ON THE APPLICATION OF SYSTEM DYNAMICS TO THE INTEGRATION OF NATIONAL RESEARCH AND K–12 EDUCATION

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Abstract—*The Idaho National Engineering and Environmental Laboratory (INEEL) is dedicated to finding solutions to problems related to the environment, energy, economic competitiveness, and national security. In an effort to attract and retain the expertise needed to accomplish these challenges, the INEEL is developing a program of broad educational opportunities that makes continuing education readily available to all laboratory employees, beginning in the K–12 environment and progressing through post-graduate education and beyond. One of the most innovative educational approaches being implemented at the laboratory is the application of STELLA© dynamic learning environments, which facilitate captivating K–12 introductions to the complex energy and environmental challenges faced by global societies. These simulations are integrated into lesson plans developed by teachers in collaboration with INEEL scientists and engineers. This approach results in an enjoyable and involved learning experience, and an especially positive introduction to the application of science to emerging problems of great social and environmental consequence.*

INTRODUCTION

The Idaho National Engineering and Environmental Laboratory (INEEL), headquartered in Idaho Falls, Idaho, along with its approximately 8,000 scientists, engineers, and support personnel, is a U.S. multiprogram laboratory that supports Department of Energy (DOE) missions by delivering science and engineering solutions to meet the world's environmental, energy, and security challenges. The mission of the INEEL is to:

- Deliver science-based, engineered solutions to the challenges of DOE's mission areas, other federal agencies, and industrial clients
- Complete environmental cleanup responsibly by cost effectively using innovative science and engineering capabilities
- Provide leadership and support to optimize the value of EM investments and strategic partnerships throughout the DOE complex
- Enhance scientific and technical talent, facilities, and equipment to best serve national and regional interests.

To achieve its mission, the INEEL must implement programs and activities that will attract top-notch scientists and engineers from a wide variety of scientific disciplines throughout the world. To help develop and implement these types of ambitious programs, the INEEL established the Education and Research Initiatives (ERI) division.

The ERI division is an innovative organization created to support INEEL short- and long-term missions and critical outcomes by ensuring a seamless integration of research and education beginning with K–12 and continuing through the professional careers of INEEL employees. The ERI staff accomplishes this by providing INEEL employees with resources and information, promoting research and development opportunities, supporting employee continued education and development, and supporting and encouraging the INEEL's links to education and the academic community.

The ERI Pre-College Education Department, which facilitates the integration of INEEL activities with the external K–12 academic community, supports DOE's mission to encourage student development in science, mathematics, engineering, and technology, and represents a critical part of the Laboratory's long-term strategy to achieve its mission. The Pre-College Education Department (a) brings the acclaimed science curriculum of the JASON Foundation to Idaho through the U.S. Office of Naval Research; (b) is a collaborator in the Math & Science Equipment Gift Program, which is driven by executive order; (c) manages Teaming Teachers with INEEL and Student Action Team programs, which bring teachers and students into the laboratory for summer internships; (d) sponsors a statewide scholastic tournament and an annual science and engineering expo; and (e) serves as the infrastructure for many innovative program activities designed to integrate the research life of the INEEL with the academic life of area schools—this integration is based on system dynamics and its application through the use of STELLA© software.

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APPLICATION OF SYSTEM DYNAMICS TO K–12 CURRICULA

A major challenge facing the INEEL is to integrate its research agenda into the K–12 curricula in a way that leads to a more thorough and realistic student and community understanding of its mission, and an enduring student interest in science and engineering that will translate into long-term careers in these disciplines. The INEEL must quickly condition these new employees to approach the world as it truly exists: complex, interdisciplinary and tightly interconnected. Interestingly, the difficulties faced by the INEEL in preparing its current workforce to meet the challenges of the future mirror those faced by K–12 educators in preparing their students for the future. Education is normally compartmentalized into separate subjects and again into separate periods of instruction, none of which are integrated. Students learn to solve one problem in one subject at a time, as opposed to the real world where problems are complex and tightly interconnected. Similarly, the INEEL has graduated students and new employees who are most comfortable working in compartmentalized subject areas, such as engineering, physics, or chemistry; many are not used to approaching problems as they truly exists in the real world. Consequently, the process experienced by K–12 students or teachers when becoming INEEL employees is fraught with confusion and difficulty. When students arrive at the laboratory for a summer tenure, they are immediately expected to synthesize a perspective and framework of understanding in a new, highly complex and interdisciplinary environment, without the necessary experience. In response to this difficulty, the INEEL's Pre-College Education Department is beginning to implement programs that prepare students for a potential short- or long-term tenure at the laboratory. More importantly, these programs help generate an interest in preparing for scientific and engineering studies and careers that increasingly break from traditional compartmentalized boundaries. As global problems, such as environmental sustainability, energy shortages, resource depletion, etc., become more pressing, systematic, and interdisciplinary, complex thinking will become an increasing requirement. Thus, through the K–12 education programs, the INEEL is attempting to help students not only make direct contributions to the strategic mission of the INEEL, but also to contribute directly to the future of the planet.

System dynamics is the heart of INEEL programs designed to provide an innovative K–12 introduction to science and engineering. It originated from the work of Jay W. Forrester at the MIT Sloan School of Management.[1] Coyle defined system dynamics as "…a method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world."[2] In a second definition, Coyle focused more on control theory and management science, which are the historical birth parents of system dynamics. According to Coyle, "System dynamics is that branch of control theory which deals with socioeconomic systems, and that branch of management science which deals with problems of controllability."[2] Importantly, Coyle's definition highlighted those aspects of system dynamics that make it such an appropriate tool for application to emerging, critical global challenges, such as global climate change. Global climate change is representative of a set of environmental challenges that are dynamic in nature, with the possibility of observable effects following internal or external system perturbations only after many generations of human activity and natural response to those activities. Both potential solutions to and impacts of global climate change are likely to impact fragile socioeconomic systems. Thus, the need to consider scientifically engineered solutions within the context of potential impacts upon these socioeconomic systems becomes imperative. Further, the understanding that people who are an integral part of complex systems and thus, inherently, have as least some small measure of ability to exact change on those systems, represents a profound and empowering idea to K–12 students. Developing the understanding that individuals, working either together or apart, both impact and potentially manage the future of complex environmental systems, seems to infuse K–12 students with the desire to learn more, and subsequently determine to what extent they as individuals can, in fact, change the world.

When K–12 students are first exposed to system dynamics, they are naturally prompted to ask, "What is a system?" A system is usually defined as a combination of two or more elements that, aside from being relevant to the student, are interconnected for some purpose. A bicycle, a car, and a bus are all systems for transportation. On a larger scale, the collection of roads and vehicles represents another transportation system. On a still larger scale, this system could include the socioeconomic and environmental impacts of various transportation systems and their management. As Andy Ford pointed out, "The distinguishing feature of a system is the impression that the whole is more than the sum of its parts".[3] Oftentimes, however, students from radically different socioeconomic or cultural backgrounds may in fact have different concepts of what defines a particular system. For example, the heart of one student's transportation system might be a new car, while buses or feet might represent the only possible transportation options for many others. Thus, the study of systems, in general, provides students with the idea that all definitions of the physical world and its associated natural or man-made systems must be derived within the context of a consensual group understanding and agreement. Equally important, the group must understand and agree on what represents the system's ideal long- and short-term dynamic behavior.

Because the application of system dynamics tools, such as STELLA ©, requires groups to agree on system's definition, boundary, and behavior, system dynamics forges the kinds of interactions that eventually lead to consensual understanding among diverse groups of students. In this way, system dynamics acts as a sort of "Rosetta Stone," which allows groups of students to translate diversity into a symbiotic shared understanding that results in the application of powerful group energies and resources toward the solution of a complex problem of system behavior.

System dynamics is almost uniquely capable of addressing two fundamental questions. What system structure gives rise to a given behavior? How can that system be modified to produce a different behavior? To facilitate the understanding of dynamic systems, system dynamics relies heavily on computer-based modeling, simulation, and analysis. Modeling tools typically support the development of multiattribute, multiscenario simulations that provide us with insight about the dynamic, developing behavior of complex systems when exposed to a myriad of internal or external, known or predicted perturbations. In this way, system dynamics represents an analytic path that, when carefully followed, allows us to forecast, at least in a comparative sense, the future.

To more clearly understand how system dynamics is applied, it is necessary to understand the concepts of stocks and flows. System dynamics builds systems using the analogies found in grammar. Stocks act as nouns in the sentences that describe the system; flows act as verbs. This grammatical language turns out to be well suited for adaptation to teaching K–12 students system dynamics. In fact, a legendary student distaste for the formal study of grammar is often to some degree moderated after a brief introduction to system dynamics. Language suddenly becomes a kind of system that can be used, modified, changed, played with, and in many myriad ways, charged with creativity, if one applies this creativity within the framework of consensually accepted rules, and if one is totally aware of the potential impacts of this creativity upon all groups and individuals to which one is attempting to communicate. In parallel, teaching visual programming of complex and new scientific and engineering concepts is dramatically aided by this analogy to grammar.

Figure 1 illustrates the concepts of stocks and flow. These two diagrams, prepared using STELLA©, portray simple input and output systems of a piggy bank and carbon dioxide flow through the atmosphere. The first diagram, designed for younger students, illustrates that the amount of money in a child's piggy bank at any given time is dependent upon the allowance received during that time and the allowance spent during the same period of time. A parallel story is told in the second diagram. It illustrates that the amount of CO_2 in the atmosphere is dependent, at least in part, upon the quantity "put in" and the quantity "taken out" during a given period of time. All parameters that are known to effect atmospheric CO_2 could easily be included as flows and converters to provide a more detailed and realistic simulation of the dynamic history of this parameter over time; for example, since the beginning of the Industrial Revolution. In short, our system can be designed to address any and all factors that we know or can speculate to have significant impact on atmospheric CO_2. In the second illustration in Figure 1, we have shown a simple system that focuses on the relationship between atmospheric CO_2 and the rate it is released or absorbed into the atmosphere, both of which are complex functions of many parameters. If, for example, we are given a requirement by a customer (e.g., student, teacher, or society as a whole) to decrease the release of CO_2 into the atmosphere and increase the rate of gas absorption, then we can manipulate both parameters in any way we choose to determine at what point in the future the required outcome will be achieved. The scenario of choice, which in this case would possibly be defined by decisions about energy and society, could cover a range of predictions based on historical trends, future predictions, or simply a curiosity to see how a randomly chosen scenario might influence outcomes. System dynamics gives us the freedom to forecast the future based on any social/cultural, scientific, or personal whims or data we, as individuals or groups of stakeholders, may wish to include in our mental models. Importantly, giving students an opportunity to pose, test and potentially alter their notion of how complex

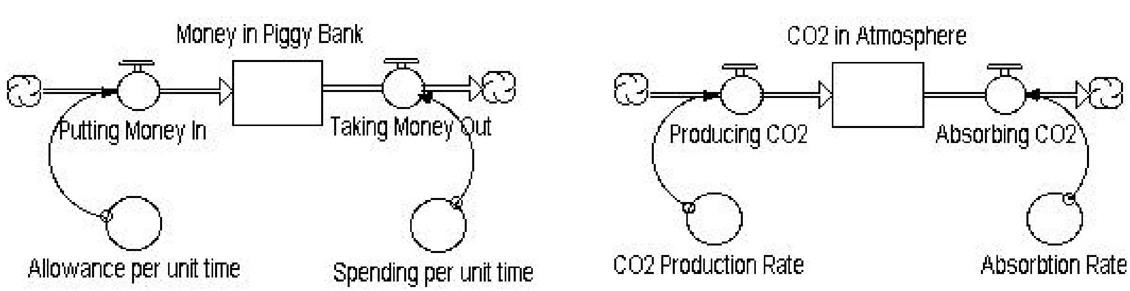

FIGURE 1.
SYSTEM DYNAMICS STOCK AND FLOW DIAGRAMS.

systems behave is one of the more important functions of system dynamics.

Unfortunately, system dynamics models are often misrepresented as predictive models, when in fact they are primarily designed to foster general understanding. General understanding of the dynamic behavior of complex systems is important, especially to students. Without this understanding, it is difficult to truly understand how specific elements of one's education—math, science, economics, history, even grammar—are applied as integrated wholes to the decision making process. What follows is an example of how this general understanding of the dynamic behavior of complex systems, within the context of an interdisciplinary environmental challenge of interest to the INEEL, is imparted to K–12 students.

EXAMPLE OF ATMOSPHERIC CO_2 SIMULATION FOR APPLICATION IN THE K–12 CLASSROOM

The following news item appeared in the April 17, 2001, issue of *USA Today*:

> "Researchers with the National Oceanic and Atmospheric Administration have found evidence that indicates that the rate of global warming is accelerating and that in the past 25 years it achieved the rate previously predicted for the 21st century (2 degrees Celsius per century). Writing in the March 1, 2001 issue of Geophysical Research Letters, Thomas R. Karl, director of the National Climatic Data Center in Asheville, N.C., and his colleagues analyzed recent temperature data. They focus particularly on the years 1997 and 1998, during which a string of 16 consecutive months saw record high global mean average temperatures. This, Karl notes, was unprecedented since instruments began systematically recording temperature in the 19th century. During much of 1998, records set just the previous year were broken. In its Second Assessment Report in 1995, the Intergovemmental Panel on Climate Change (IPCC) projected the rate of warming for the 21st century to be between 1.0 and 3.5 degrees Celsius. Karl and his colleagues have already observed over the past 25 years a rate that is between 2 and 3 degrees Celsius per century. The IPCC study used a "business as usual" scenario with regard to emissions of carbon dioxide and other atmospheric constituents. Karl and his colleagues aren't ready to say for certain that the rate of global warming has suddenly increased, because they know unusual events sometimes happen. Given the steady increase in atmospheric greenhouse gases and their decades-to-centuries atmospheric residence time, he urges that studies be conducted to better understand how society can minimize the risks of climate change and prepare for more, and perhaps even more rapid changes to come."[4]

For students in grades 10–12, the above article represents a good starting point for the interdisciplinary study of global climate change. The article accomplishes two important objectives that set the stage for additional student study and discussion: data are presented to strongly argue the case that global warming is a real and measurable phenomenon, and the important connection is made between global warming and atmospheric greenhouse gases.

Typically, students are asked to read this article, and then, in an unstructured and unmoderated forum, discuss their thoughts, questions, ideas, and concerns. Typically, the following questions, or close variants, can be expected during the discussion:

1. Why is a global warming rate of 2–3 degree Celsius per year a "big deal?"
2. How, exactly, do atmospheric greenhouse gases contribute to global warming?
3. What human activities or technologies represent the largest contributors to the increase of atmospheric greenhouse gases?
4. Is there a way in which greenhouse gases can be "captured" or sequestered?
5. How can humankind address issues of environmental and socioeconomic sustainability in light of these issues?

Interestingly, these questions very nearly parallel the exact set of questions professional scientists, including those working at the INEEL, must both ask and attempt to answer. Thus, in less than an hour, without introducing one equation or analyzing one chemical reaction, student energies and interests are captured and transported into the collective mind of scientists who must ask and answer these very same questions. Suddenly, nearly every student in the classroom, no matter what his or her background or academic interests, wants to contribute in some way to the challenge at hand. More importantly, in part because of the enthusiastic and occasionally heated discussions that emerge during a discussion of global warming, nearly every student understands, perhaps for the first time, how science and engineering are not sterile and boring, but instead, connected in a very real and direct way with the social and political issues that will ultimately direct the human path into the 21st century.

In a traditional classroom, introducing an article from the popular press might be useful to stimulate student interest in an issue that relates to science, but rarely would the discussion detract from or indeed form the heart of the class lesson plan itself. However, in the application of system dynamics, the discussion represents the heart of the lesson, which is fundamentally the integration of subjects that are generally compartmentalized. The above example illustrates why it is important that system dynamics be applied to directly demonstrate how various subjects (e.g., chemistry, engineering, economics, political science) are embraced by the five questions, and why it is important to both the problem and its potential solutions.

After the introduction, which includes selected readings and an unstructured discussion, the teaching team consisting of the regular class instructor and an INEEL researcher, begins a more rigorously structured discussion of the problem (greenhouse gas emissions in this example). This discussion is carried out in parallel with an interactive introduction to STELLA©, at which point, only the most basic concepts of stocks, flows and converters are addressed. The diagrams illustrated in Figure 1 form the basis for the discussion (although Piggy Bank might be replaced with Bank Account and Allowance with Income.). Then, through a series questions and discussions led by the instructors, a computer simulation of a system, which represents all the elements of the system that are most critical to its behavior, is gradually constructed. Figure 2, below, represents an example of the kind of system that generally results.

It is important to note that when examining this actual STELLA© stock and flow diagram the system is actually quite complete. This system, which was actually developed in two 1-hour classroom periods, could in fact be used to develop a comprehensive understanding of the critical parameters—together with the feedbacks that link them—that must be thoroughly understood and researched if scientists and engineers can begin to understand how best to manage global greenhouse gas emissions.

Once the STELLA© simulation has been completed, and the student's understanding of the system involved in the increase of global greenhouse gasses and the general mechanisms through which gasses are both produced and sequestered has been demonstrated, then the class is free to examine scenarios that result in additional understanding of the options open to society to control emissions—produce less or sequester more. Students, working as teams, are challenged to reduce the stock of atmospheric greenhouse gasses by a set amount over a predetermined period of time. Once the students determine, through direct STELLA© simulation of their scenarios of choice, how to achieve the goals, the teams compare solutions and thoroughly discuss the technical as well as social and economic practicality of each scenario. Typically, the introduction, mode

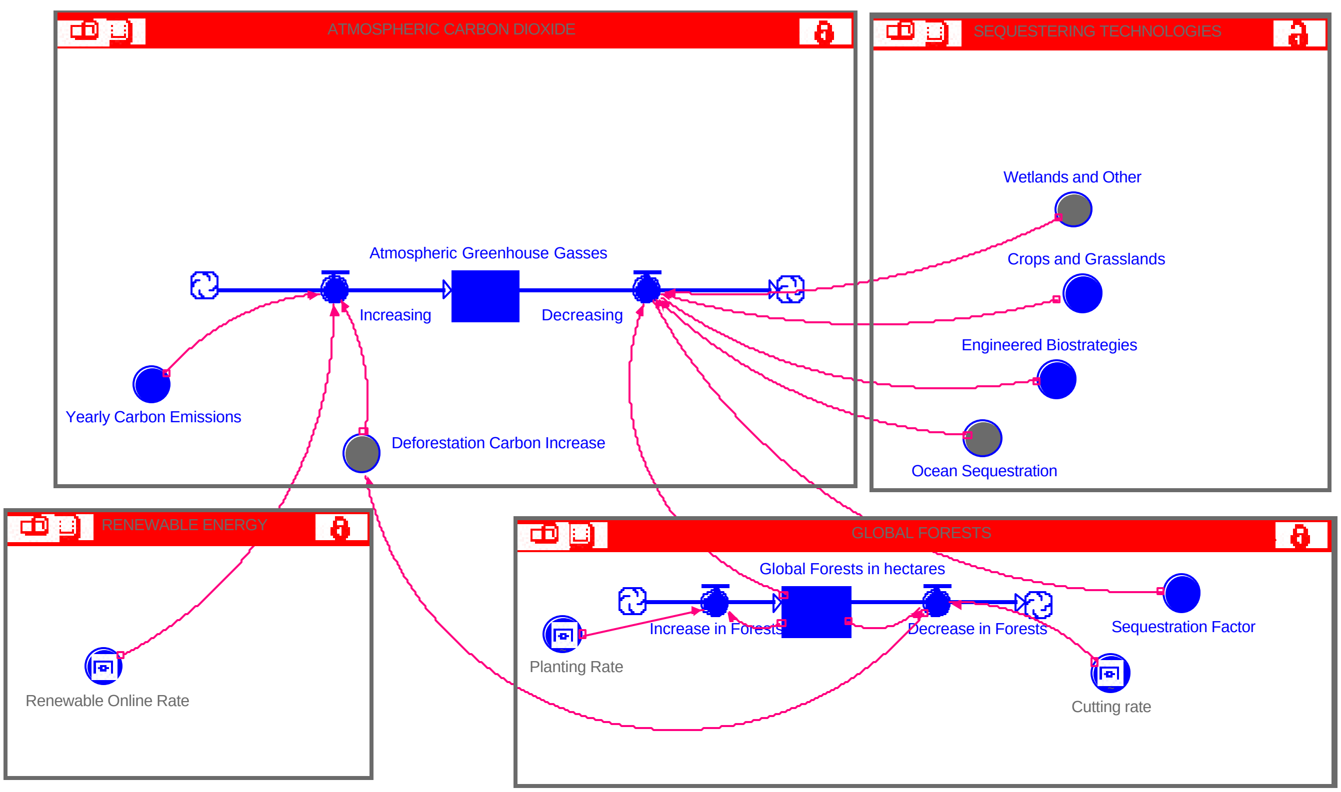

FIGURE 2.
STOCK AND FLOW SIMULATION OF GREENHOUSE GAS EMISSIONS AND SEQUESTRATION.

development, scenario testing, and discussion can be accomplished in one week, provided the instructors supply all data necessary to run the model; although one of the authors of this paper has accomplished this in three intensive, energy-filled and enjoyable days.

CONCLUSION

This paper presents an example of a learning approach, which the INEEL, working in collaboration with local schools, has introduced to K–12 students to (a) allow their educational experience to move beyond the boundaries of traditional and compartmentalized subject areas, (b) inspire them to think more systematically about the world at large, (c) impress upon them the interdisciplinary nature of the great environmental challenges that face humankind, and (d) introduce them to the real function and contributions made to society by U.S. national laboratories such as the INEEL. As Paul Davidsen has said: "…Academic boundaries no longer constitute the boundaries of our imagination or our investigation. Historic and economic considerations are merged with physics and chemistry in our study of ecological issues."[5] This, of course, is how it must be if we are to meet and overcome the environmental, energy, and economic, and national security challenges facing us.

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