System Dynamics Models Created by High School Students

Diana M. Fisher

School:	Franklin High School 5405 SE Woodward St. Portland, Oregon USA 97206 (503) 916-5140
Home:	7405 SW Cresmoor Dr. Beaverton, Oregon USA 97008
Internet Address:	dfisher@pps.k12.or.us, dmfisher@jps.net

For the past nine years a system dynamics modeling course has been taught at Franklin High School in Portland, Oregon. Two years later a formal systems modeling course was taught at Wilson High School in Portland. Three years after that a systems modeling course was taught at LaSalle High School in Portland. Each of these schools currently has a two year program offered, with Franklin offering a third year course for the first time next year. A significant subset of high school students in these three schools have indicated such a strong interest in learning to create system models that these courses continue to grow and the curriculum expands. In each of these high schools systems modeling has also made inroads into the regular curriculum of mathematics, physics, social studies, biology, physical science, environmental science, and even religion classes. High Schools in Beaverton, Oregon, Vancouver, Washington, Roseberg, Oregon, Fairbanks Alaska, and McAlister, Oklahoma are a few other locations that have system dynamics modeling evolving in their curriculum.

What is even more apparent, as teachers at these schools communicate with each other, is that high school students can create models addressing significant issues, have the skill to create such models correctly, and can explain their work in such a way that it is readily apparent that they know about which they speak. Student papers have been read by people both within and outside the education community. The Sym*Bowl[1] systems modeling competition for high school students, now in its fifth year, selects six judges annually to read some of these papers and query the students on their models. Of the six judges, three are professional modelers and three are teachers. Barry Richmond, president of High Performance Systems, was a judge during year four and year five. He commented last year:

> *I was in awe of the breadth of topics the students had taken on and of the originality and ingenuity they showed in pursuing their diversely chosen arenas of study. I developed a tremendous respect for the general quality of thought, insight generated, and clarity of expression evidenced in the work, as well as for the sheer magnitude of effort that must have been put forth by most teams. Finally, I experienced a deep sense of joy for the flexing of intellectual muscles, and the soaring of intellectual spirit these students were demonstrating. This work was EXACTLY the reason STELLA was created--to give people the freedom to think in a more rigorous way about whatever it was they wanted to think about!*

With this said, the quality of student models has been an evolutionary process. Early models exhibited some raw mistakes in concept and execution. Each year the models improve. A significant part of this improvement has to do with the fact that the teachers are learning more

[1]Sym*Bowl was the creation of Dr. Ed Gallaher, research pharmacologist at Oregon Health Sciences University in Portland, Oregon. Dr. Gallaher uses system dynamics modeling in his drug research and when he instructs medical students. He is an enthusiastic advocate of systems modeling at the high school level.

about what constitutes good modeling practice and what qualities a good model must exhibit. Dr. George Richardson[2] has made a significant impact on many of these teachers. He has taken time to give them formal instruction on several occasions, after which the teachers collectively felt their ability to analyze and design correct system models improve substantially. His work is evidenced by the improvement made in the character and structure of the models their students have subsequently produced.

What follows are a couple of examples of models that exhibit some serious mistakes that were made in the early years of the modeling classes and a larger set of good models that are more recent products of the modeling classes. The mistakes are presented in deference to Professor Jay Forrester, who feels people learn a significant amount by viewing the mistakes of others. The examples of good models are presented to show the quality of model that students can produce.

Housing Availability Model: This model was an attempt to capture the land constraint on a growing population in a city. The students located the data identifying the current available land, zoned for residential property, in Portland, Oregon. They determined Portland's current population and net growth rate. They wanted to determine how long there would be space available to build houses for this growing population. More than one mistake is apparent in this model but the one that merits its inclusion is the trigger mechanism.

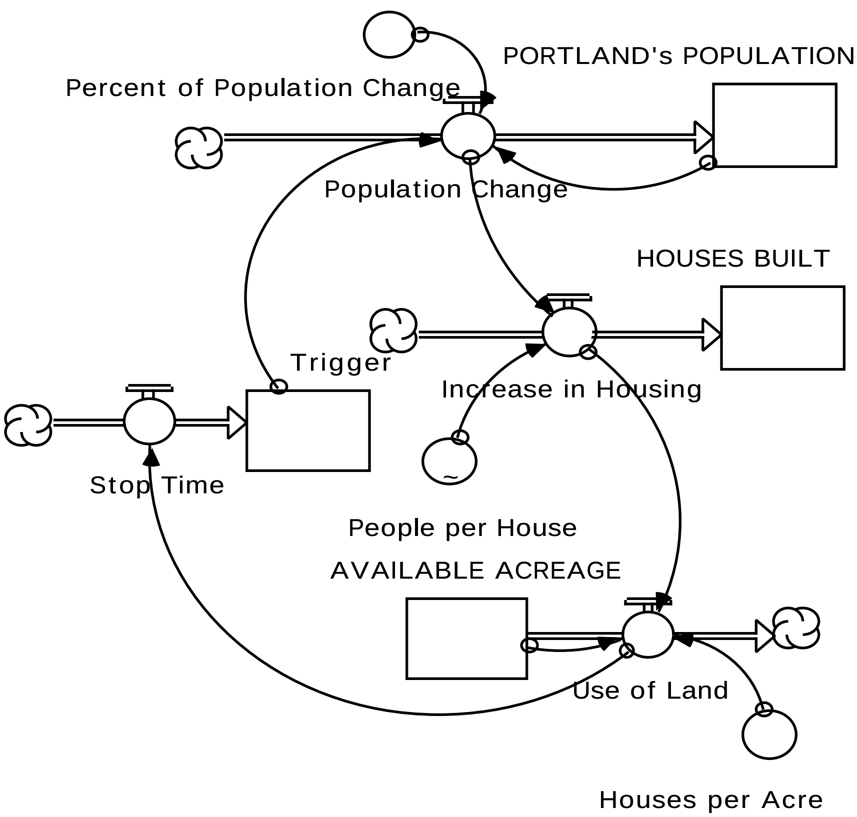

Figure 1: Housing Availability in Portland, Oregon

The students wanted the population to stop growing when there was no longer space available to build houses for these people. The implementation of this concept in the model was to

[2]Dr. George Richardson is a professor of public administration, public policy, and information science, at the Nelson Rockefeller College of Public Affairs and Policy at the State University of New York at Albany.

immediately turn off the population growth as soon as all land was consumed. Dr. George Richardson took one look at the graph and circled the sharp transition points in each curve. He said the real world almost never transitions in sharp curves.   He then took the teachers through the classic urban growth model and introduced "multiplier" or "effect ..." factors and how to model transitions using a flexible influence graphical component.   It was an important lesson, one translated to all second year modeling courses and to those more advanced lessons for the accelerated students in first year of modeling.

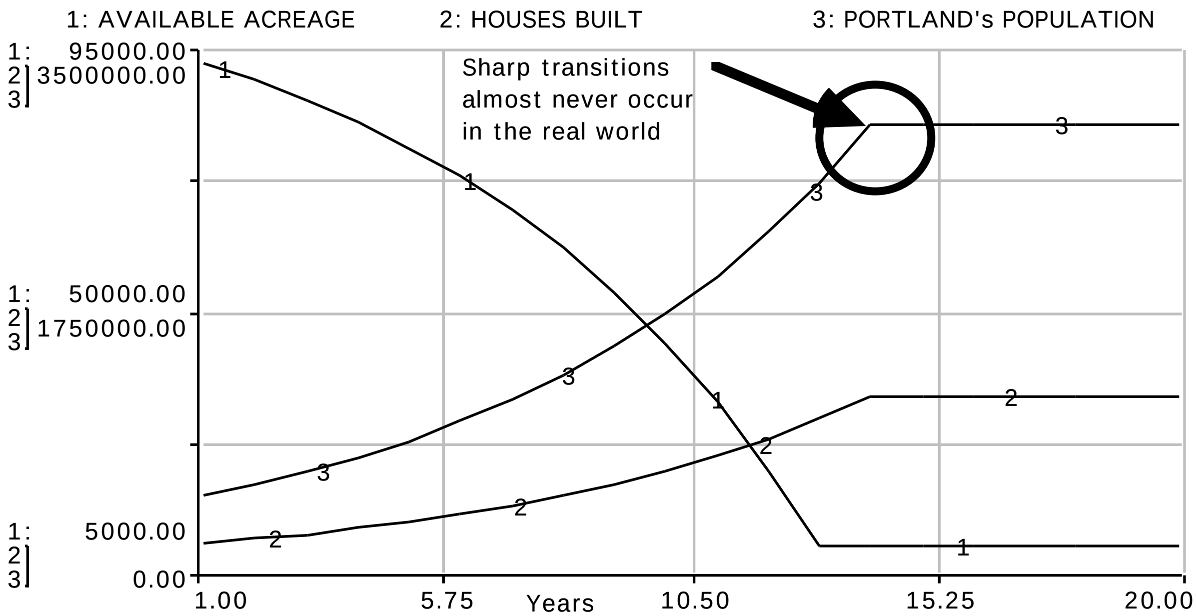

Figure 2: Graph of Housing Availability, Land Availability, Population Growth in Portland, OR.

Earth's Orbit Around the Sun Model: Another model, predating the previous example, attempted to replicate the behavior of the elliptical pattern of the orbit of the earth around the sun.   The mistake in this model is not apparent from the diagram structure. As a matter of fact, it was the students' conviction that the model must be designed correctly since the diagram made sense. The graph of the path, however, was consistently linear. The students rechecked the numeric values. They could not find the error. Finally, the question about dimensional consistency was raised. The students had placed a value in the "G" converter to represent the universal constant in the equation for the gravitational force between two objects. As is often the case, the students found the formula in a book and used the number without regard to the units involved. When all values were recalculated, with attention to dimensional consistency, the correct shape for the path was displayed by this model. Although the instructors had been reminding students about dimensional consistency, it soon became an obsession passed from teacher to student every year, in every class.

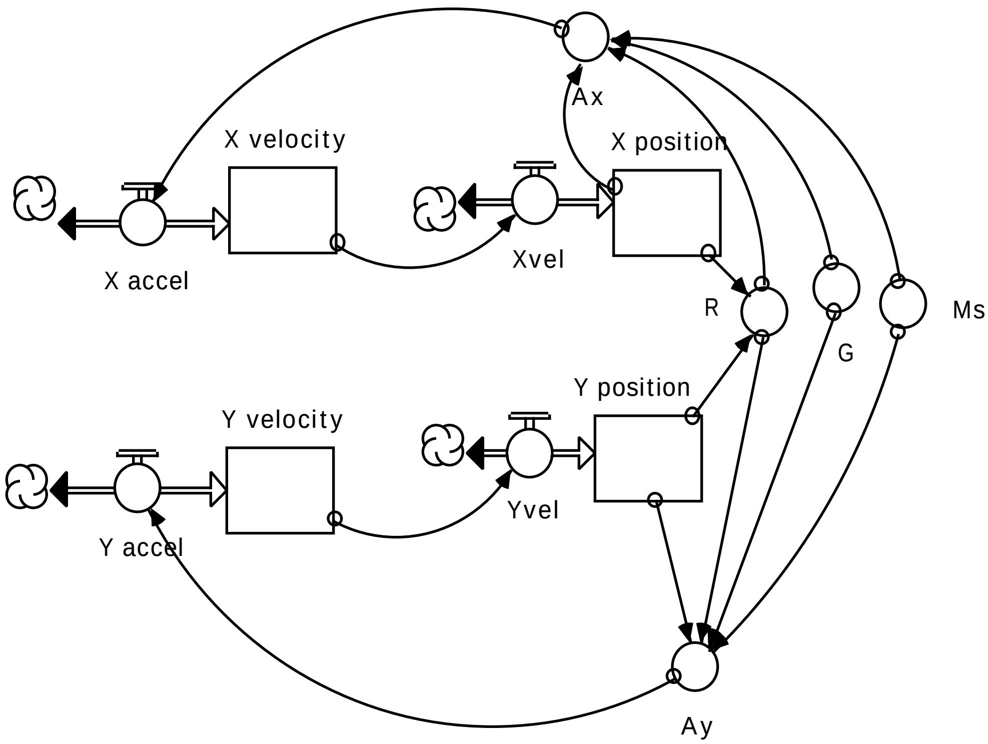

Figure 3: Orbit of the Earth Around the Sun

Time of Death Model: The model below won first place in the first Sym*Bowl competition in 1996. The students who created this model had taken the forensic science course offered at Franklin High School and wanted to know more about how coroners determine the time of death. There were two main reasons this model was worthy of distinction The first was the model's structure. Core structures exhibiting classical behavior patterns over time are central to the instruction in the modeling courses. The students knew that the behavior should be convergent and started with a structure that would produce such a behavior. After conversing with a local coroner they learned that there were over a dozen factors that are considered in determining the time of death of a corpse. The students knew they could not include all the factors, so settled on three that made sense to them and that they thought they understood well enough to include in the model. The factors included were ambient temperature, the weight of the body, and whether the person wore dry clothing, wet clothing, or no clothing at the time of death. Including the ambient temperature was not difficult, since it represented the target value to which the body temperature converged. The decrease in body temperature was inversely proportional to the body weight. But, how to determine the clothing factor? The second reason this model was given recognition was the fact that the students conducted a simple experiment to determine the clothing factor value. They took three empty milk jugs and filled them each with water of about 98 degrees Fahrenheit. Around one jug they placed a dry towel, around the second a wet towel, and around the third, no towel. Then they recorded the decrease in temperature of the water in each jug every fifteen minutes for three hours. From this they determined a clothing fraction to associate with each clothing scenario.

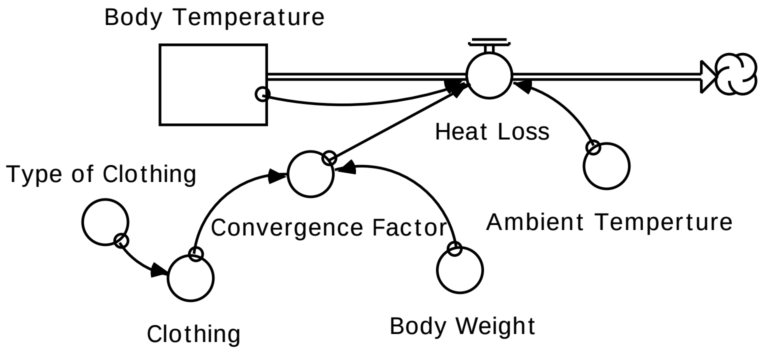

Figure 4: Determining the time of death of a corpse

Consumption of Alcohol Model: Although the following model was not created early enough in the school year to be included in the Sym*Bowl competition, the students did excellent research and created a model which, according to Dr. Ed Gallaher, models the pharmacokinetics of alcohol absorption and metabolism very well. Dr. Gallaher was the professional the students consulted when they could not understand some of the formulas they encountered in their research. Many scenarios involving the pharmacokinetics of alcohol can be tested using the model. The amount and type of alcohol consumed can be altered. Particularly, the difference between consuming alcohol that is carbonated, like beer, or concentrated, like whiskey, or both carbonated and concentrated, like champagne can be studied. Whether the drinker is male or female, a moderate drinker or an alcoholic, a large person or a small person can be regulated. Any combination of the previous factors can be considered. When Dr. John Sterman[3] first observed this model diagram he identified an important feedback that could be added between the blood alcohol concentration (BAC) and the alcohol consumed. This was not included by the students at the time, because they never thought of that feedback. The teacher, however, did not forget the observation, and used it as an example of "soft" feedback for students to consider.

In addition to the factors mentioned above students wanted to weigh the relative importance of each factor in determining how long a person needed to wait, after consuming a certain amount and type of alcohol, before their BAC was below the legal limit for driving. It was quite surprising to the students the length of time it took the BAC to decline, and that the decline was largely linear rather than exponential.

[3]Dr. Sterman is director of the Sloan School of Management at Massachusetts Institute of Technology and first saw this student model diagram at the International System Dynamics Conference in Cambridge, Massachusetts in 1996.

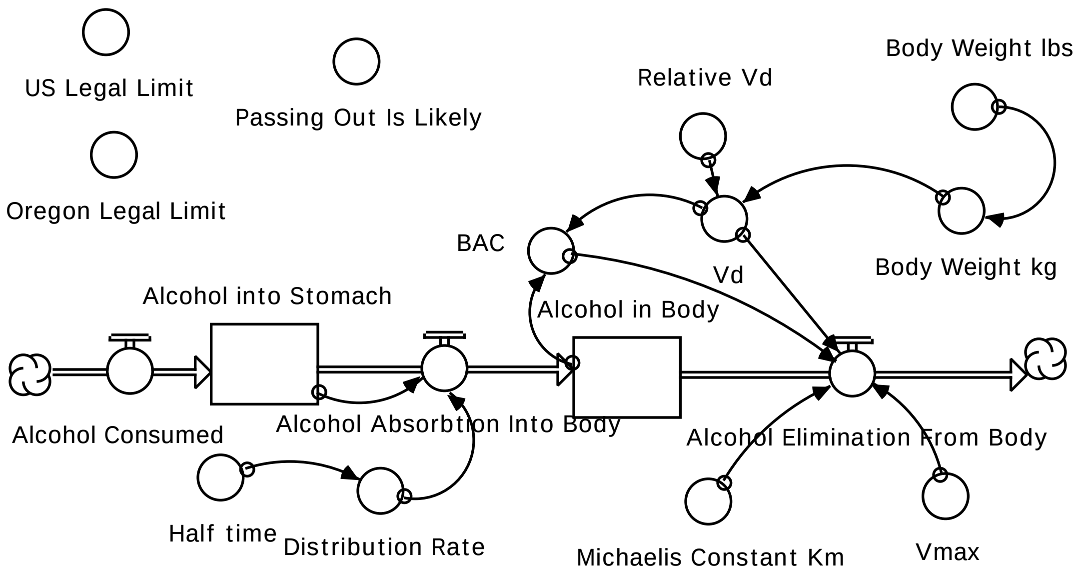

Figure 5: Pharmacokinetics of Alcohol Consumption

The following graph shows the blood alcohol concentration for a 125 pound (56.8 kg) male drinking six twelve ounce beers over a two hour period. You will notice that upon cessation of drinking the BAC level still rises, since it takes time for the final amount of alcohol to be absorbed into the rest of the body. Notice also that the elimination is primarily linear, as should be the case. Alcohol is a weak drug taken in relatively large quantity. Consequently, the drug receptors work at maximum capacity during most of the time the drug is in the system. The BAC level becomes exponential when it is at a relatively low level. Although that characteristic is not displayed in this graph, it does function correctly in this model.

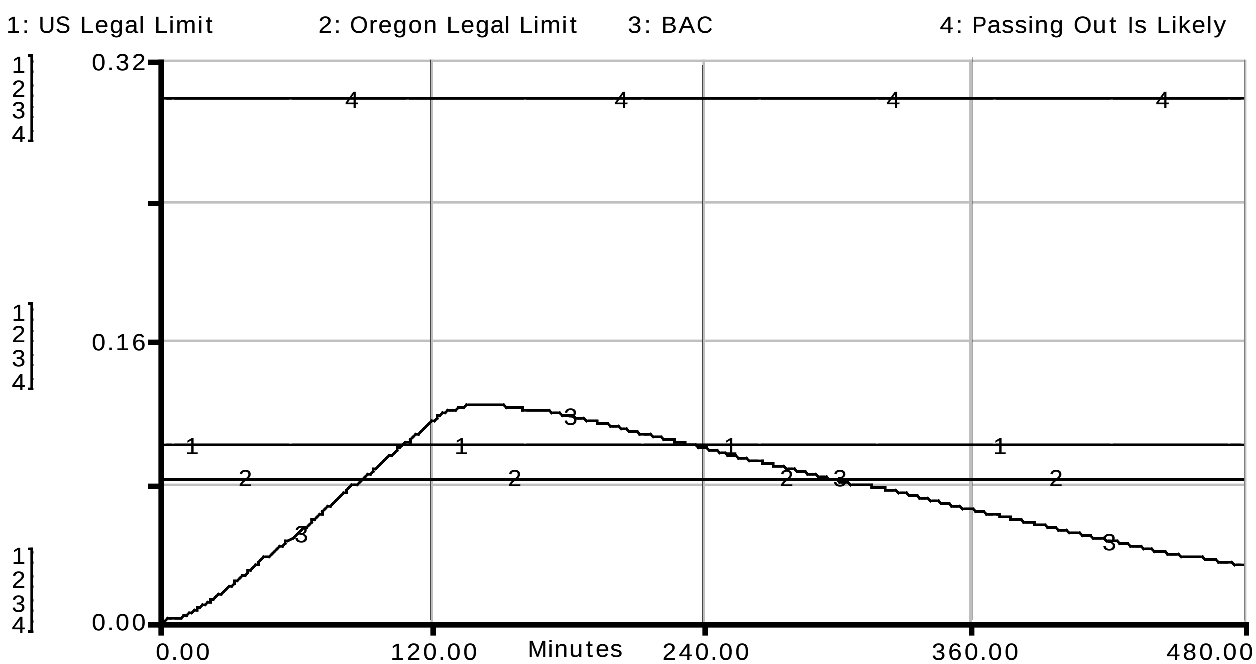

Figure 6: Blood alcohol level for a 125 pound male drinking six 12-ounce beers in two hours.

Tree Harvesting Model: The model below won first place in Sym*Bowl in 1999. It is a simple population model, differentiating the age of the trees that would be harvested in Oregon. The students were interested in whether the current manual regeneration policies followed by the logging companies would produce sustainable forests in Oregon. Their model indicated the current practices would not sustain the forests. The students' scenario only considered harvesting trees via clear-cutting. Most of the data regarding replanting was obtained from a senior forestry management student at Oregon State University. He said that the replanting rate is designed to provide sustainability when considering the full range of harvesting practices currently in place in Oregon.

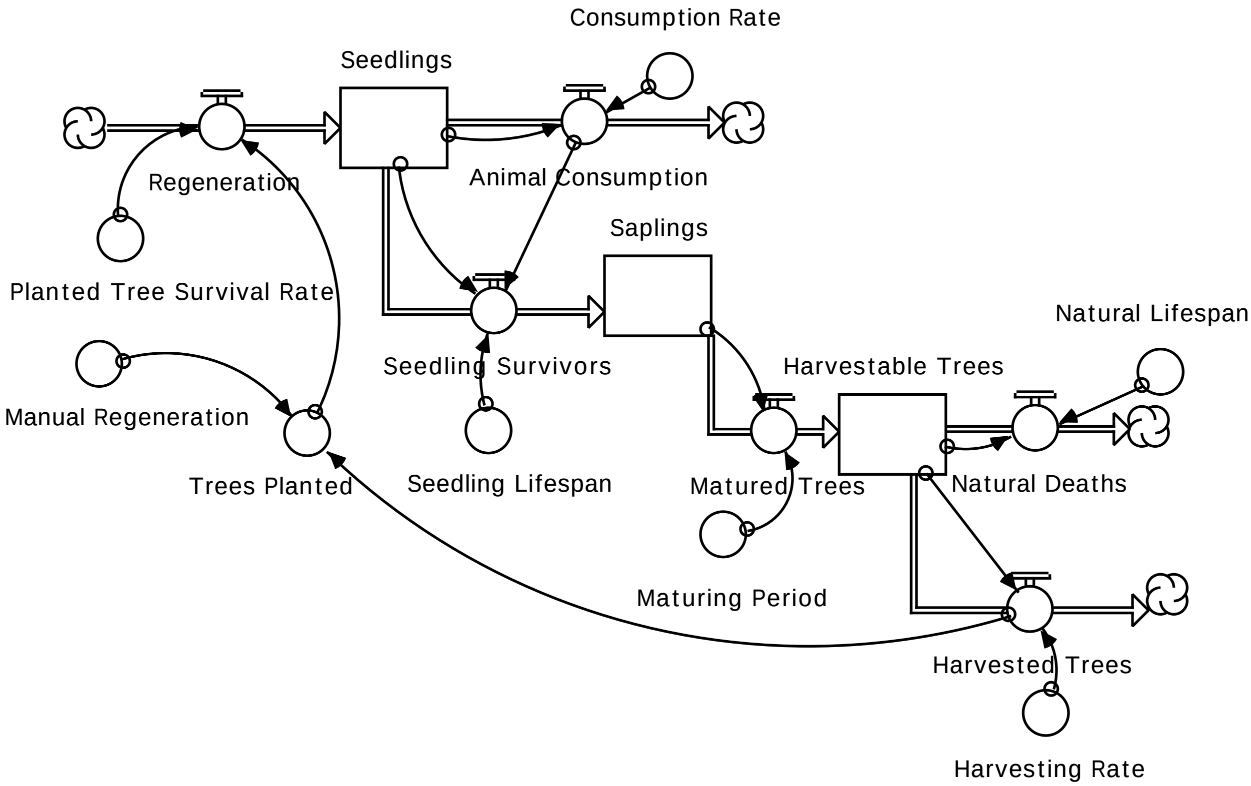

Figure 7: Testing Policies for Sustainability

The students anticipated three leverage points in the model. The first was obvious, the harvesting rate. The second was the manual regeneration rate. The students found that even doubling the manual regeneration rate did not appreciably change the sustainability of the forests considered. Very few of the replanted tree survive, especially in a clear-cut region. The third leverage point considered was the animal consumption of the seedlings. This produced the major surprise in the exercise of this model. The students were told that about 25 percent of the seedlings are lost to animal consumption each year. On government land almost nothing is done to protect the seedlings. On private land where logging is allowed significant effort is made to protect the seedlings. Those efforts include placing cones around the seedlings, placing salt-licks in the region for the animals, planting shrubs around the seedlings to deflect consumption of the seedlings. Altering the consumption by animals as little as 10 percent produced dramatic results. This was a surprise to everyone and certainly a basis for policy change in forestry management.

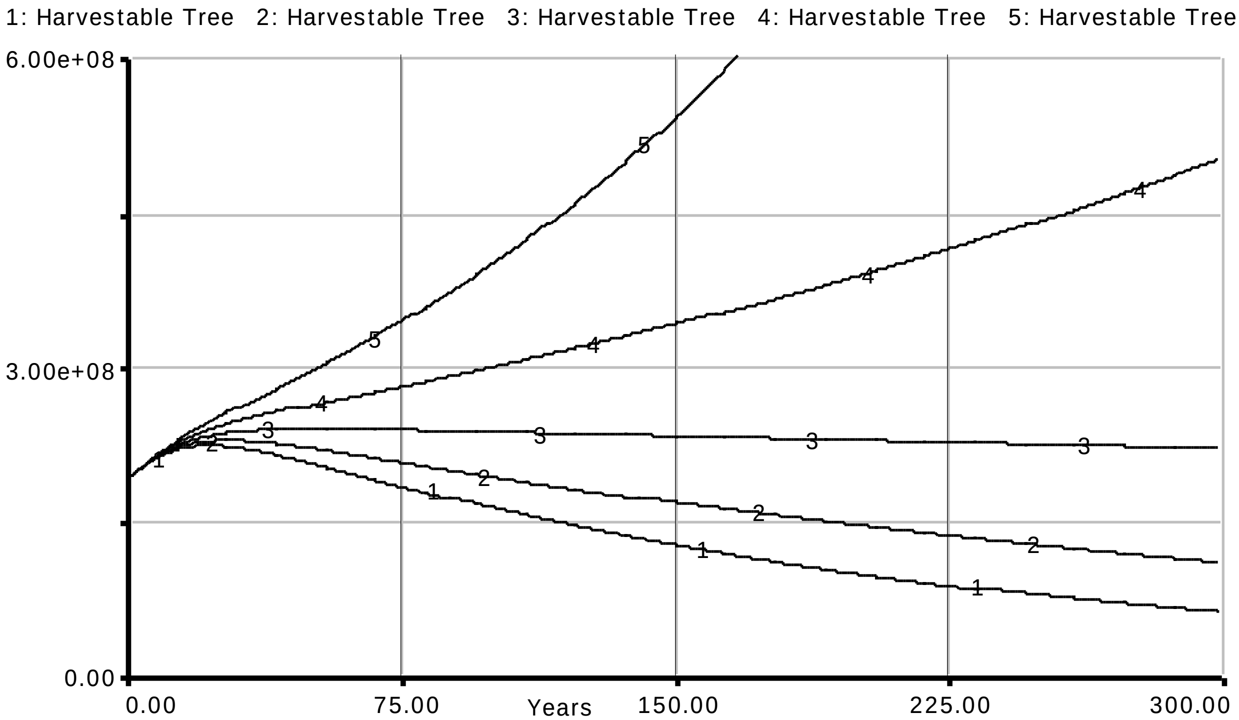

Figure 8: Changing consumption rate: graph 1 = 0.25, graph 2 = 0.20, graph 3 = 0.15, graph 4 = 0.10, graph 5 = 0.05

The paper these three students wrote for this model was featured in the first fall issue 1999 of the Creative Learning Exchange. The paper demonstrates not only an understanding of how the model functions but that students can communicate, to a diverse audience, the most important lessons learned from creating such a model.

Cocaine Addiction Model: The study of simple drug pharmacokinetics is part of the regular curriculum for the first year modeling course at Franklin High School in Portland, Oregon. This is primarily due to the interest and support Dr. Ed Gallaher has demonstrated in pre-college education in the Portland region. He served as the main reference person for the student who created the following model on cocaine addiction. The student was stimulated to learn about the physical process of addiction because a person in her family was addicted to cocaine. Dr. Gallaher, consistent with his belief that it is important for a student to test many scenarios before he/she can understand why a particular behavior pattern occurs, had this student do dozens of trials with simple models over a period of about two weeks before zeroing in on the specific characteristics of cocaine addiction. The partnership made a lasting impression on this student.

The model demonstrates how dopamine, which is naturally released by the cells in the human brain, normally is reabsorbed shortly after release. The model has the dopamine released at regular intervals, and reabsorbed according to a rate 'Ku,' representing the fraction of dopamine outside the cell that will be taken back into the cell each time unit. This 'Ku' fraction depends upon how many drug transporters are available for the "uptake." Cocaine interferes with the reabsorption schedule of the dopamine. The affinity (stickyness) of the cocaine to the drug transporters causes fewer transporters to be available for dopamine reabsorption. When the dopamine is outside the cell it reacts with dopamine receptors. The extended time the dopamine is outside the cell causes the "high" sensation from using cocaine. The problem is that when dopamine is outside the cell for an extended period of time the dopamine receptors begin to break down. In the introduction of the paper the student explains,

"...My model shows how cocaine alters the amount of dopamine that is released to the synapse, and how long that dopamine is there. I am using my model to demonstrate an idea, or how a system works, and not to produce accurate data. The "high" a person experiences when using cocaine, is not the brain acting on the cocaine itself, but acting or responding to the amount of dopamine that is in the synapse. When dopamine is in the synapse, receptors respond to it. When dopamine is left in the synapse at a greater amount for a longer amount of time, the number of drug receptors breaks down, resulting in fewer receptors to act on the dopamine. As a result, more cocaine is needed to create the same sensation as before. When more cocaine is used more drug receptors break down, reducing the amount that responds to the dopamine in the synapse, and more cocaine is needed the next time to receive the same sensation."

This model tied for first in design, execution, and (paper) explanation of how the model works. Unfortunately, the presentation portion of the competition was very stressful for this student and she finished third in the overall Sym*Bowl competition in 1997. The model is presented here as a recognition of the quality of her work.

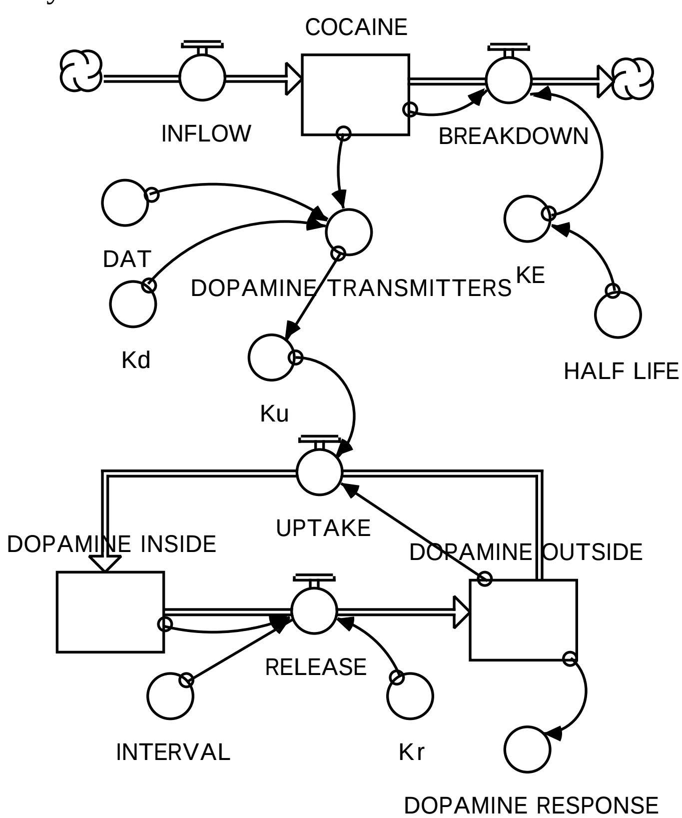

Figure 9: Cocaine Addiction Model

China Demographics Model: The final model presented won the Sym*Bowl competition in 1998. This student was very interested in China's one-baby policy and wanted to determine the ramifications of such a policy over time. He did extensive research, writing for and receiving original data documents from the Chinese government. The elegance of the approach this student used is one of the reasons this model was saved for last. The student started with a very simple population model, shown in figure 10.

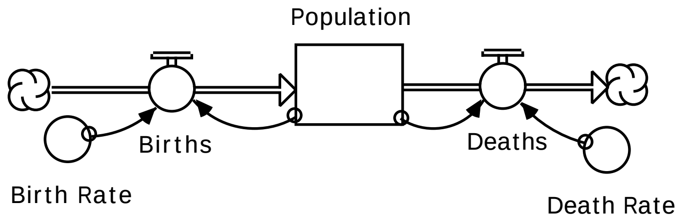

Figure 10: First stage China population model

With this simple model the student tested different initial populations for China, starting each at the beginning of a specific decade and using associated birth and death rates for that time period. He projected each population to the year 2050. He noticed that each simulation run produced a very different final population and that if he started with the year 1960 the projected population actually decreased, rather than increased. (He explained the possible reason for this using historical context.) He decided almost immediately that he needed more detail in the model.

The initial simulation time for the second model was set to 1980 because the one-baby per family policy was introduced by the Chinese government in 1979. The population was separated into male and female compartments, since a shortage of females was projected as a result of this policy. The second stage model is shown in figure 11.

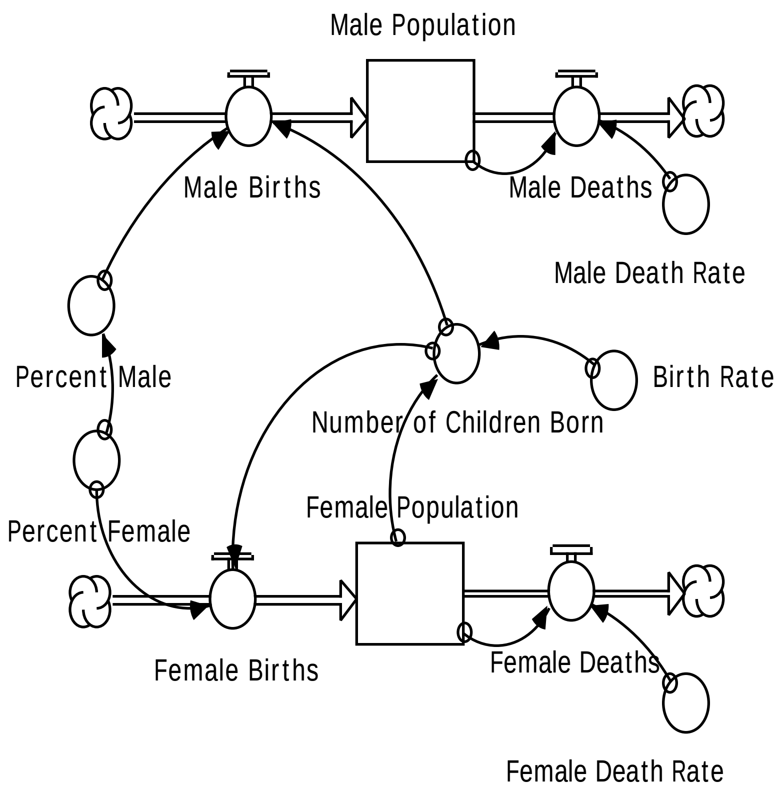

Figure 11: Second stage China population model

This model was an improvement. The male and female population projections to the year 2080 showed an ever widening spread and the total population did not grow as quickly as in the aggregated population model (figure 10). However, the second model did not produce results consistent with real data this student obtained from the Population Information and Research Center in Beijing. He felt that, to obtain the necessary results, he had to create a model which included age distribution. He wanted to include infants separately, since they have an especially high death rate. He also surmised that "small differences in the infant mortality rate of females [could] have powerful effects in later years."

Two segments of his final model are shown in figures 12 and 13. The first model segment contains a high level view of the male population. An identical segment for the female population exists in the actual model but is not included here.
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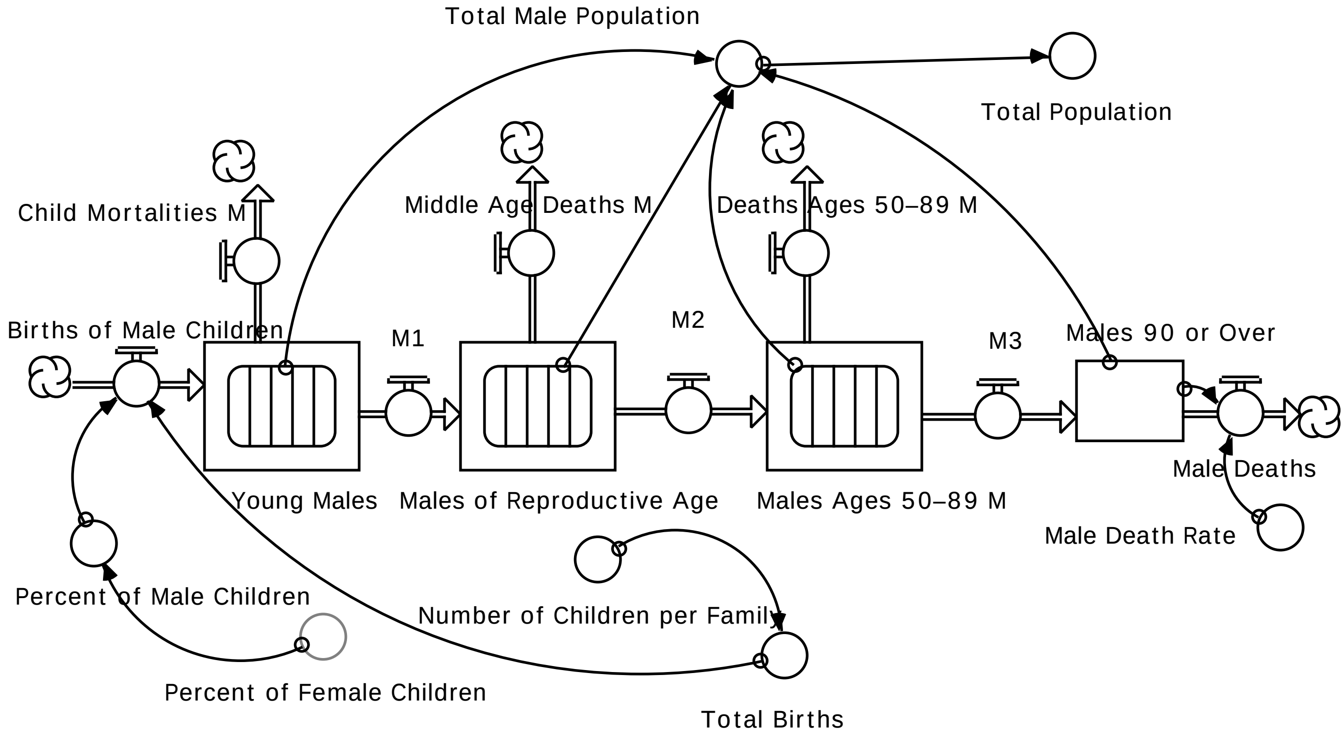

Figure 12: The Male Population Segment of the China Demographics Model

To maintain a simple view for the reader, yet include the detail he wanted regarding age group death rates and maturation, he created submodels for each aggregated population group in the top level. One example of such a sub-model diagram is shown in figure 13.

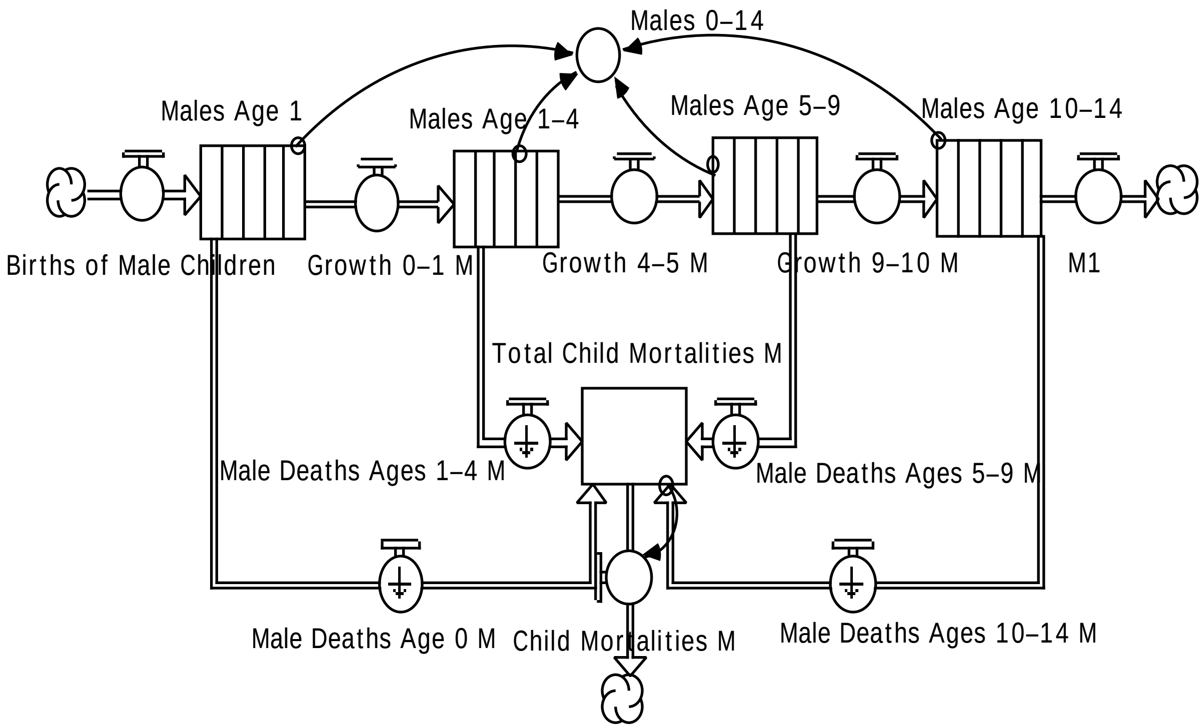

Figure 13: Submodel under the Young Males Segment of the Male Population Model shown in figure 12.

Finally, a graph displaying the results of the simulation from the year 1990 to the year 2090 is included below.

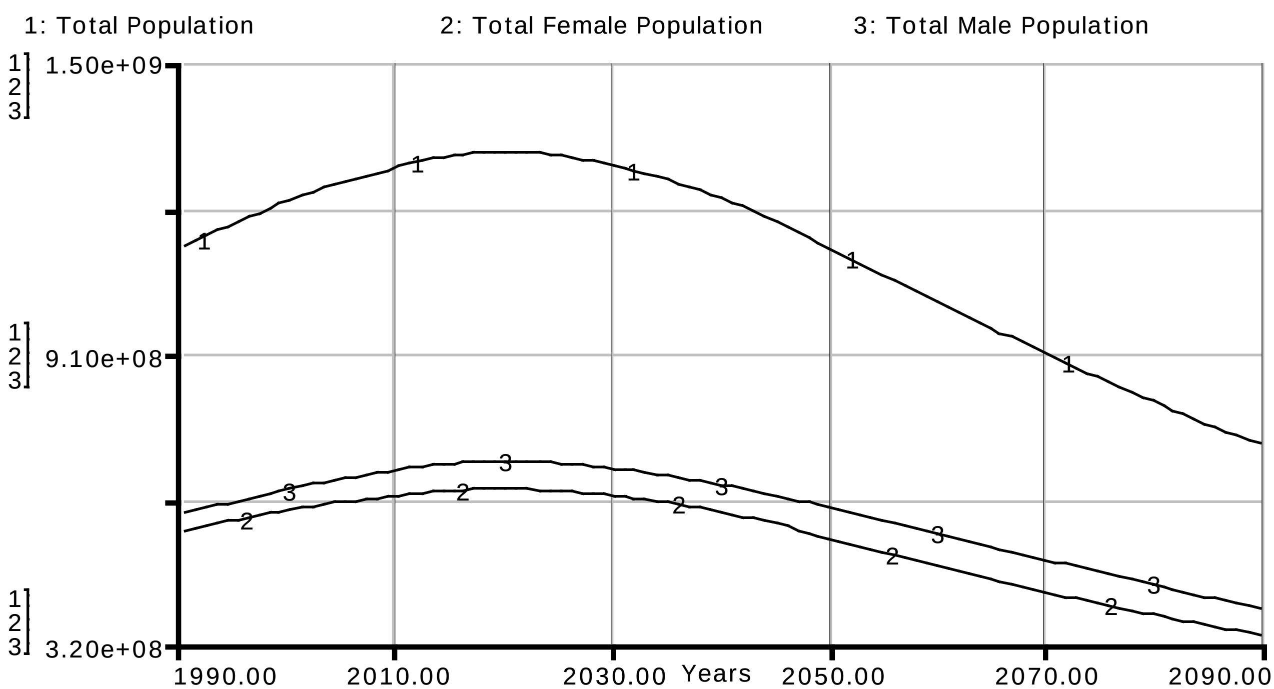

Figure 14: Projection of male, female, and total China population from 1990 to 2090

The design of the three models to study the one-baby per family policy in China, with the explanation for why each of the first two were insufficient, the extensive research, the validation, and the exceptional paper produced marked this effort as probably the best model presented in the first four years of the Sym*Bowl competition.

The examples in this paper represent a few of the best models students have produced in the past five or six years. Not all students produce models of high quality, but all produce models that increase, significantly, their understanding of the problem they were trying to model.

It is hoped that the examples included in this paper demonstrate that high school students can conceptualize and design models dealing with significant issues. Over three-fourths of the models presented here were developed by girls. What is not illustrated in this paper, but is even more powerful evidence, that the students understand what they have modeled and the results of the models, are the student papers. Sym*Bowl organizers have, for the past three years, collected the papers for all the competing teams and given a copy to each participating school. In 1999, for the first time, many of the competition models and papers were made available on CD.

We have found that our students are the best spokespersons for systems thinking and dynamic modeling. Listening to the students will convince even the most steadfast skeptic that high school student CAN understand this level of analysis.