PROGRAMS TO SUPPORT THE DEVELOPMENT OF SYSTEM DYNAMICS-BASED CURRICULA

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Abstract

Over the past several years, faculty at Trinity College have engaged in a number of projects to develop their modeling skills, to incorporate modeling into established courses, to use modeling as a foundation for new interdisciplinary courses, to develop modeling skills in our students, and to reach out to pre-college educators to support their development in similar directions. Our more successful experiments share at least one common element: They begin with a conceptually simple theme, and then systematically and progressively build complexity, realism, and connections to more diverse fields, around that central theme. Such structure allows the development of entire courses on the foundation of system dynamic modeling, rather than episodic modeling exercises common in many other educational settings. An additional benefit is that several of our experiments have begun to provide unexpectedly reinforcing support for other experiments.

In this contribution we briefly describe these recent experiments which, together, can provide significant support to pre-college educators and educational systems seeking to enhance the system dynamics components of their curricula. Our efforts to provide initial modeling training for teachers rested upon a graded sequence of modeling exercises progressively developing more complex, realistic models of human population growth, then connecting the population dynamics to other topics of interest to the teachers. Recognizing this strategy as an effective one for building modeling skills, we have used it as the conceptual foundation for an interactive computer-based Tutorial for the building of STELLA II models. This Tutorial can support independent learning of this language, serve as a self-paced adjunct to more traditional modeling instruction, or provide a means to convey basic skills and concepts to students using models within a particular course. Following these successes, we developed in 1993 an interdisciplinary (primarily biology, history, and economics) college course (Plagues and People) in which a simple model of disease transmission served as the core model with which to develop diverse scenarios addressing historical, social, and economic factors of disease in settings ranging from ancient Greece to the modern case of AIDS. A more recent course was based on initially simple models of human population growth and explored how human population dynamics have influenced migration and settlement patterns, war and conquest, resource exploitation, disease, and the development of social and economic systems.

Introduction

System dynamics has been widely perceived as having value in the education of students ranging from primary grades through the collegiate and university levels (Draper and Swanson 1990; Forrester 1992). Recognizing the positive and negative feedback loops that characterize the wide diversity of systems with which students are obliged to deal, developing the critical thinking skills required to define the components of these systems and to understand the interconnections of those components, and recognizing the connections between frequently segregated disciplines of study, all serve to strengthen the quality of students' learning and prepare them to effectively deal with the systems they will encounter in "real life." At Trinity College a number of faculty from several departments were seduced by this vision of education and began to explore the utility of system dynamics at the college level.

As members of the Trinity College System Dynamics Group moved individually and collectively to develop collegiate-level applications of system dynamics, we experimented with a number of approaches to integrating simulation models into our various courses (Heinbokel et al., 1991).

In those individual courses and our first collaborative course, we identified five approaches by which such simulation models could contribute to our students' education:

1. Use of models to illustrate behaviors of systems; this is essentially the use of computer models as "electronic chalkboards,"
2. Individual student manipulation and exploration of pre-constructed models such as the commercial Learning Lab in Resource Management (High Performance Systems, Inc., 1988) or various instructor-generated models,
3. Manipulation and exploration of pre-constructed models designed for interacting groups of students such as Fishbanks Ltd (Meadows, 1989) and similar simulations developed at Trinity,
4. Facilitated construction of models in which the instructor and the students collectively engage in building and then exploring a model of the dynamic system of interest, and
5. Independent student construction of appropriate models.

The first three approaches dominated our use of system dynamics in our individual courses. Each approach can appropriately support our specific educational goals, although these types of uses tend to be episodic rather than systematic in these courses.

Our first exploration of more systematic use of system dynamics to support an entire course was an experimental course in 1990, in which we developed the concepts and techniques of system dynamics and then collaboratively engaged our students in constructing a model of a small New England subsistence farming community (Heinbokel et al., 1991). The resulting model, which required approximately 6-8 hr of class time, was the foundation of a recent paper (Potash, 1994).

The excitement of this very successful experiment to systematically use system dynamics as the methodological foundation of an entire course and to progressively build modeling skills and systems mind-sets in our students stimulated our subsequent explorations. Our resulting experiments (at least the successful ones we report here) have shared two features:

1. They are interdisciplinary,
2. They build progressively from the simple to the ever more complex and realistic description of a single, basic topical theme.

An additional feature of our group's development is that, in addition to supporting our collegiate needs, these experiments are transferable to pre-college educational levels. In the remainder of this paper, we will discuss three of these experiments.

Teacher Training in System Dynamics

In order for teachers to effectively engage their students in system dynamics-based approaches to education, the teachers themselves must be trained in the construction of computer simulation models. It is possible for non-modelers to use models constructed by others; in our experience, however, teachers unfamiliar with the discipline and conceptual requirements of actual model building are unlikely to be able to realize the full potential of these approaches. Accordingly, an effective and efficient protocol for training teachers is needed in order to provide effective and efficient guides for student engagement.

We have been involved in numerous training programs, both as students and as instructors. Based on those experiences, we have developed a basic approach to the initial training of teachers. This approach is characterized by several components:

Focus on a Single Theme

We have found in both our instructional uses of simulation models and in teacher training settings, that a progressive development of a single basic theme most effectively supports student learning and development. In our training sessions we focus on human population growth throughout the program. We have come to believe in this approach for several reasons:

1. By progressively building ever more complex and realistic models of a single process, we take our students stepwise from the familiar and comfortable to incrementally more difficult scenarios. The steps are never large; the new learning is tightly coupled to previous learning, so that students are never far removed from a solid foundation. There is a potential danger here, however. If we focus exclusively on this theme, we miss the opportunity to show th

general applicability of system dynamics to a full range of appropriate systems. We overcome that danger by frequently digressing to point out and to engage our students with systems that are structurally similar to the population model being developed. For example, when dealing with simple exponential population growth, we will digress to consider other positive feedback loops. Regardless of how far we digress or how valuable those digressions are, however, we are careful to return to human population growth for the next lesson.

2. Growth of biological populations, especially the human population, is a fairly intuitive process in that the basic system structure of stocks (population size) and flows (birth, death, and migration rates) is easily visualized and does not require extensive explanation.
3. Human population growth is a critically important aspect of our world. The simple models we use in this program present valuable and often unexpected lessons to the students using them. Therefore, by following this theme, we provide our students with valuable knowledge and insights quite apart from the training in simulation modeling that is our first priority.
4. Population growth connects to myriad other disciplines. This has two special values. First, it is relatively easy to develop connections between population growth and other systems in such fields as economics, history, environmental affairs, etc. Second, perhaps as a corollary to the preceding, teachers should be able to connect some aspect of their individual curricular responsibilities to the population models we have been building in class.

Model Good Teaching

Since we have found that there are many effective uses of system dynamics models in our teaching efforts (see above), we carefully illustrate those applications as we progress through the training program. For instance, we explore the initially surprising power of exponential growth through a demonstration of the impact of slight changes in the population's growth coefficient and by having the individual students explore the implications of the growth rates presently being experienced by a diversity of current countries. As we proceed, we engage students in small group explorations of models already built, and we collaboratively build some of the later models. Finally, students, in small groups or individually, are responsible for independently building a model that may serve some useful purpose in one of their classes during the next academic year. We are very clear while we are pursuing such exercises that we are demonstrating a variety of teaching approaches, so that the students will have observed and experienced a wide range of pedagogic approaches.

Multi-disciplinary Groups of Students

We find the ideal training situation is one in which the students represent a wide range of disciplinary interests and skills. This helps to avoid an overly tight focus on purely population growth processes and to expose all the class participants to the greatest possible diversity of topics and approaches. In addition, working with specialists in other fields reinforces the idea that system dynamics provides a means to connect traditionally disparate areas of study.

Caveat

We are confident that this type of training program develops good, albeit basic, modeling skills in the teachers with whom we have worked. They are not expert modelers at the end of this training, but they have the rudimentary skills necessary to begin to create and to apply useful models. Unfortunately, providing individual teachers with modeling skills and insights is not sufficient to guarantee that their students will profit from this training. Implementation of system dynamics in an educational system is also strongly dependent on the number of other local teachers with system dynamics training (to provide a mutual support and trouble-shooting group) and on the degree of administrative support (to provide the facilities, to provide logistical and equipment support, and to encourage and reward teachers for growth in this field). Without these two additional pieces of the system in place, our experience shows that it is very unlikely that significant progress will be achieved in getting simulation models or systems thinking approaches into the curriculum.

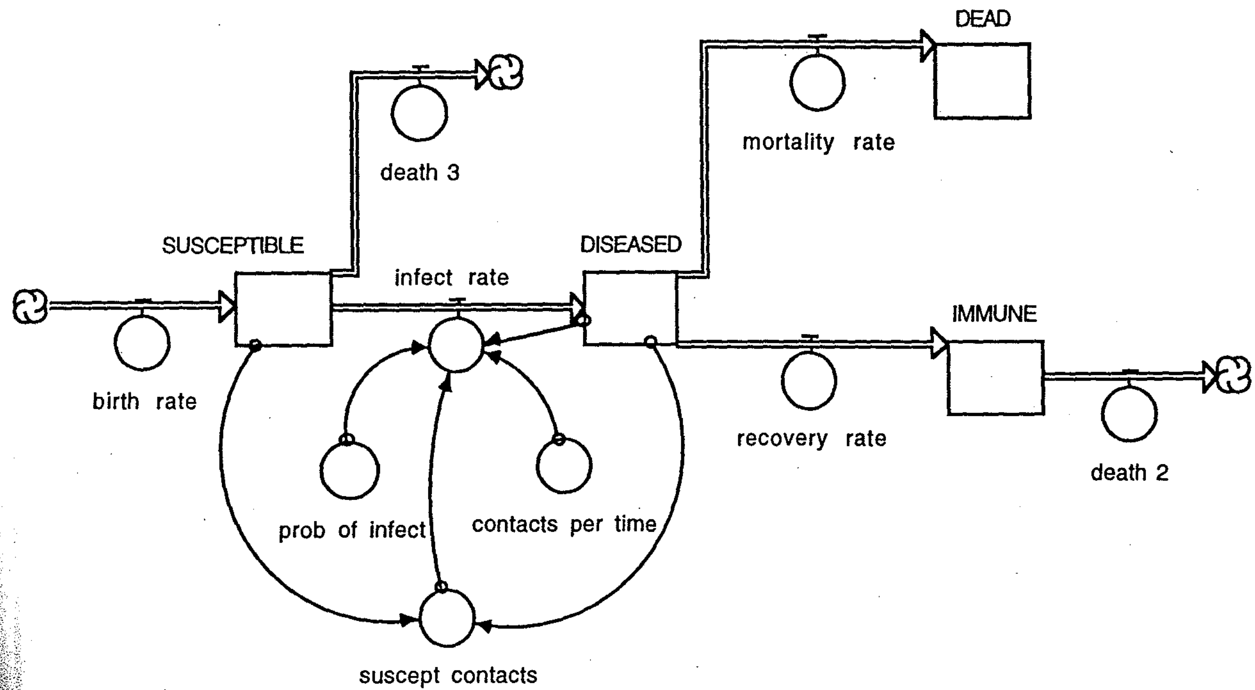

Figure 2: The basic STELLA II model used to illustrate disease transmission in a variety of historical scenarios. Note that not all necessary converters are included in this simplified illustration. The definition of the "infect rate" flow is derived from Glass-Husain (1991).

The final exercise, focusing upon the current AIDS epidemic, modified the original disease model into an elaborate model with seven disaggregated sub-populations, each of which, depending upon social (in the case of intravenous drug use) and/or sexual behaviors, were identified as entertaining different risk factors. Class members were divided into teams to research current literature on both numbers resident in each subpopulation and statistical data relating to risk factors. In the final weeks of the class, each team took responsibility for "plugging" their data into the overall model: and, to the amazement and gratification of instructors and students alike, a working model was actually completed and largely mirrored the predictions of the U.S. Centers for Disease Control! Students then defined specific potential leverage points in the modeled system and explored policy options to affect the projected course of the epidemic.

The obvious strength of "Plagues and People" rested in its capacity to illustrate the critical combination of biological and social factors in shaping historical epidemics. Further it created a workable STELLA II model which accurately reproduced how the AIDS epidemic functions in the present and what the future may hold. It was equally clear, however, that while students were comfortable with models which the instructors either constructed or corrected, students in the "Plagues and People" experiment were not capable of independent model building at the conclusion of the experiment. This recognition then formed the foundation for our most recent interdisciplinary experiment.

Population Dynamics and the Human Experience

Our second interdisciplinary experiment, conducted during Spring 1995, focused explicitly on developing model-building skills. Reflecting upon our success in our teachers' institutes and our Tutorial in using variations on a population model, we chose as our theme "Population Dynamics and the Human Experience." This course was designed to explore how such diverse aspects of the human experience as resource exploitation, war and conquest, disease, and the development of social, political, and economic systems all have roots within the dynamics of hum...

Development of an Interactive Tutorial for Construction of STELLA II® Models

One deficiency with the standard intense modeling training programs which we have experienced both as students and as instructors is their "once-through quickly" nature. That is, in the limited time available, students are guided quickly through a sequence of progressively more complicated exercises as more and more skills and insights are developed. Consequently, there is little or no time available for review of or self-paced progression through the lessons. Additionally, once the training program is completed, there are few opportunities for students to go back systematically to review materials that were not sufficiently reinforced for long-term memory. As a result of our experiences and, more forcefully as a result of specific requests by our students for such a learning aid, we have constructed an interactive, computerized Tutorial to provide a resource for individuals interested in independently learning and applying STELLA II programming.

Tutorial Design Rationale

The basic design features of our Tutorial are based on a number of considerations resulting largely from our experiences both as students and as instructors in training workshops:

1. We desired that the Tutorial be a useful resource both for the beginning modeler who needed a coordinated and progressive set of exercises to build a set of technical modeling skills as well as for more experienced modelers needing an occasional resource to review or refresh a particular concept or tool.
2. We felt that the Tutorial needed to engage the user in the actual construction and exploration of a set of models in which progressively more complex and realistic dynamics were developed.
3. We believed that the models and the user's progression through the modeling exercises needed to follow a single theme. For the same reasons that we have focused our training workshops on the theme of human population growth (see above) we chose to follow that same developmental sequence within the Tutorial. Not accidentally this results in a Tutorial that very closely parallels our training program format and content. The Tutorial, therefore, serves as a direct review vehicle for our students; experience has shown, however, that it also functions well as a stand-alone training resource for other individuals with whom we have not worked directly.
4. Although we designed the Tutorial to serve a number of audiences--from beginning modelers to more experienced individuals--we have maintained a primary focus on the technical skills necessary to build STELLA II models. The Tutorial is not designed to provide a significant foundation in the underlying systems thinking (e.g. the centrality of feed-back loops, common dynamic archetypes, or the role of structure in defining system behaviors) or in the pedagogic applications of models. The Tutorial then should be considered a useful component of a larger training program. The form or manner in which those other components can be provided is quite variable and can be molded extensively to fit the specific needs of a given situation.

Basic Features of the Tutorial

The basic design of the Tutorial uses guided construction of STELLA II models through simultaneous use of HYPERCARD 2 (® Apple Computers Inc.) for modeling instruction and navigation through the Tutorial components and STELLA II (® High Performance Systems, Inc.) for the actual construction and manipulation of the simulation models. A window containing an active STELLA II program is typically superimposed over a larger HYPERCARD 2 card that contains the instructional text and the navigation buttons for maneuvering through the Tutorial. A typical screen from the first Chapter of the Tutorial is shown in Fig. 1.

The Tutorial contains two major and one minor components. The first major section is the set of eight Chapters that progressively guide the user through a set of increasingly complex and realistic models, developing progressively more sophisticated modeling skills in the process. Following the sequence of developments in our training workshops, these sequential topics are:

1. Compound (or exponential) growth (Chapters 1-3; most of the major building blocks and tools are introduced in these initial chapters)

(Chapters 3-4)

4. Multi-causality (Chapter 5)
5. Use of "soft" converters (Chapter 6)
6. Use of multiple or dis-aggregated stocks (Chapter 7)
7. Connecting populations to other systems (Chapter 8)

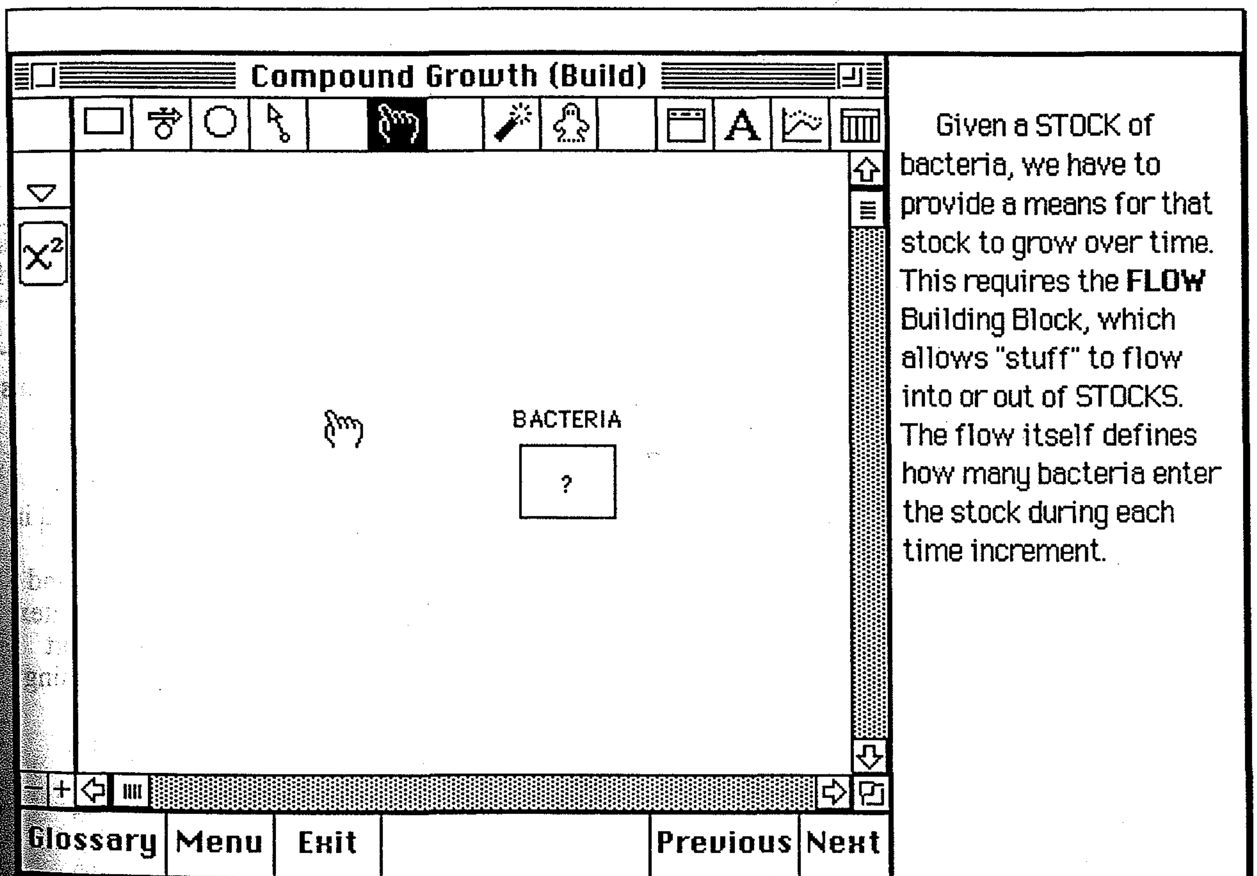

Figure 1: A sample screen from the first Chapter of A STELLA TUTORIAL. Note that the STELLA II window is active (shadowed) and overlies a HYPERCARD 2 card containing text and navigation buttons.

The second major section of the Tutorial is the Glossary that can be inferred from Fig. 1. Since we desired that this Tutorial serve as a basic reference tool for more experienced users (in addition to serving as a coordinated training vehicle for beginning modelers), we designed a reference section or "electronic user's manual" to provide a convenient source of explanation and support for the major components and features of STELLA II. This Glossary can be entered in two ways: use of the Glossary button at the bottom of each instructional card or by clicking on any bold word or phrase in the instructional text. Once in the Glossary, the user will find graphical and prose explanations of these features and often the opportunity to move to the portion of the Tutorial in which that particular feature was initially or most completely explained. When the Glossary has served its purpose, the user can return to the original departure point in the Tutorial by clicking a "Return" button.

Finally, in response to our students' requests to have the resources of the Tutorial available to them while they were building their own models, we have incorporated a simple unit consisting of a blank, untitled STELLA II screen overlying a HYPERCARD card permitting access to the

Glossary and, through the Glossary, to the rest of the Tutorial. In this manner students engaged in building their own models can refer back to the Tutorial lessons, if necessary.

Development of Interdisciplinary System Dynamics-Based Curricula

A final, but ongoing, experiment has been to test our belief that the power of systems thinking and dynamic modeling in an educational setting will be more powerfully developed and demonstrated if entire courses or curricular units are built on this foundation, rather than employing occasional episodic modeling exercises within more traditional curricula. While our efforts have been at the college level, we believe that they are equally appropriate at the pre-college levels.

Plagues and People

In the Spring 1993 semester, we taught a curricular experiment entitled "Plagues and People." The premises behind this experiment were: 1) that epidemics have played a major role in shaping the course of human history; 2) that effective study of such events would require merging the traditional disciplines of history, biology, and economics; and 3) that use of dynamic modeling would provide our students with powerful tools to understand the dynamic interactions of these episodes and to test that understanding by engaging in "what if?" games with the modeled systems. The dynamics of epidemics--where they arise, how they infect, and ultimately, what they do to reshape and redefine human behavior and institutions--dictated that we needed to illuminate the critical intersections between 1) the biological systems of disease and 2) the social factors contributing to the spread of disease and the subsequent impact of epidemic eruptions measured in socio-economic terms.

The governing strategy for teaching the course involved combining 1) classroom lecture and discussion on the principles of systems and diseases and the specific historical and disease context of individual epidemics and 2) computer lab times initially to allow students to develop comfort levels with STELLA II and later for learner-directed exercises in building, modifying, or running existing models.

A fundamental STELLA II model, constructed collaboratively by the instructors and the students, formed the basis for an examination of three major historical epidemics (Fig. 2). Using data culled from historical and current sources, students were able to develop working models which provided impressive discoveries:

A smallpox epidemic struck the Roman legions in the Second Century A.D. as they were returning from a campaign in Egypt and then diverted to fight anew on a reopened Germanic front. Students employed their understanding of smallpox and of the historical record, where a continuous flow of "susceptible" new soldiers were rushed to the front, to construct a STELLA II model which reproduced the resultant series of epidemic episodes. Fascinated by their discovery that disease casualties exceeded actual war deaths, the class chose to further explore the financial ramifications of fighting an unexpectedly expensive war. Using a three-tier STELLA II model of Roman taxpayers, its army, and its treasury, the exhaustion of Marcus Aurelius' reserves and his subsequent decision to feed inflation through the printing of new money provided an economic lesson of more than mere historical curiosity.

An examination of the Fourteenth Century European "Black Death" presented students with a series of new biological lessons, among them 1) a secondary host system, which explains how a disease can remain "lurking" in the background even in the momentary absence of active human infection and 2) the critical role played by immunities, both natural (genetically variable) and acquired, in producing a distinctive series of episodic epidemics, each of gradually diminishing intensity. Insights gleaned here were used to construct models which illustrated how, following the end of the "Black Death," rural populations, suffering from a collapse in food prices attributable to the disproportionate effect of the plague in densely-packed urban settings, subsequently migrated to the cities, in turn, creating conditions for later food shortages and the ultimate demise of the feudal system.

Conscious attention in the earliest stage of the course focused on using our Tutorial as a vehicle for generating student comfort with the basic concepts of systems and the mechanics of using STELLA II. Concomitantly, each lesson in the Tutorial was complemented by a substantive assignment which challenged students to develop an appreciation for the basic biological principles of compound growth, survival curves, r versus K growth, and, most importantly, the limiting factors which alter or control the rates of growth.

The historical evidence, defining four distinct historical epochs of human population growth, provided the context through which to examine how, where, and to what degree humans have succeeded in altering "carrying capacities." Identification of two major "revolutions," agricultural and industrial, accorded students the means to identify how and where "carrying capacities" have been substantially altered, through improved facilities for food production and the capacity of increasing numbers of non-food producers to exercise their labors to improve the quality of life.

Model-building skills progressed by the fourth week to the point where students were building and running disaggregated population models (e.g. Fig. 3), which enabled them to differentiate between current "developed nations" which have undergone a demographic transition and so-called "underdeveloped nations" which are currently experiencing unprecedented population growth.

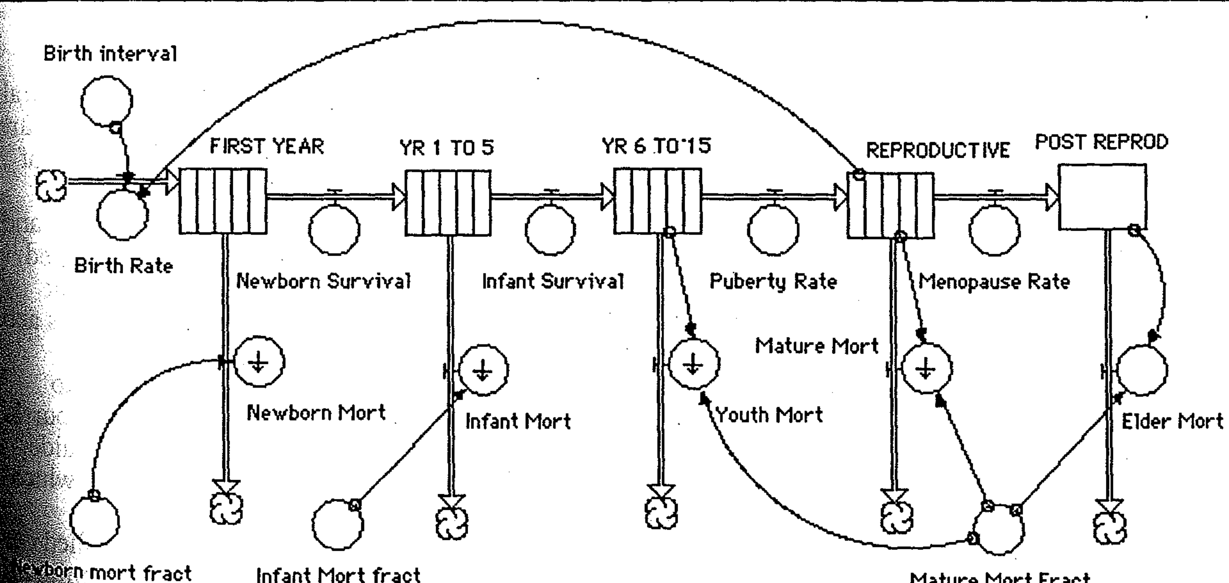

Figure 3: A basic model of the current population of Malawi. Student exercises were to connect this basic model to their perceptions of the Malawian agricultural and industrial systems to explore the mutual controls of these systems on each other and identify and explore policy leverage points.

Once the basics of both simulation modeling and population growth were understood, the class proceeded to examine how the growth of populations and the development of modern agriculture have proceeded in parallel with each factor providing some measure of control over the other. The history of the agricultural system of the United States provided the foundation for those explorations. Subsequently, as agricultural productivity was capable of supporting larger populations and agricultural efficiencies permitted greater proportions of people to leave the farms, urbanization and its accompanying industrialization arose. As with the agricultural revolution, the industrial revolution was closely tied to major changes in demographics. Again the population and the industrial dynamics were mutually dependent on and mutually controlling of each other.

This understanding of the historical interdependence of population, agriculture, and industry in the developed world set up the final class project. The underdeveloped nation of Malawi was selected and students were given demographic, agricultural, and industrial data, with which to define the current dynamics and to formulate a "policy paper" whose intent was to devise realistic strategies for fabricating a sustainable and, for Malawi, improved standard of living.

Feedback from students in this course reinforces our own belief that the topic of population dynamics, developed carefully through sequential model construction, is an excellent vehicle for teaching model building while concomitantly providing a valuable interdisciplinary learning experience around a topic of current import.

Summary

The recent experiences of faculty at Trinity College of Vermont in engaging our students and pre-college educators in the application of system dynamics simulation models have been productive, exciting, and mutually reinforcing. Our initial experiences guided our design of a training protocol for educators who wish to use simulation models within their curricula. This protocol appears to be effective and efficient in meeting its objectives, although other factors at the educators' home institutions will significantly influence the ultimate outcome of that training in regards to student outcomes. Our success in applying the two bases of this training program, a focus on the progressive development of a single central theme, and the use of systems models to cross traditional disciplinary boundaries, stimulated and supported our subsequent experiments.

Responding both to the success of our training approach and to the expressed needs of our students and the educators with whom we have worked, we have developed an interactive Tutorial for supporting the construction of STELLA II models. This Tutorial follows the thematic structure of our training workshops and provides a Glossary feature to inform users of specific features of the modeling software. The resulting Tutorial has not only provided us with the means of accelerating and better supporting our training program, but has provided us with a convenient and time-saving means to get our students to a reasonable level of modeling skills through self-paced and independent work on their parts. This allows us to move much more quickly, and without losing valuable classroom time, from the technical details of modeling to the substantive issues and dynamics of the systems we wish to explore in our college courses.

Finally we have experimented in moving away from our initial episodic use of modeling to support pieces of our individual courses to a much more exciting focus on interdisciplinary courses which are totally dependent on a progressive development and use of simulation models to guide the thinking and learning of our students. We have consciously chosen to focus on courses which cross traditional disciplinary boundaries ("Subsistence Farming," Plagues and People, and Population Growth and the Human Experience). In these courses we have adapted and applied our training philosophy in beginning with a simple basic conceptual core that we subsequently build in complexity. Throughout these courses we have relied extensively on the manipulation and construction of simulation models to support our students' learning and thinking. We firmly believe that, in this latter aspect of our experimentation, we have found an extremely powerful tool for effective and far-reaching teaching and learning. We advocate further explorations of this approach to address education's frequently stated need to engage our students in critical, interdisciplinary, and self-directed learning.

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