be overemphasized. Our curriculum must fit the current US educational system or it will not be accepted here on a wide scale.

The next step up the hierarchy (a pyramid is a good visual) is transference of learning from one subject area to another. If the first group of learners constitute the base of the pyramid, the next step up, those who study more than one module (both predator-prey and burnout, for example), will start on the path to recognizing the generic structure, across disciplines, that can generate oscillation. The more lessons and modules studied, the greater the chances of internalizing the structure. This audience is probably a smaller audience than the base, hence the pyramid shape, but the steepness of the angle is unknown.

“Internalizing the structure” is not the same as internalizing the principle. There are many ways to illustrate that structure causes behavior, that problem sources should be sought within the bounds of the system, that lasting change to a system’s behavior is achieved through reorganization of structure, not by placing blame on forces “out there.”[6] More families of models will be needed. More links to real-life situations will reinforce this and other principles. Those closer to the top of the pyramid, who devote the time and effort needed to work through a number of lesson plans across a range of model families and systems principles, will get to the deeper insights and will have the best chance at becoming a systems citizen. The quality of the materials made available for this endeavor will help to determine how large that population becomes.

[6] Another important insight is that of perspective. It is not necessarily detrimental to have oscillating populations of either predators or prey. For some tightly linked species, it can be their natural relationship to do so. It is only a “problem” in human terms. Further, consider processes within our bodies - an EKG of a healthy heart versus flatline behavior, or the interactions regulating glucose and insulin. Behavior persists despite wide variations in exogenous, buffeting forces because these systems “want” to oscillate (we need them to as well).

Further, if the project materials are to be adopted by school systems on a wide scale to create systems citizens, then it will be beneficial to align with established education movements such as the Partnership for 21st Century Skills (http://www.p21.org/).

The partnership advocates a framework for 21st Century Learning:

- Life and career skills
- Learning and innovation skills
- Information, media and technology skills
- Core subjects and 21st century themes

Ultimately, how to use a library of models to create future systems citizens is a topic that needs thoughtful discussion and input from professionals in many disciplines (educators, system dynamics practitioners, and specialists in learning science, media-designed curricula and website development are a few that come to mind). Professor Forrester's ideas about the need for and benefits of a systems education are presented in *Learning through System Dynamics as Preparation for the 21st Century* (2009).

Project Progress

The pilot project is intended to mitigate risk inherent in undertaking pioneering research with direct practical application. Therefore, the models and learning materials produced in this stage must be full-fledged, classroom-tested materials that can illustrate standards of quality for future content. We have had the good fortune to bring together world-class modeling expertise (Professors George Richardson of SUNY Albany and Michael J. Radzicki of WPI) plus expert domain knowledge in K-12 education (Lees Stuntz of the Creative Learning Exchange and Anne LaVigne of the Waters Foundation Systems Thinking Project) to form an advisory committee to oversee the activities of the pilot project. Our trial-and-error, iterative process of development will hopefully result in a smooth, clearly-marked road for others to travel. Particularly for system dynamics practitioners interested in contributing to the project, the world of K-12 education may be a new world in which to navigate.

For example, consider the one-stock logistic growth model shown below.

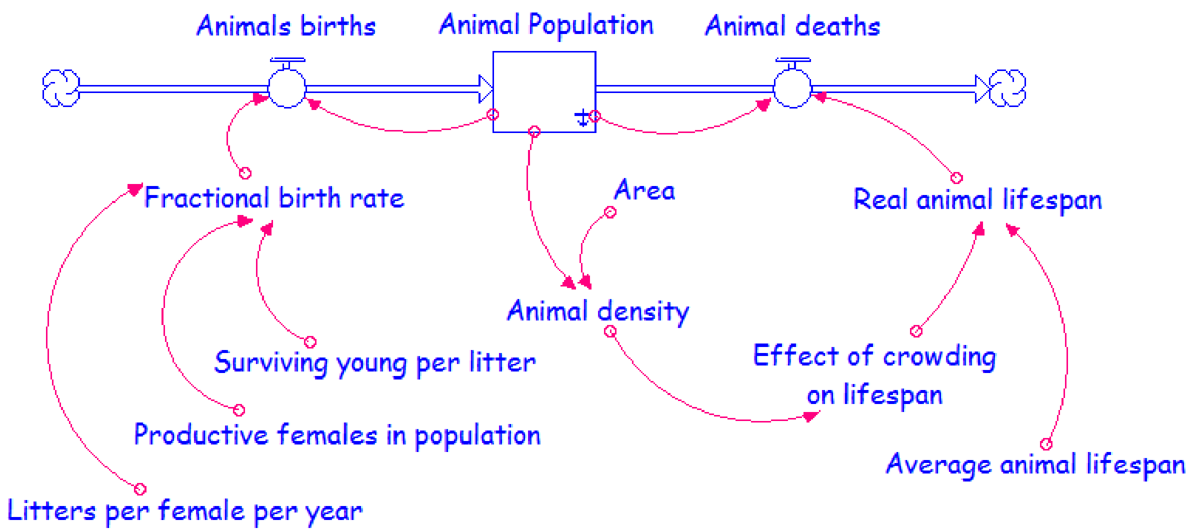


Figure 1: Understanding oscillation can start with understanding logistic population growth

This model was presented by Mass and Senge (1975) in the aptly-titled paper *Understanding Oscillations in Simple Systems*. Their idea for gaining an intuitive understanding of why oscillation occurs was to show a clear example of why it *cannot* occur in a one-stock model. The logistic growth model is already taught in mathematics and biology lessons, so adding this model as a precursor to our predator-prey module makes sense on many levels:

- The visual model structure can help students understand the mathematical theory
- The mathematically-inclined can experience the theory in a real-world context
- Model experimentation reinforces system dynamics concepts needed for further study (flows accumulating in stocks, stocks decoupling flows, dynamic equilibrium, standard behavior patterns, and so on)

Making the conceptual leap from logistic growth to the coupling of two species in a predator-prey relationship is then aided by pointing out the “missing structure” in the one-stock model and adding it, in the simplest possible way, to the next lesson:

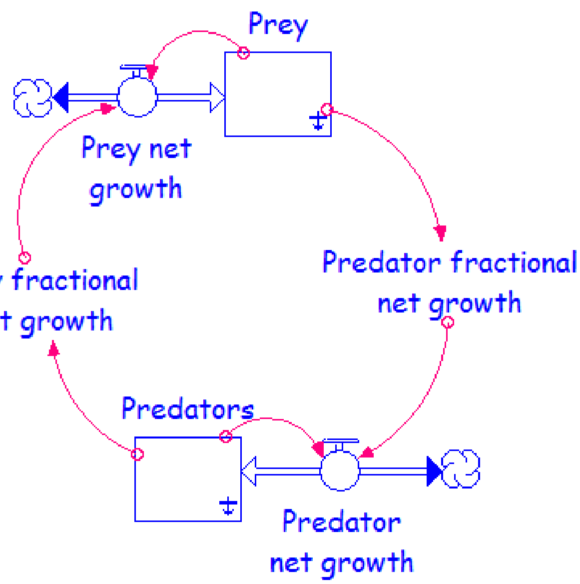
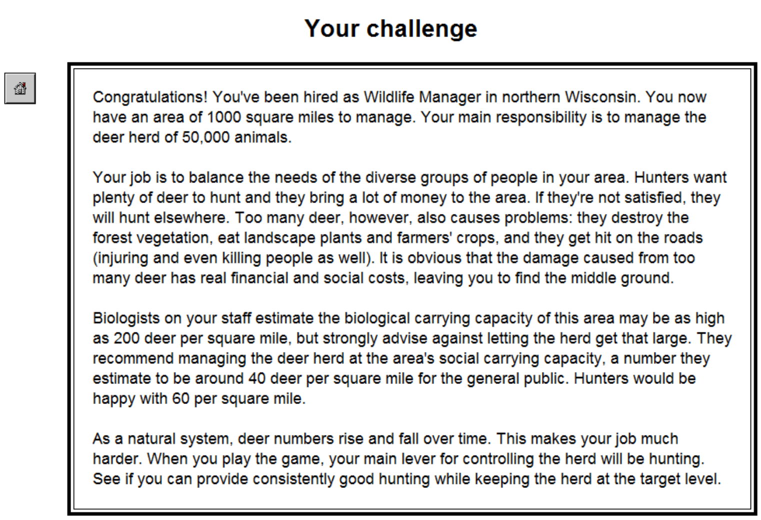


Figure 2: The coupling of two species in a predator-prey relationship is a logical next step to logistic population growth

Model sequences proceed in this manner for all modules (predator-prey, burnout, etc). Along the way, insights for various age groups are brought forward via separate interfaces utilizing the same underlying model. Age-appropriate supplementary materials such as websites for further reading, suggestions for classroom activities and handouts to accompany the lesson plans are also part of each module. The same child can conceivably encounter the logistic model shown above as a second-grader, work with intermediate-level models as he gets older and then end up spending time in high school with a role-playing model that puts him in the driver's seat as Wildlife Manager in charge of a Wisconsin deer herd.



Your challenge

Congratulations! You've been hired as Wildlife Manager in northern Wisconsin. You now have an area of 1000 square miles to manage. Your main responsibility is to manage the deer herd of 50,000 animals.

Your job is to balance the needs of the diverse groups of people in your area. Hunters want plenty of deer to hunt and they bring a lot of money to the area. If they're not satisfied, they will hunt elsewhere. Too many deer, however, also causes problems: they destroy the forest vegetation, eat landscape plants and farmers' crops, and they get hit on the roads (injuring and even killing people as well). It is obvious that the damage caused from too many deer has real financial and social costs, leaving you to find the middle ground.

Biologists on your staff estimate the biological carrying capacity of this area may be as high as 200 deer per square mile, but strongly advise against letting the herd get that large. They recommend managing the deer herd at the area's social carrying capacity, a number they estimate to be around 40 deer per square mile for the general public. Hunters would be happy with 60 per square mile.

As a natural system, deer numbers rise and fall over time. This makes your job much harder. When you play the game, your main lever for controlling the herd will be hunting. See if you can provide consistently good hunting while keeping the herd at the target level.

Figure 3: Informational screen from the role-playing model in the Predator-Prey module

Each model or set of models submitted to the project (including those produced during the pilot project) must clearly address one of the characteristics of complex systems, as listed in this document. This serves as the goal or objective of the model or models. Behavior of interest must be described, including why it is of interest. In addition, the model(s) and materials should address the following questions:

- What is the intended intuition/understanding that the audience should learn?
- What are the anticipated changes (in attitudes, beliefs, understanding and/or actions) in the audience that are expected as a result of interacting with the models and materials?

A minimum set of standards for models and materials is listed below:

Model Standards

- Robust behavior, dimensionally correct variables, fully documented equations
- Documented policy experiments
- Discussion of policy space to improve system behavior
- Documented transferability of structure

Standards for Teaching Materials

- Web accessibility of all the materials and simulations in a manner that is attractive and enticing to both students and teachers
- Material development which maximizes independent accessibility for students and adults from alternative environments such as home-schooling, after-school clubs as well as independent study in public and private schools
- Teaching points for teachers in a format that is familiar
- Instructions for accessing and using the models in the classroom
- Ideas for future model extensions/applying the information in new areas

At the International System Dynamics Conference, representative lessons will be tested in a workshop format. While a majority of the sequence models for the pilot project will be complete by this time, feedback from the workshop will inform development of supporting documentation and curriculum materials. For further information about this project, please contact the Creative Learning Exchange (www.clexchange.org).

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