Using Systems Dynamics as a Core Tool for Content Teaching: A mature Use of System Dynamics in the Pre-College Environment

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Abstract: Most efforts to bring System Dynamics concepts into the pre-college environment have focused on episodic use of System Dynamics in traditional classes or on teaching modeling. At Wilson High School, in Portland, Oregon, this effort has been extended for the last eight years by the development of two courses in which Systems Dynamics is more fully integrated into the curriculum. One, an Environmental Science course, uses models to develop traditional content and allow students to experiment with scenarios and policies that cannot normally be explored in depth. Most course topics are explored using models. The second and older of the courses, Science, Technology, Society/World Issues, was designed from the beginning to use systems concepts to explore all topics. The course has evolved substantially, but continues to base content choices on the unique capabilities of System Dynamics to explore complex problems.

Use of System Dynamics in the pre-college environment goes back at least twenty years. That initial work has grown to involve teachers at all levels of pre-college work. The number of teachers and students using System Dynamics has shown the predictable exponential growth. Yet even the most realistic advocates of System Dynamics will admit that they had hoped its growth would be faster and more dramatic. The power of dynamic models and systems thinking as a tool for learning and for motivating questions is obvious to them, yet the broader educational community seems unconvinced (although perhaps "unexposed" is a better description.). Work done by a group of educators and System Dynamics professionals in June 2001 in Essex Massachusetts included a plan for the gradual expansion of System Dynamics usage. The plan includes a radical move away from the two primary ways System Dynamics in K-12 education has proceeded. It advocates emphasis on large-scale development of models and curricular materials targeted for specific courses. Further, those courses that are taken by the largest numbers of students, identified as providing the most leverage, should be given priority. By contrast, past efforts have concentrated on teaching modeling skills to students and episodic inclusion of some systems concepts in existing courses.

LEARNING FROM FAILURE (or is it success?)

When advocates of Systems Dynamics in K-12 education look to past educational innovations, successful and unsuccessful, as a means of developing a strategy, they most often look at the use of computer interfacing in science. Certainly some lessons can be learned there. In a relatively short period of time (15-20 years), use of interfacing grew from an innovation practiced by a few to the norm across the United States. As attractive and reassuring at that success might be, it may be more appropriate and relevant to look at the evolution of computer programming in the K-12 environment. In the late fifties and early sixties computer programming courses began to appear in American High Schools. The use of computers in all areas of society began to broaden. The widely held assumption was that as use of computers increased, more students would be taking computer programming courses. The appearance of the first microcomputers at home and in schools was accompanied by the expected increase in the number of students taking programming courses. Some boldly asserted that all students would eventually need to learn to program. At that time, using computers meant programming computers. The historical record shows a very different outcome. Many computer science educators now lament the failure of their programs, pointing to declining enrollment and narrowing of offerings. These facts point out that it is possible to be fabulously successful without being successful in the way intended, and, thus, without being aware of the success.

The goal of the computer educators of the fifties and sixties was often expressed as "preparing students to use computers in all aspects of their lives". Arguably that has been achieved to a degree they probably never envisioned. However, it was not achieved the way they envisioned it. Most people who use computers do not and cannot program them, nor do they want to. At the same time, their use of computers has changed their lives. They do not need to program computers; they need to use programs on their computers. They need to know how those programs work, in a superficial way, while "power users", customizing their software and writing macros, may be considered as doing some minimal programming. This does not diminish the need for teaching programming, though it may diminish the number who need to do it.

Pre-College use of System Dynamics may now be at the same place that computer programming found itself in the early sixties. Students are beginning to learn how to model. Use of models in classes is increasing. But, is it reasonable to expect all students to model, or will we expect them to use models? The recommendations developed in the summer 2001 meeting in Essex point toward an increased emphasis on use, while maintaining support for modeling. Further, the model use envisioned involves larger scale and more systematic use of models in classes rather than the episodic use now prevalent.

EXPERIMENTAL COURSES AT WILSON HIGH SCHOOL

The experience obtained at Wilson High School in Portland, Oregon, in developing two courses that fit the recommended approach can serve as guideposts for the process. One, "Science, Technology, Society/World Issues"(STS/WI), is a course built around the unique capabilities System Dynamics brings to exploring the complexity and interrelated nature of social/cultural development and technology. It shows what can be accomplished where System Dynamics concepts have an established pattern of use at several levels. The course fulfills both social science and science requirements, but is unlike any other course offered by either department. The content and approach is interdisciplinary and seminar based. It was created to showcase the power of System Dynamics and to provide an environment for students exposed to System Dynamics to experience it as a tool, rather than as a discipline in itself. STS/WI presents a model for what can be done to expand and extend the curriculum. It is a vision of the future.

The other course is a traditional one with content that is ideally suited for explorations using Systems Thinking and Dynamic Modeling. "Environmental Science Using Dynamic Modeling" is built around the Advanced Placement Environmental Science curriculum, employing dynamic models to explore a wide range of topics. It presents traditional material in greater depth, with the option for experimentation though simulation. The course represents a "mature" use of System Dynamics in the traditional curriculum, which, if extended throughout the K-12 curriculum, would result in System Dynamics evolving as the unifying tool/theme of learning.

Although the STS/WI class preceded the Environmental Science class by four years, this would probably not be the case for most schools. Extensive work in System Dynamics had been done in at least five different curriculum areas in the school, creating an environment receptive to this unique course. More commonly, the entry point for more extensive use of System Dynamics will be through traditional courses. Thus, it will be most instructive to look at the development of models and curriculum for the Environmental Science course as a guide for others courses.

1.) DEVELOPING A SYSTEMS BASED ENVIRONMENTAL SCIENCE COURSE

Choosing to develop this new Environmental Science course using dynamic models as a key instructional tool would be a natural fit in any case, but was particularly appropriate with the strong focus on System Dynamics in the school. Environmental Science deals in the broadest sense with the evolution and operation of ecological systems. Patterns of growth, patterns of change, interaction of elements of the system are traditionally studied from a descriptive perspective, with some attempts at quantifying patterns of change. Some of the earliest mathematical modeling outside of mathematics and physics was devoted to simple biological (ecological) systems. Current research practice often involves extensive computer modeling. Perhaps more than any other discipline, the content of Environmental Science classes fits the perspective and structure of System Dynamics.

Environmental science topics are now included in many secondary biology courses. With the development of an Advanced Placement course outline and Exam, it is increasingly appearing as a discrete course in secondary schools. Environmental Science and Ecology are even more widely offered in colleges and universities, with an increasing number of institutions offering degrees in environmental studies, often in conjunction with other disciplines, including both public policy and economics, two other fields particularly well suited to development using System Dynamics.

In developing the System Dynamics based course used at Wilson High School, close attention was paid to the structure of the Environmental Science Advanced Placement Exam. This test enables secondary students to earn college credit after completion of a course based on guidelines developed by the College Entrance Examination Board's (CEEB) Advanced Placement Program. The series of Advanced Placement Exams are based on analysis of material normally presented in college courses. They reflect current thinking at the college level about the key content appropriate for a first year course.

These Advanced Placement Exams, and the college courses they reflect, have historically had major impact on secondary course content. Secondary courses tend to reflect changes in the college-level courses. Thus, the Wilson course, designed to fit these standards, is potentially broadly adaptable to other secondary environments. The models and curriculum materials developed for it are suitable for use in regular biology courses, Advanced Placement Environmental Science courses, and college level Ecology/Environmental Science courses.

The first step in developing the models to be used in the course was preparation of a matrix linking the recommended course content and some basic System Dynamics tools/concepts. The matrix is included in the Appendix. The key topics for the course content reflect the Advanced Placement Environmental Science course outline[1]. While the System Dynamics concepts selected are consistent with most introductory works on System Dynamics, they probably most closely reflect the content of Andrew Ford's *Modeling the Environment*[2], the first college level text in which developing modeling skills is an integral part of the development of Environmental Science content. The matrix indicates which System Dynamics concepts can be used in models developing the standard Environmental Science content. It should be noted that linkage is indicated only if the content can be clarified or extended by a model, or if a model can provide an opportunity to experiment with the ideas. This was determined by an examination of the Environmental Science texts most commonly used for Advanced Placement courses[3] for specific content suitable for modeling. Each of the texts arranged topics differently, yet adhered to the basic course description suggested by the Advanced Placement Board. Models chosen for development were ones that explored concepts or problems common to most or all of the texts.

Computer modeling, usually with purpose-built or traditional line-code software, has become a standard technique used in environmental science research. Thus, virtually every topic listed in the course description could be explored using the System Dynamics concepts. That would, however, be an exercise in modeling and not necessarily useful. Vital in developing the models and curricula used in the Environmental Science course has been a focus on what is the goal of model use. Central to this consideration is the belief that the course is not explicitly about System Dynamics. To the contrary, it is about teaching Environmental Science using the unique capabilities of System Dynamics, a very different proposition.

Both explicit focus on System Dynamics and the more indirect approach chosen for this course result in an understanding of some systems concepts. The purpose of that understanding is what must be kept in mind at all times. In this course, students are not being taught to model. Rather, they are being taught to use and make simple modifications of models, recognize characteristic model behaviors, and identify the limitations of models. They must learn to evaluate whether or not model results reflect the reality they are familiar with. They must explore policy implications with models as an experimental tool. Decisions on inclusion or exclusion of System Dynamics concepts

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[1] *Environmental Science Course Description*, (New York, N. Y.: The College Board, 2002) pg.6
[2] Ford, Andrew, *Modeling The Environment: An Introduction to System Dynamics Modeling of Environmental Systems, (*Washington D.C.: Island Press, 1999.)
[3] *Environmental Science Course Description*, (New York, N. Y.: The College Board, 2002) pg.5

and models must be subservient to that purpose. This is very different from the purpose of Ford's book, which was a vital resource in developing the course. His text is designed, as noted in the preface, "for college students with an interest in systems and the environment. It introduces the use of system dynamics models to understand and manage environmental systems. The book provides material suitable for two semesters of study at the undergraduate level. It can also be used for a graduate course in computer simulation applied to environmental systems."[4] In his text, the development of System Dynamics and Environmental Science are equal in emphasis, with perhaps a slight edge to the System Dynamics.

In the Wilson course, primacy of purpose was always ceded to the Environmental Science material. As an early attempt to use System Dynamics in a course in which many students will have little System Dynamics background, development of systems concepts had to be limited. If this course was to be useful as a model for similar courses in other schools or other content areas, it could not be designed so that only experienced modelers could teach it, only students with modeling background could do well in it. The course materials were designed so that all System Dynamics concepts were introduced through Environmental Science ideas. In no cases were System Dynamics topics presented "free standing", that is, as the focus of a lesson or lessons.

Development of the specific models used has drawn upon the work of many involved in both pre-college and college level applications of System Dynamics. The use of models for the sake of model usage was avoided. In each case where a decision was made to use an existing model or develop a new model, primary consideration was given to what new knowledge or capabilities the model could bring to addressing the material. Once this was done, final selection of models was based on what model use skills/concepts had already been developed, which were still regarded as desirable.

In this, the fourth year of the Environmental Science course, most of the identified models have been developed, with some revised two or more times. The models and supporting curriculum are being developed in part with funding from the Gordon Brown Fund. The models, with only a few exceptions, tend to be simple models with only four or fewer stocks. The sequence of models matches the sequence of topics in the text used at Wilson High School, *Environmental Science*[5].

There has been a significant amount of discussion in the K-12 System Dynamics community about allowing/requiring students to actually look at the model versus only exposing them to the authoring/control level of the STELLA models used. Not surprisingly, the rationale for each approach lies in the perceived weakness or flaws of the other approach.

Those who insist on students seeing, or better yet, building each model, suggest that simply running the model using controls on the model interface turns the model into a black box. There is no understanding of the model structure, no recognition of the linkage between basic model types and behaviors, no understanding of the logic and the

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[4] Ford, Andrew, *Modeling The Environment: An Introduction to System Dynamics Modeling of Environmental Systems*, (Washington, D.C.: Island Press, 1999) pg. ix

[5] Nebel, Bernard J. and Richard T Wright, *Environmental Science*, (Upper Saddle River, New Jersey: Prentice Hall, 2000.)

limitations of the model. There is no accompanying learning of System Dynamics concepts. The same results could be obtained using a spreadsheet or traditional line code.

Those who only want students controlling models, not building, modifying, or looking at them, suggest that without spending too much time explicitly teaching modeling, students learn nothing about modeling or System Dynamics from looking at a model. System Dynamics can be used without reference to the model. They also suggest that looking at the model can intimidate students, making the think that System Dynamics, like the common perception of mathematics, is “too hard for most people”.

The models and activities developed for the Environmental Science course present a more balanced perspective. Students run some models without looking at them, they build some, and they modify others. In all cases, the curriculum materials and the debriefing suggestions are designed to develop System Dynamics concepts in the context of Environmental Science behavior. We believe it is essential that models not be “black boxes” generating answers. At the same time, we recognize that even if System Dynamics eventually becomes the unifying tool for learning, thinking, and problem solving, most people will never need or want to know how to build complex models.

SETTING THE STAGE: KEY CONCEPTS AND MODELS FOR A SOLID INTRODUCTION

In any course, in any discipline, there are certain key ideas and vocabulary that are prerequisites for any significant work, any development of real understanding. They are important because they permeate every aspect of the field. Failure to master them at the onset of study will preordain failure, while mastery enhances the prospect of success and even the generation of new knowledge. In Environmental Science, two concepts inform virtually all later work: sustainability and patterns of growth. If we substitute “stability” for sustainability, these same two concepts are keys to looking at problems through System Dynamics. A third concept, delays, is also central to understanding dynamic systems, yet little discussed explicitly in Environmental Science texts. Study of those texts reveal, however, that many of the concerns and problems at the core of environmental problems involve what the systems dynamicist would refer to as information and material delays.

Because these ideas are so central to both disciplines, the first models and activities developed and used in the course provide an introduction to them in both contexts. These activities also provide a vehicle for introducing students to the mechanics of running and building STELLA models. These models/activities are usually done in the order presented over a period of a few weeks at the beginning of the course. They set the stage for later work.

Sustainability Activities – Sustainability is one of the key concerns looked at in Environmental Science courses. The fact that unrestricted growth and sustainability are mutually exclusive drives much of the work in ecology. These activities involve the use of two models developed from models first produced by the CC-STADUS project in 1993. Updated and improved, the Deer model and the Mohenjo Daro simulation look at two populations that rely on a single resource for their growth and survival. Run in their default mode, they result in overshoot and collapse. The students attempt to stabilize the populations by changing some variables controlled by sliders. This activity introduces students the use of the authoring/control level of STELLA models. They learn to use buttons and sliders to run and modify models, as well as get experience evaluating Behavior Over Time Graphs (BOTGs). Though not explicitly identified, they have their first exposure to exponential growth.

Delays - In System Dynamics we deal with material delays, as in an aging chain or inventory adjustment, and information delays, created by the structure of the connectors in a model. In some topics in Environmental Science, such as demographic shift or the rise of CFC's in the atmosphere, we deal with delays directly analogous to the material delays. We also deal with a type of information delay similar, but not identical to the information delays of models. The ecological examples are more of a perception/information delay. Problems are not noticed until they reach a certain level. Ozone depletion is a good example of such a delay. The depletion went on for years until the effect was large enough to notice. There are many situations studied in Environmental Science in which such delays play a key role in reacting to and dealing with the problem. The need for better data to eliminate surprises due to such information delays is a key factor in planning problem analysis. This Delay activity is a somewhat artificial simulation of a delay situation. Students attempt to control the level of a reservoir by adjusting outflow. The only information thy have to work with is the reservoir level the previous month. Their information is effectively delayed by 1 month. The need to keep track of behavior and look for patterns as a way of dealing with the delay provides the students with a first look at coping with delays. This activity provides a reference point for later discussion of delays in the course.

Patterns of Growth – Almost every topic in Environmental Science involves patterns of growth and dynamic stability. Surprisingly, while most texts identify the various patterns: linear, exponential, S-shaped, and overshoot and collapse, they fail to make a key point about perceptions. Most environmental processes exhibit a basic exponential growth pattern. Yet, most people do not anticipate that, "because most people think *linearly* and think of growth as a linear process"[6]. This modeling activity develops and understanding of the basic patterns of growth through construction of models reflecting each. This is a directed modeling activity. Students are guided, step-by-step, through the construction of the models. This provides them with an opportunity to become familiar with the basic pieces of STELLA, as well as the display options. It is not intended to prepare them for independent modeling, merely to provide the basic experience that should allow them to manipulate simple models. It also acquaints them with the basic model structures that exhibit linear and exponential growth. The concept of limits to growth as a control, through graphical functions, is also introduced. These activities provide the students with the basic ideas of growth that later models and later content topics will be based on.

[6] Meadows, Donella H., Dennis L. Meadows and Jorgen Randers, *Beyond The Limits*, (White River Junction, Vermont: Chelsea Green Publishing Company, 1992.) pg. 16

EXTENDING THE SKILLS AND CONTENT: LOOKING AT POPULATION RELATED MODELS

The three activities already discussed prepare the student for further study of Environmental Science a well as further development of System Dynamics tools and use of more complex models. The three activities form part of the first month of the course. During the same period, the *Fish Banks*[7] activity provides further background and experience in looking at sustainability. The next segment of the course looks at the basic concepts of ecosystems from the perspective of sustainability. Some simple models are used in this section. The unit introduces the ideas of trophic levels and food webs, the models and activities used here are simple and do not introduce new System Dynamics tools or concepts. They essentially replicate the ideas of the earlier Deer model, with activities and models focusing on three level systems (producer, herbivore, and carnivore). The focus is on achieving and maintaining balance. Students explore the impact of small variations in the populations initiated by partially exogenous factors (hunting, disease, drought, etc.) The oscillations induced are looked at only superficially. Greater analysis of oscillations is delayed until the discussion of predator-prey relationships.

This preliminary work is followed by a number of activities centered on population growth. These activities are integrated into roughly three months of coursework. The population-centered activities provide the framework for introducing and developing important System Dynamics ideas. Feedback, both positive and negative, is discussed. The importance of loop dominance is developed as students explore how population growth is moderated. Limits to growth begin to be a centerpiece of the discussion. The concept of dynamic stability, rather than traditional ideas of equilibrium, begins to emerge. Finally, as more complex interactions are explored, oscillations, particularly linked oscillations are explored.

An extension of the population models and population interactions is exploration of natural selection, speciation, and succession in ecosystems. This key ecological topic is easily modeled and becomes a subject of experimentation rather than history and conjecture. The use of models in developing these topics allows students to explore some ideas that are often mentioned in Environmental Science courses, but rarely explored in detail. Students run experiments to see why quickly maturing species are more resistant to environmental stress than slower maturing species. They can experiment with the impact of new species, or the elimination of a predator. Their work becomes more "scientific" rather than anecdotal.

In all cases, the activities are driven not by pure numbers, but rather by patterns of growth and patterns of change. Students are challenged to predict outcomes, analyze patterns of behavior, and propose policies to solve problems or produce specific outcomes. The emphasis on model usage is never a numerical answer, always a "why".

Basic Ecosystem Models – These activities involve looking at a simple two-organism (plant – herbivore) and three-organism (plant – herbivore – carnivore) ecosystem initially in a steady state situation. The effect of small perturbations is looked at qualitatively. The model is not explored in depth. It is only used to develop a basic understanding of

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[7] Meadows, Thomas L. and Thomas Fiddaman, *Fish Banks Ltd.,* (Durham, N. H., University of New Hampshire, 2001)

what is necessary for an ecosystem to achieve stability. The species are not specified, the consumption and reproduction rates are chosen to facilitate a steady state situation that does not oscillate wildly when perturbed.

Basic Population Models - This sequence of activities takes the models developed in the *Patterns of Growth* activity and extends them to examine real populations, both human and non-human. They include not only traditional birth and death structures, but immigration and emigration as well. These first population models focus on single species without limitations on growth. They include use of actual data from various resources (CIA, World Health Organization) to make country specific population projections.

Intermediate Population Models - In these models, the basic population structure is extended with simple factors that will affect the growth patterns, such as population density linkages tied to reproduction and death. Available space is another limiting factor that is explored for both plants and territorial animals. The traditional study of populations in ecology always includes limiting factors. These activities provide an opportunity to explore the factors and see how they control what would otherwise be unrestricted growth.

Linked Population Models (including predator-prey relationships) – These activities begin with a simple steady-state predator-prey model. After exploring why it is steady-state, students explore a number of scenarios in which the system is perturbed. The oscillations induced are explored, including damped and un-damped systems. Student criticism of these traditional models as unrealistic due to the perfect steady-state initial conditions resulted in the development of a second series of models and activities in which random factors produce a dynamic stability around central values. This second set of activities provides an excellent illustration of the advantages of using dynamic models and systems concepts in presenting the material. Traditional Environmental Science texts and materials never make the point that even in a stable ecosystem an individual species' population will vary from year to year or season to season. Students working with a model of a system developed that idea by thinking about what a horizontal graph of a population meant and comparing it to what they knew about the real world. Then they worked with the model, with teacher assistance, to make it more realistic. Also used at this point are models in which species compete for resources. These models and activities are still under development. The first trials were unsatisfactory, the second effort somewhat more successful. A lack of firm real-world data makes this task more difficult.

Evolutionary Pressure/Succession Models – This series of models provides some options for exploration. One sequence returns to the competition model, but presents a scenario in which an environmental change gives a strong survival advantage to one of the species. This advantage can be varied to explore how seemingly small advantages can have major impacts on species distribution. Andrew Ford's Industrial Melanism models are modified and provided with support materials to allow students to explore a well-documented historical case involving survival advantage linked to variation of a single trait within a species. A hypothetical model of the survival advantage of sickle-cell trait in malaria-rich environments has been tested and is under further development, as is a model of beetle-survival in the aftermath of the Chernobyl reactor accident. Supporting materials and activities for all these models allow students to experiment with survival advantage factors and speed of change. Related models, which explore the ability of populations to recover from environmental stress, are also used. These models emphasize relative success of organisms with different characteristics in similar niches, such as early maturing versus late maturing organisms, long generation length versus short generation length. Models of traditional ecological succession, such as the well-documented transitions from meadow to climax forest, have been developed, but are currently not being used. The models presented little gain in understanding over more traditional approaches and as such, the time commitment is not justified by the outcome.

Demographic Models – These activities focus on the concept of demographic shifts. Population distribution changes, by gender or by age cohort, can have a tremendous impact on ecosystems and cultures. While demographic pyramids are a standard resource for analyzing a nation's current and future problems, dynamic demographic pyramids (pyramids that display demographic change over time) are nearly impossible to find. These models fill that niche. Three different models are used. The first is a country specific demographic model focusing on Zambia. Students run the model with the default settings, then analyze what changes in the economy, population, culture, food, water and resource supply will occur as a result of the projections. They then explore a number of possible alternative scenarios driven by changes in the birth rates. An alternate activity involves a generic demographic model, with data sets provided for more than 60 countries. This activity is carried out in the same manner as the Zambia activity, but each student follows a different country. If the Zambia activity is chosen, a class discussion of the different options facing Zambia closes the activity. If the generic model is used, students are involved in a broader activity in which they act as an advisor to the leaders of the country they are exploring. They make a formal presentation on future trends and problems, with recommendations for responses and changes. The demographic model is used to support the predictions and proposed changes. Regardless of which option is chosen for the first demographic model, all students participate in an activity focusing on the Chinese one-baby per family policy. This activity uses a detailed demographic model of the Chinese population that won the SYMBOWL competition in 1998. The model uses actual data provided by the Chinese census bureau. Working in groups, students analyze the effects of the policy on all aspects of Chinese life, assuming different levels of rigor in enforcing the policy. The group reports are presented to the entire class and discussed.

Advanced Population Models – These models and activities are designed to tie together all the systems skills and content developed in the course. They also link all the fundamental Environmental Science ideas with the impact of one species on the global ecosystem, humanity. The existing population models are linked to generic non-renewable resources, then to partially and fully renewable generic resources. From these generic situations, students move on to models of oil use, land use, agricultural production, and water use. Using these models, students examine individual countries and make predictions about future trends and problems. Still in development are models that link all of these key resources. The focus of these activities, as well as the demographic activities, is the linkage of Environmental Science and policy. The models provide the tools for testing policies. Perhaps the most important goal of the course is instilling into the students the realization that policy decisions are the key to the future. Further, good information and the ability to analyze and predict are vital to good policy decisions. Their System Dynamics experiences are designed to give them a glimpse of that.

THE ENDGAME: INTERESTING MODELS AND PROBLEMS THAT FLOW FROM THE CORE IDEAS

The last one-third to one-half of most Environmental Science texts shifts emphasis and style. The earlier parts focus on broad problems with great themes like sustainability, food webs, trophic and demographic pyramids, evolutionary change, and the growth of populations. These are unifying concepts with broad implications. The later sections seem almost mundane by comparison, focusing on narrower ideas that flow from the broader concepts. We study soil, the hydrologic cycle, biodiversity, food production and distribution, energy use, and the multitude forms of pollution. If the study of Environmental Science can be likened to a picture, the early part of the course and the models developed for it are like the outlines and basic color selection for portions of the picture. The rest of the course fills in the fine details.

It is possible to build dynamic models that show the important fine details. It is entirely appropriate if the intent is to solve a specific problem. It is less important, however, if the goal is developing understanding broad trends and patterns of behavior. Thus, the remainder of the course uses fewer models, even though many could be built. Some of the models are completed; others are still in development and testing. All focus on illustrating the broad outlines of the more specific problems that constitute the remainder of the course. Policy implications rather than numeric accuracy or detailed replication of a specific scenario are the focus.

Food/Soil Models – The connection between soil degradation and agriculture is explored. Students link this model to a population model for a specific country. Using agricultural production figures per hectare, they then try to determine the carrying capacity of the soil, establishing one of the limiting factors on population growth. This model is then expanded to look at all land use in a country, including shifts in land use among forest, prime agricultural land, pasture, and marginal land. The focus on discussion here is land use, population, and sustainability.

Water models – Watershed models and country models are used here. One model, focusing on a simple watershed, is used to explore the hydrologic cycle in broad terms. In development is a narrower model looking at a reservoir/aquifer scenario linking multiple uses and the need for sustainability. Both models are more descriptive than accurately quantitative, although in both cases students are required to manage water with certain restrictions placed on them. Also under development is a similar model in which students must determine what the safety margin is for water distribution management in a system with some variability of precipitation. The country models simply look at overall national water supply and the various needs. It is tied to a population model, establishing another limitation on growth. Under development is a model linking both agriculture and water.

Energy Models – Only two energy models are used at this point. One addresses the use of oil and the projected supply, allowing students to explore the availability of oil in the future. The other explores projected energy needs for different levels of industrialization/modernization worldwide. This model allows students to make projections and recommend priorities for energy development.

2.) CURRENT STATE OF THE SCIENCE, TECHNOLOGY, SOCIETY/WORLD ISSUES COURSE

The STS/WI class developed rather differently than the Environmental Science course. It began as an exploration of interesting topics and questions that could be enhanced through the use of models. No pre-existing, well-developed syllabus for the course existed. Collaborative efforts by three K-12 teachers and two college level faculty led to the initial course. Some topics and activities were spectacularly successful, others spectacular failures. The specific content has evolved, and the focus on System Dynamics has evolved as well. The emphasis on detailed development of System Dynamics skills and tools has diminished. Yet the course remains very much a course, in which the tool, System Dynamics, is equal in importance to the social science and science content. This approach will rarely fit other curriculum areas, although it may be reasonable for some mathematics courses and personal finance/economics courses. Nonetheless, this course has provided useful insights. In a sense, it has been similar to an engineering prototype or a "concept car" developed by an automobiles manufacturer. It has pushed the limits of using System Dynamics in the K-12 environment. From it, we have a broader understanding of the capabilities and the limits of Systems based courses.

As taught today, the course prepares students for the Advanced Placement Exam in Human Geography. It has not, however, been designed around the guideline for that exam. Rather, the course reflects the broad outlook of *Beyond the Limits*, with students actually exploring sectors of the World3 model as they develop key concepts in the course. The intent is to prepare students to become what Barry Richmond often referred to as a "Systems Citizen".

CURRENT COURSE SUMMARY

Since System Dynamics is the tool that holds the course together, the first part of the course focuses on learning the language of that tool. Students begin by looking at Behavior Over Time Graphs. Interpreting graphs is the single most vital operational skill in this course. Both the STELLA models used and much of the resources accessed present time-scale graphs. Students begin by looking at or drawing the BOTG for a thermostat, a bathtub, and a checking account. These are all fairly standard STELLA models built in the first few days of a modeling course.

Understanding what stocks and flows are comes next. Students look at constructing stock/flow "sentences" as a means of expressing relationships. From there, student proceed to mental maps, stock-flow maps, and finally, functioning basic models. Along the way, students learn to build and identify models that exhibit linear and exponential growth patterns.

Having developed the basic tools and skills, students now proceed to develop simple population models. This population model is the unifying piece throughout the rest of the course. All further work is ultimately reflected back on population growth and the factors that support and restrict it. The population model begins with a bacteria model, then is extended to larger organisms. Gradually, the model is extended to include total fertility rate, carrying capacity, density, oscillation, life span, age structure, and quality of life.

The model is converted to a model of human populations. Quality of life then becomes a reflection of GNP/person. Other variables, if not explicitly defined, are discussed in terms of the real-world variables that control them. Fertility, for example, is discussed in terms of per capita income, education of women, and government social services. The model is used to explore a number of countries. It is modified to include immigration and emigration.

Policy questions and discussion now becomes the focus. Why do people emigrate? What controls fertility rate? What controls education? The "whats" and the "whys" lead to an understanding of the dynamic forces that drive a country or a culture. The details may not be explicitly modeled, but the basic model leads to the questions that fill in the details.

The course proceeds like a helix, always circling back at a new level. Every cause is analyzed. Rationales for implemented policies are examined. Emigration produces immigration when the migrants arrive. Why are there immigration policies, in general? What drove (or drives) specific immigration policies and changes in those policies? What are the similarities between the German “guest worker” policies and the United States’ policies toward migrant laborers?

Agriculture and trade are considered next. They, in turn, are reflected back on population growth and immigration. The transitions from small family plots to large family farms, and ultimately, industrial farms are explored. The impact these changes have on the family size, immigration, and trade flow naturally from consideration of the agricultural revolution. Issues of large-scale use of hybrids, monoculture, pest management, and dependence on chemical fertilizers bring up still more connections, more questions and problems.

A logical next step is the consideration of resources in general. Renewable, partially renewable, and non-renewable resource enter into the models used and the problems posed. It becomes increasingly clear that the growth in populations and knowledge opened up new opportunities, but also created new conundrums.

As students move through these cycles, they constantly do research. They are comparing birth rates in different countries and cultures. They look at agricultural yield and fertilizer usage. They collect the raw data that defines the system they are looking at. Then, using the models and other resources, they must make evaluations, projections, and predictions. They must identify which policies have worked and which haven’t. They must test and develop new policies, or adapt old ones. They have to think and analyze, the real goal of the course.

Consideration of natural resources leads inevitably to examination of production and energy utilization. This leads to a general study of the process of modernization and industrialization, historical, current, and future. Again, simple models and multiple data sources provide the tools for this exploration. Particular attention is paid to future energy sources in juxtaposition with use rates in the industrialized nations.

The consideration of all the factors yields a total view of what is happening in a culture. Experimentation with this broad view is facilitated by the use of sectors of Urban Dynamics and World3. They provide a lab environment for students to experiment with.

LESSONS LEARNED: TRANSLATING THE ENVIRONMENTAL SCIENCE AND STS/WORLD ISSUES EXPERIENCES TO OTHER COURSES/DISCIPLINES

After almost fours years of work developing and using systems concepts and curriculum materials for an Environmental science class, and eight years designing and redesigning the STS/World Issues course, there are some obvious considerations that can inform any similar work in other courses.

- Begin with a thorough survey of current content taught in the field. Focus on the concepts taught in the 3-5 most commonly used textbooks and supplementary lab manuals. If an Advanced Placement or International Baccalaureate course guide exists, use those as well in establishing the list of topics.
- Pay attention to the sequence of topics as well. In some fields, most notably physics, there is little variation. In others (Global Studies/World Civilization, Biology, Economics, etc.) there is more variation. Identify which of the early topics lend themselves to very simple models that can be built with only one or two stocks.
- Develop the early models with a range of approaches including model building, model modification (changing values or functions within models) and simply running models.
- Design the curriculum materials to provide for discussions after the actual activity. This debriefing time allows monitoring of what students actually did and learned and provides an opportunity to fill in gaps if they missed key ideas.
- While it may be possible to develop models for every key concept in the content area, that is neither necessary nor wise. Focus on those concepts that will benefit most from a System Dynamics approach. Look for ideas that can be learned more easily through experimentation. Topics that require mathematical techniques too sophisticated or too time consuming for students to do through normal means, but nonetheless are important or interesting concepts in the curriculum are also good choices. Consider problems that are normally explored qualitatively rather than quantitatively.
- Over a period of time, develop alternate models and activities for each chosen concept. Also add additional concepts to be modeled. (This does not contradict the previous point! Develop a cafeteria approach to materials. One class may need meatloaf, another burritos! Tailor which materials are used to the class, or even to the teacher.) This will be especially useful if the materials are to be shared or disseminated.

- Never lose sight of the fact that most interesting/important relationships involve feedback. (Jay Forrester is fond of saying "The richness is in the feedback".) Do not hesitate to model ideas in which feedback does not play a key role, but understanding feedback, especially quantitatively, is often difficult. Modeling and experimenting with it can often clarify important ideas.

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Back to the Top