

Teaching System Dynamics to Teachers and Students in 8-12 Environment

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System Dynamics at the pre-college level, its time has come. Enough teachers have sufficient comfort with technology. Tools such as STELLA II and PowerSim have provided the broad-based language for communication and understanding.

A recently awarded 3 year National Science Foundation grant, CC-STADUS (Cross-Curricular System Thinking and Dynamics Using STELLA), is training 165 high school math, science, and social studies teachers in system modeling using STELLA II. Teachers develop some models within their curricular areas. Then cross-curricular teacher teams are formed to design at least one large model and develop curricular materials around the model so it can be used immediately in their classes. The training is done by high school teachers and by speakers from industry who use modeling in their work. The teacher participants are responsible for sharing their knowledge and expertise with other faculty and with students in their classes.

High school students are using systems concepts at various levels. At the lower levels (especially with "at-risk" students) the teacher demonstrates how a model is designed and students manipulate the model and predict new behavior. At the middle level, students develop a model as a class activity under the direct guidance of the teacher. At the highest level, students select a topic of interest, formulate boundaries, work with an information resource person, and work with a modeling resource person to develop a model and present it to a class.

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This paper will present two topics: First, the details of training math, science, and social studies teachers in systemic modeling during a three week summer training, and second, teaching high school students to do systemic modeling.

Part I (Training the teachers)

On May 7, 1993, the National Science Foundation awarded funding to the project CC-STADUS (Cross-Curricular System Thinking and Dynamics Using STELLA). Over three years this project will train 165 high school math, science, and social studies teachers in system modeling using the STELLA II software developed by High Performance Systems. The principal investigators are: Diana M. Fisher, Project Director, (Math/Computer teacher at Franklin High School, Portland, Oregon, USA), Ron Zaraza, (Physics teacher at Wilson High School, Portland, Oregon), Dr. Andrew Jonca (Professor of Mathematics with specialty in Numerical Analysis,

Pacific University, Forest Grove, Oregon), and Steve Carlson (Assistant Superintendent, Blaine County Schools, Hailey, Idaho).

The first summer training was held at Franklin High School in Portland, Oregon, from July 7 to July 24, 1993. During this time 36 teachers (13 in math, 13 in science, and 10 in social studies) from the Portland metropolitan area participated in an intensive (8am-4pm) three-week workshop. Twenty different schools were represented. There were eight core team presenters, of whom seven were high school teachers (2 in math - Diana Fisher, Eileen Rogers; 2 in science - Ron Zaraza, Karen Kelly; 3 in social studies - Joan Kent, Jim Dyal, Patrick Murphy) and one a math professor (Dr. Andrew Jonca) from Pacific University. There were also various industry presenters - Dr. Edward Gallaher, research pharmacologist, VA Hospital and professor at Oregon Health Sciences University, Portland, Oregon (presented model of drug assimilation in the human body), Michael Newsom, economist and mathematician, Bonneville Power Association, Portland, Oregon (presented model of hydro-electric dam), Dr. Gerry Stokes, Global Program Office Director and Scientific Director for Atmospheric Radiation Measurement Program for the US Department of Energy (presented "Global Change and Modeling"), Nancy Miller, senior research scientist, Battelle Labs, Richland, Washington, (presented climate modeling), Dr. George McRae, Professor of Mathematics, University of Montana, Missoula, Montana, (presented discrete modeling and recurrence relations), and a three day presentation by Steve Peterson, STELLA II co-designer, High Performance Systems, (presented the fundamental concepts in system dynamics and the beginning ideas behind formulating larger models).

The goals of the workshop were to establish a rudimentary understanding of system dynamics, familiarity with the STELLA II software as the communication tool, and experience in cross-curricular team dynamics while designing models that could be used at the high school level with students. Attempts were made, in the training, to provide teachers with experiences and materials they could provide for their students. The design of the entire project and all the training experiences were determined by teachers who are teaching in the high school classroom. Participants must be teachers in the high school classroom.

It is suggested that cross-curricular opportunities be provided for students¹, yet most teachers have never had an opportunity to learn in such an environment. They are supposed to divine how to make this significant step. It is no simple feat. The project attempts to provide this environment for the teachers. A problem that presents itself is determining a way to promote communication between the disciplines. The STELLA II software is a critical tool at this point. It is a language that is both simple and powerful. Its visual nature allows inclusion of those not given to quantitative analysis. It can be used as a structured method of diagramming in the same way as mind maps are used in social studies. STELLA II's multiple definition capability provides power to those whose expertise lies in quantitative analysis. It provides power to define a system in as mathematically rigorous a fashion as the traditional equation(s) definition. STELLA II's visual nature allows the user to conceptually distinguish between quantities varying in time and their rates of change. It furnishes to the modeling environment three essential components. The first is affording the ability to visualize the functional relationships, showing clearly what components depend upon what other components. This evolves during the design of the diagram. It is referred to as "laying out the plumbing" in the STELLA II manual. The second is supplying the mathematical rigor by defining the dynamics behind each component of the functional relationships. The third is requiring the designer to clearly specify the set of initial parameters that determine the initial state of the system. These are not trivial issues in modeling, especially at the high school level.

For a cross-curricular effort inclusion is the key term. Were it not for the STELLA II (and similar) software there would not have been the possibility of bringing system dynamics and cross-curricular problem solving to the high school level. Inclusion - the chance to bring in those disciplines where the truly significant problems lie, social studies (policy making);

inclusion - the chance to bring in those students who have been excluded from mathematical power due to the equation interface for solving problems. (In the twenty-five years I have been teaching I have never encountered the potential for change that is more significant than a systemic approach to problem solving using a visual tool that includes more players in the process. This is a crossroads, an evolutionary leap in our ability to address significant problems at the high school level. It is a great time to be a teacher.)

The training takes place over three weeks. The first week an activity is presented that provides the groundwork for the cross-curricular nature of the training. The participants work through the Fishbanks2 simulation. This is an exercise in which the participants form groups, each of which is the board of directors of a fish company. Each group's goal is to maximize its assets over a simulated 10 years of fishing. The companies make decisions about the number of ships to buy and where to send those ships in the hope of obtaining an optimal number of fish, which are subsequently sold. During the course of the activity problems arise that must be dealt with. The companies can deal with the problems individually or collectively. How the problems are solved determines the outcome of the simulation. After the activity, the dynamics of the behaviors are analyzed, and real-world situations are presented that were similar in nature to the problems that occurred in the simulation. Discussion then ensues on the potential alternative solutions that could have been chosen. This discussion includes scientific data that could have been collected and policy decisions that could have been made. At the end of the first week a STELLA II Fishbanks3 model, developed at MIT, of this simulation is presented and the teachers (on the computer) work through different policy decisions to see if the outcome could be altered.

Before the teachers can use the STELLA II Fishbanks model they need to learn to use the STELLA II software. The middle of the first week is dedicated to introducing the software in a segregated environment (ie, the math teachers in one room, the science teachers in another, and the social studies teachers in a third.) The reasons for this are: First, when introducing a new approach to solving problems, it was felt that a connection to the teachers area of strength was important. Within their comfort zone they are better able to handle something new. Secondly, in order to obtain commitment to a new approach, it is better to allow teachers to see how it is relevant and useful within their curricular area. They can see how to approach some of the topics they currently teach in an alternate way. Thirdly, in the last week, when there will be cross-curricular teams, the teachers will have to be willing to give up some of their own immediate application for the good of the team effort. With all the materials and models the teachers develop in the first week which are directly related to their curricular area, they are more willing to work on tasks during the third week which may benefit their classes indirectly.

So, the majority of the first week is spent in segregated curricular work. The math core team teachers teaching the math teachers, the science core team teachers teaching the science teachers, and the social studies core team teachers working with the social studies teachers. Topics and materials are those used by the trainers in actual high school classes. The only difficulty during the first week of the training was for those participants who were not Macintosh computer literate. It was not overwhelming, but it did create some additional obstacles for those few teachers.

The second week brought in the industry experts. Each expert presented his/her topic and provided hands-on exercises for the teachers. It was intended that each expert present in 1 to 1.5 hour blocks and provide 1 hour of hands-on activities in between. This did not always occur. Some persons lectured longer than 1.5 hours, frustrating the teachers. For the summer of 1994 the importance of hands-on exercises for the teachers has been reemphasized to the speakers.

During the third week there was still an occasional speaker (early in the week) but the majority of the week was spent in listing topics for models (participants determined the topics), choosing teams to work on a given model, and designing a working model with supporting curricular

materials. A surprising phenomenon occurred. Early in the training a special effort was made to help the social studies teachers feel comfortable with this new system dynamics modeling concept and the use of the STELLA II software. The social studies teachers adapted better than anticipated. At this point the trouble arose with the math teachers. They were hesitant to join cross-curricular teams. This came as a surprise. They were reluctant to work out of their curricular area. The topics were not of a mathematical nature, in the sense that they would not fit into a traditional math class. The math teachers wanted to do more models that would apply directly to their classes. It was necessary to discuss the nature of team efforts and cross-curricular projects. It was restated that in the world most systemic modeling topics arise in the science and/or social science (policy decision) area. It is natural that those topics were the ones listed by the group. In the group effort, the social studies or science teacher was to explain the fundamental components of the model and how they interrelated. She/he would also be responsible for describing the behavior of the system as the modeling process unfolds. It was the responsibility of the math teacher to translate that behavior to the correct underlying mathematical definition to get the model to work correctly. In a sense the science/social studies teachers defined the problem, and the math teachers made it work. This was a new role for the math teachers. Those leaders among the math participants were willing to do this after a discussion and the others followed, albeit, still reluctantly. For the second summer training, it will be necessary to establish this role responsibility early on so there are no false expectations. In the end the math teachers found, for the most part, the exercise as participants of the modeling team interesting and useful. It was interesting to watch the dialogue between members as the models evolved. The math teachers certainly were a critical part of the modeling process. Even though they could use only parts of the final models in their classes, the experience was useful.

Some of the responses by the summer participants: "It was great to work closely with people from other disciplines." "Outstanding course, a great opportunity to work in a cross-curricular group and have something concrete to bring back to my class and my colleagues." The best thing about the course was "the variety of information and the opportunity to work with other teachers not in my area." "...doing the group project." "Working together in an interdisciplinary way." "Getting to work in teams of 2-4 with other teachers..." "Most challenging and exciting thing that I've done in 25 years of teaching. I wish I could stay in training for 3 more weeks." "...this has been the most challenging and rewarding workshop that I have ever attended..." "Great stuff. Another week for working in cross-curricular teams and it would have been perfect."

The models developed by the participants were reviewed by Dr. Andrew Jonca and Ron Zaraza. It is intended that these models be made available to other teachers in the future. As Dr. Jonca reviewed the models he made certain observations that will be incorporated into the guidelines for model development for the two subsequent summer training sessions. Although the models were well documented there was one subtle omission. The most critical change Dr. Jonca suggested was requiring more documentation about why the modelers chose the particular components that were ultimately included in the final model. If other teachers are to be able to use the models being developed it must be clear to others why certain decisions were made. Dr. Jonca also produced the first sixty pages of a potential book for high school math teachers entitled "Math Behind STELLA" used in the summer training sessions. In this book he introduces the necessary basic concepts of derivative, antiderivative, differential equations, Euler's Method vs Runge-Kutta methods of integration, stability, among other very important topics. It is intended that this book be finished over the course of the three year grant and also made available.

Currently negotiations are taking place with a commercial publisher. If the publisher decides that the materials are not commercially viable another avenue for dissemination will be determined. The project PI's feel strongly that the materials produced by this project must be made available to other teachers. It is the only way system dynamics will gain a foothold at the

pre-college level. Training teachers is not enough. There needs to be a reservoir of materials for teachers who want to incorporate a systems approach in their classroom. The Creative Learning Exchange is a start, but it needs the support of all projects involving system dynamics at the pre-college level.

The participants from the summer CC-STADUS training requested monthly meetings during the subsequent school year. They had the responsibility to use system dynamics in at least two of their classes during the year, to present what they learned in the summer workshop to the faculty at their school, and to design at least one additional model to be sent to the project PI's during the year. The 5 core team members who were not PI's each chose 7 participants to support and evaluate. They were to visit the participants class once to observe the use of system dynamics in the classroom. This is working out well. It is necessary to have this level of accountability so the teacher does not go through the whole school year without applying what was learned. In addition, the Northwest Regional Laboratory is the official evaluation group for the project. They are interviewing the participants, trainers, and industry partners and observing classes in order to write a summary report.

The evaluations of the first summer have been very positive. The second summer applicants were accepted from around Oregon outside the Portland metropolitan area. The third summer applicants will be accepted from around the Northwestern United States.

At this point "at-risk" students have not been addressed. The CC-STADUS grant will provide training for teachers of "at-risk" students in the second summer of training. There will be a two day workshop, held before the three week workshop, to address system behavior activities with these students and provide recommendations and materials for that student group. Ron Zaraza will provide the training. He has already used system ideas in his lowest level physical science class, a class with mostly special education students or students identified as at-risk for other reasons. That class participated in the Fishbanks simulation activity. They were then given the STELLA Fishbanks model and asked to manipulate the parameters in order to maintain a stable fish population and keep the fishermen in business. While the students were not able to make the modifications on their own, they were able to identify key factors that would affect the fisheries and cause changes. Running the model with their suggested changes, Ron was able to engage them in lengthy discussions about cause and effect in the fisheries. Students used a number of problem solving strategies to try to develop self-sustaining fisheries.

After this initial activity, STELLA II was used in other areas of the course as well. One activity common to the low level classes and higher ability classes is graph interpretation. Using simple STELLA II models, students were introduced to the basic graph structures (Linear, quadratic, exponential, and inverse). They were then asked to describe the relationships between variables not modeled by looking at graphs. Some of these relationships were later modelled using STELLA II in an all class activity. Students were also asked come up with other relationships that fit the graphs.

STELLA II, used in conjunction with an ultrasonic motion detector, was used to teach the students about kinematics and dynamics. These topics are not normally gone into in much depth in low level physical science classes because the students do not possess the mathematical tools to deal with them. The graphic/conceptual approach made possible by STELLA II allowed these students to attempt and understand sophisticated problems they would not normally have seen. After testing these approaches with the physical science students, they became part of the regular conceptual physics curriculum as well.

Part II (Training the students)

The first part of this section will present those activities used in a high school modeling class. The second will present those activities used in a second year algebra class at the high school level.

In the school year 1992-93 Franklin High School provided its first course in "Mathematical Modeling Using Computers." It was a one semester course. Prerequisites were concurrent enrollment in a second year algebra course or above, or teacher approval. Two of the students who participated in this first class had never taken, nor did they plan to take, second year algebra. They successfully completed the course. The content of the course was: 4-5 weeks on data analysis/ curve-fitting techniques and error analysis, and the rest of the time on system dynamics using STELLA II. During the system dynamics section, students were provided exercises in creating simple generic models as specified in the STELLA II User's Guide manual (an excellent resource). They were also given examples of models of larger scope (Fishbanks model, Easter Island model, and activities culminating in the design of a drug assimilation model). During the last three weeks of the course students were to design, document, and write a short paper on a model of their choice. The students worked in teams. It was an exciting time for all. It was necessary for the students to have a resource person who was responsible for explaining the behavior inherent in the topic under study. Those teachers/resource persons would help the student with the choice of components upon which to focus. They also were to assist in overcoming any misconceptions in the interactions between components in the system. Some of the resource persons knew STELLA II and some did not. The resource person was not always able to provide the data for the models. During this process a significant problem arose that was not anticipated. It was difficult finding the data for some of the models. As schools become connected to the Internet, and as teachers make connections with more persons outside of education willing to work with students as resource persons, this problem will be resolved (somewhat). At this point, however, it is still a significant problem. Neither the school, nor the public libraries are or will be sufficient to serve the student's needs in this endeavor.

In the year 1993-94 the modeling class at Franklin High School was extended to a year. The first 4-5 weeks are still spent on data analysis. The rest of the year is dedicated to system dynamics using STELLA II. Exercises given in the previous year were again presented, with the addition of a demonstration of the Hamlet model designed by Pam Hopkins, an English teacher in Tucson, Arizona. Also Dr. Andrew Jonca presented concepts from Physics, Economics, and Biology using STELLA and traditional mathematics. The majority of the second semester was dedicated to projects. Students were to get into groups of two or three, choose a topic, find a resource person, collect the data needed, design and document their model, write a short paper explaining the model and their assumptions, and make at least one presentation to the rest of the class. Students dissolve and reassemble teams throughout the second semester as projects conclude and new ones begin. The objective is to take the students through the entire process of modeling so they can be independent by the end of the year, able to understand what is reasonable to model, how to make assumptions, how to determine the variables to include, how to create and refine a model, and most important, how to explain the model to others. This process was reasonably successful the first year (reasonably because 3 weeks proved to be too short a time frame to accomplish all goals - but indicated they could be accomplished). The second year has already shown a significant improvement over the first year in student and teacher readiness.

When incorporating the ideas of system dynamics into a second year algebra class the problems are entirely different from a modeling class. In a second year algebra class there is very little space for new topics. The curriculum is packed with topics that are supposed to be covered. So the first task was to determine what to throw out. Actually this turned out to be less difficult than anticipated. Guidance came from the NCTM standards and from a changing perspective about how to teach the course from a system viewpoint. The changes at this point appear to be minimal, in the sense that, most of the time the course appears to be following most of the

traditional topics. However, the emphasis, the view from which the topics are introduced is different, and the word problems are supplemented with STELLA assignments. The focus is on how things grow, and how that growth pattern differentiates one outcome from another. An ultrasonic motion detector is used to introduce some of the growth patterns - how different motions produce different graphs. Then a STELLA diagram is designed to define the given motion. This gives the students a visual description of the growth pattern. From the STELLA diagram the equation is developed. Then the usual exercises in equation manipulation follow. When the word problems arise, they are defined using the equation approach and/or the STELLA diagram approach. Finally experiments are conducted or data provided so students can determine an equation for a growth pattern where the numbers do not work out neatly. In this case data analysis (curve fitting) techniques are used. This strategy works well for the traditional topics in second year algebra - linear growth, quadratic growth, exponential growth, oscillation. It has been evident that the inclusion of STELLA has provided students another way to understand these growth patterns. In fact, when a reference to a previous growth pattern has been made students invariably recall the STELLA diagram before the equation in order to describe it. Students of traditionally lesser ability have commented on the ease of understanding the STELLA diagrams, and have complained that they are not used more often. The inclusion of a more systemic approach and the use of STELLA diagrams in the definition of the traditional growth patterns has enhanced the learning significantly and required only about 15 class periods in the school year.

Data was collected last year on the number of (non-honors) second year algebra students who elected to take another year of mathematics. The students from the traditional (non-honors) second year algebra classes were compared to the students from the (non-honors) second year algebra class using STELLA. From the class using STELLA 78.9% of the students went on to take another math class compared to 60.6% for all the other non-honors second year algebra classes. (Students going on to take another math class were identified as those students who had successfully completed the first semester of pre-calculus or math modeling the subsequent year. Note: Second year algebra is the terminal math class required for college admission.)

It is apparent that many of the growth pattern approaches used in the second year algebra class could easily be incorporated into a first year algebra class. If and when this occurs, the second year algebra classes could start to study some of the more sophisticated growth patterns fundamental in system dynamics. When this occurs more interesting and realistic problems could be addressed. Eventually, it would be useful to introduce the traditional growth patterns from a project perspective, similar to the work done by Frank Draper in 7th/8th grade science in the Catalina Foothills School District, in Tucson, Arizona. Once the second year algebra class has evolved to this point it could be counted as truly approaching algebra from a system dynamics perspective. It is important, however, not to throw out the necessary skill development in the effort to bring in the project approach. Consequently the process is still evolving. As more teachers become facile with the system approach to solving problems more material will be available to meet the needs of teachers in diverse environments.

Ron Zaraza has used the STELLA II software in his physics classes. He has had his advanced placement physics students design models to address the more difficult problems in the regular physics book so that those students who have difficulty understanding the material/problems using a traditional approach may have an alternate way to view and interact with the phenomenon under study. To prepare them for this use of STELLA II, the basics of STELLA II modeling as applied to motion were part of the lab activities in the advanced placement course. STELLA II is also used in the course to present new ideas and to address problems which cannot be solved with the mathematics used in the course (pre-calculus level).

In regular physics classes, STELLA II is used as part of a "cafeteria" approach to teaching. Most topics are taught several different ways to increase the probability that one approach works with

students. STELLA II, with its visual approach, is one more way to present ideas. It is not the primary approach, but one of several which, when taken as a group, serve the needs of virtually all students.

A quote attributed to Albert Einstein epitomizes the underlying approach to system dynamics stressed by this project, "Everything should be as simple as possible, but no simpler."

Notes

1. National Council of Teachers of Mathematics Standards (making connections /conceptual understanding), Project 2061 Science Standards (conceptual understanding/viewing problems as wholes), and the National Council for the Social Studies (including more new technologies that address the inquiry process more effectively).
2. Fishbanks Simulation is produced by IPSSR, Hood House, University of New Hampshire, Durham, NH 03824.
3. Fishbanks STELLA II simulation is available from The Creative Learning Exchange, Lees Stuntz, Director, 1 Keefe Road, Acton, MA 01720.

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