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System Dynamics in K-12 Curriculum: An Experimental Course Prototype

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By

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1: System Dynamics
2: K-12 education
3: teaching

Abstract

This is the design, implementation, and analysis of a complete System Dynamics course taught at Massachusetts Academy of Mathematics and Science. This document contains the result of this high school level course that can be used by teachers and researchers to study the impact of System Dynamics on learning in K-12 education. The complete course materials are provided, and can be used as a basis of a future System Dynamics course.

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1 INTRODUCTION

Despite its potential to shed light on basic principles that underlie mathematics, physical science, social studies, biology, history, and even literature, system dynamics has not yet received the recognition and incorporation into basic educational systems that it deserves. [1] In general, the subject is still taught on the postgraduate level. Only the Worcester Polytechnic Institute (WPI) offers an undergraduate major in this discipline.

A small but growing number of educators at the elementary and secondary school level are, however, beginning to recognize the fundamental usefulness of this discipline as a way to understand the world. Although knowledge of calculus and higher mathematics will provide a deeper understanding of system dynamics, students of all levels can understand the concepts and methods of system dynamics and put them to use. More experienced students can create and conduct sophisticated inquiries and experiments using system dynamics software. A number of pioneering educators from hundreds of primary and secondary schools are experimenting with ways to incorporate system dynamics into the kindergarten through grade twelve (K-12) curriculums.[2] The Massachusetts Academy of Mathematics and Science, a secondary school affiliated with WPI, is the site of one such experiment.

This project, System Dynamics in the K-12 Curriculum: An Experimental Course Prototype, came about because of an urgent need to develop and implement a high school level system dynamics course at the Mass Academy. James Barys, the mathematics instructor at the Academy, received the assignment to prepare the first elective course in system dynamics, to be taught in January and February of 2002. Due to scheduling conflicts this course was moved up to

[1] Forrester, Jay W., 1992. System Dynamics and Learner-Centered-Learning in Kindergarten through 12th Grade Education. http://sysdyn.mit.edu/sdep/Roadmaps/RM1/D-4337.pdf

September of 2001. Although Mr. Barys had been interested in system dynamics for a few years, he was not yet fully prepared to design and teach the course at that time, so he decided to find a WPI student to assist him. On September 10, 2001 Professor Khalid Saeed, head of Worcester Polytechnic Institute's Social Science and Policy Studies Department (SSPS) announced the opportunity to the System Dynamics majors. Since I had helped seed the project over a year earlier, I expressed my enthusiasm in participating in this project. Three days later I began to teach at Mass Academy.

This document introduces the reader to the subject of system dynamics and the method, experiment, and outcome of a prototype high school curriculum in system dynamics designed and implemented at the Massachusetts Academy of Mathematics and Science.

This project was a preliminary study. Its original goal included design, implementation, and evaluation of teaching material. However, as most of the time was spent on developing and implementing of the material, less time than anticipated was actually available to evaluate the teaching material. Nevertheless, the process used to formally evaluate student progress could be applied to designing future studies.

The intended audiences of this report includes teachers with an interest in teaching system dynamics, high school curriculum developers, researchers and sociologists interested in the impact of system dynamics on education, and future WPI students interested in continuing system dynamics in education project.

The main body of this report describes the experiment and an analysis of data. Appendix 1 provides a detailed journal that describes how the class was conducted and what material was

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[2] Sterman, Business Dynamics (vii)

used. Appendices 2 through 9 contain copies of readings and assignments used in the class. The rest of the appendices contain a collection of student coursework.

1.1 What is System Dynamics?

System dynamics is an emerging discipline that uses conceptual and analytical tools to help people understand large, complex (and seemingly chaotic) systems. The conceptual tools allow better recognition and investigation of systems, while the analytical tools apply rigorous application of mathematical concepts that enable one to create models and computer simulations of the systems.

Since mathematics is non-discipline-constrained, any relationship -- economic, historical, natural, or social -- can be represented formally in a system dynamics model. Although the models almost always involve such complexity and nonlinearity that no analytical solutions exist, the structures and behaviors of these models can be understood by anyone with knowledge of basic algebra.

These models are used to facilitate understanding of systems and system behaviors across multiple disciplines. These models and simulations, in turn, make it possible to conduct virtual experiments to design more effective policies and structures for the systems in question.

1.2 The Massachusetts Academy of Mathematics and Science (Mass Academy)

Mass Academy, a partnership between the public high school system of Massachusetts and WPI, has a mission to nurture the math and science talents of eleventh and twelfth grade students. Students apply to the program while they are in the tenth grade; admission is competitive.

Eleventh grade students take a full-day program of courses taught by Academy faculty. Qualified twelfth-graders take college courses at WPI, and earn college credits.[3]

1.3 System dynamics at Worcester Polytechnic Institute (WPI)

System dynamics is offered as part of other subject areas and courses, both at graduate and undergraduate levels in many universities. WPI was able to offer System Dynamics as a distinct undergraduate major because the department collected a critical mass of faculty and the university favored trying new curriculum ideas.[4] WPI remains the only school that offers a major in system dynamics on the undergraduate level. The major is offered by the Social Science and Policy Studies department (SSPS).

1.4 System dynamics for K-12 elsewhere

Despite willingness to proceed with system dynamics programs at a number of schools, most teachers are not formally trained in system dynamics. Fortunately, there is a good amount of material available to help understand this discipline. This section will discuss what's available to facilitate the incorporation of system dynamics in K-12 education -- primarily the MIT System Dynamics in Education Project and the Creative Learning Exchange.

Although these materials are designated for K-12, they are appropriate for anyone who wants to learn more about system dynamics. It does take time, however, to learn to apply the material.

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[3] Based on material from www.massacademy.org

[4] Professor and WPI SSPS department head Khalid Saeed's observation.

1.4.1 System Dynamics in Education Project

http://web.mit.edu/sdg/www/educproject.html

One of the principle sources of information is the Massachusetts Institute of Technology. MIT has a System Dynamics in Education Project (SDEP) founded in 1990. The project's primary focus is to advance the use of system dynamics and learner-centered education. The group is working under the supervision of Prof. Jay W. Forrester, founder of system dynamics.

SDEP created "Road Maps," a guide to learning system dynamics. Road Maps uses various modeling exercises and a wonderful collection of literature to provide a simple and easily understandable way for learning the methods and principles of system dynamics.[5] Road Maps provides examples intended for use in a wide range of educational settings. Material from Road Maps can be reproduced for non-commercial education purposes. Road Maps can be accessed at http://web.mit.edu/sdg/www/roadmaps.html.

Another resource available from MIT is the K-12 system dynamics email list. It is run by Nan Lux, the SDEP project advisor. The email list serves as a discussion group where people can share their insights on using system dynamics and system thinking in K-12 education. More information on the discussion list is available at this URL: http://web.mit.edu/sdg/www/k-12email.html Look for the link to the archived pages on the bottom of this page. The email archive contains multiple years of discussion, dating back to 1996.

Jay Forrester also supervised the creation and editing of a set of videotapes that document his system dynamics classes with doctoral students. This set of videotapes, called "System Dynamics Seminar with Jay Forrester" is an excellent introduction to system dynamics.

1.4.2 Creative Learning Exchange

http://www.clexchange.org

The Creative Learning Exchange (CLE) is an organization that facilitates systems education. CLE provides systems dynamics teaching material to educators at cost (this includes the material prepared by SDEP). Their web site states:

"The Creative Learning Exchange encourages a view of education for primary and secondary schools based on discovery as the essence of the learning process and advocates systems education implemented through learner-centered learning.

The CLE facilitates communication among teachers and schools to help create a network of schools using systems education. It solicits teaching materials and ideas from participating teachers. The CLE will make such materials available at cost to educators. Some of the currently available materials include:

Processes for introducing systems education and learner-centered learning; Models and lesson plans from both beginners and more experienced teachers; Videotapes of teaching materials, educational approaches, and community implementation; A quarterly newsletter with feature articles and updates from participating school systems.

CLE also hosts a biennial conference on systems thinking and dynamic modeling.

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[5] Based on material from http://sysdyn.mit.edu/sdep.html

Of ongoing interest and study at the CLE is the introduction of systems education in schools. Using the concepts of system dynamics to learn about the process of education in this country, the CLE can apply the knowledge gained to school systems to further systems education."

Besides having a diverse set of papers relevant to system dynamics in education, back copies of their newsletter and a set of links to other resources, CLE's web site also contains the following things that help a person learn system dynamics modeling. One page is called "Modeling Systems Self-Taught (MSST) and Demo Dozen." http://www.clexchange.org/dd_msst/

Both MSST and Demo Dozen were creations of the Waters Center for System Dynamics at Trinity College. Waters Center has been transformed into the Center for Interdisciplinary Excellence in System Dynamics, LLP (CIESD) due to the closing of Trinity College.

Both MSST and Demo Dozen are interactive guides that require the use of iThink software. Fortunately, demo version of iThink for both Mac and PC can be downloaded free of charge from software maker High Performance Systems. Due to the interactive elements, MSST and Demo Dozen contain considerably less reading than MIT Road Maps.

Modeling Systems Self-Taught was created to help K-12 educators learn the foundations to building system dynamics simulation modeling with iThink. Each lesson includes some system dynamics concepts, illustrative models, and model building exercises with very details instructions. The first three of the seventeen MSST lessons are available free from CLE. A number of models overlap with Demo Dozen.

Demo dozen is a set of twelve case studies/ working simulators of different subject matters. Each case study follows a consistent format: After an introduction that explains the system and the problem (or goal) at hand, the user can create and test different strategies on a simulator. After that, the model and its dynamics are explained in a user-controlled slide show, ending with questions to provoke further thinking. Incidentally Demo dozen has a great introduction module that contains excellent and concise definitions of system dynamics.

2 METHODOLOGY

This section describes the three parts of this project: design of teaching material, implementation of the material, and measurement of student progress.

2.1 Designing the course

Toward the beginning of the project Mr. Barys and I determined the scope and duration of the course, and planned an informal syllabus. To create the course material, I incorporated material from my notes of WPI introductory system dynamics classes taught by Professor Michael Radzicki, literature such as John Sterman's "Business Dynamics," videotapes of "System Dynamics Seminar with Jay Forrester," and my recollections of system dynamics courses and assigned readings. I created a teaching plan for each class that consisted of outlines of important ideas.

2.2 Implementing the course

I generally kept to my prepared outline as I taught. When appropriate, I asked students oral questions and encouraged discussion, to make sure they understand the concepts. When necessary, I spent extra time on a subject by providing more examples and asking more questions. I kept a detailed journal of the classes and materials taught was kept (Appendix 1).

The class consisted of nine students, a small and size manageable size. I noticed immediately there were two or three students who would dominate discussions if left unchecked. I recalled information from a psychology course taught by Professor James Doyle[6] and I incorporated material that would encourage group participation. One technique is to call on different individuals to answer questions so the dominant students won't be the only ones to speak in class. I also provided candy in a few classes to students who volunteered to answer questions. The candy served as an incentive for those who had not yet spoken. while temporally restraining those whom just spoken from answering more questions (because they would be eating the candy).

These students retained their enthusiasm throughout the course, and participation rate increased to a high level for all students.

2.3 Measurement of student progress

Student progress was documented by written and anecdotal evidence[7]. The anecdotal evidence appears in the journal (Appendix 1). The written section includes student assignments and measurement of student perspective.

2.3.1 Beginner Modeling Exercises

Students were provided with a blank copy of a written exercise (Appendix 4). This assignment tests students on their ability to identify stocks and flows. Students also had to indicate polarity relationships between variables in causal loop diagrams. A sample answer key to the questions is available in Appendix 5.

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[6] The class was Psychology of Decision Making and Problem Solving. It was a class for system dynamics group modeling but I find the material helpful in many situations.

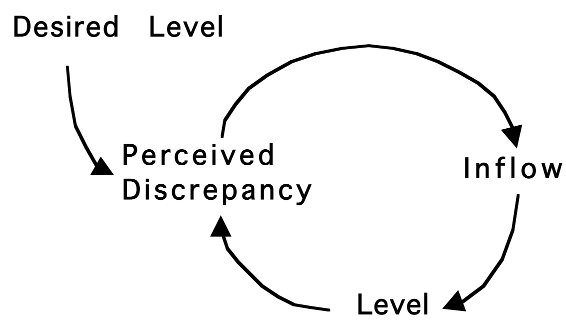

Figure 2.1: Causal loop without polarities

The students were expected to add the + or - link polarities and also (+) or (-) loop polarities for the examples shown. To determine polarity of individual links, we look at each link independently and assume all other variables are constant. If the cause is increased the effect increases, the variables would all be going in the same direction. This is represented with a positive sign at the head of the arrow. If the cause is increased and the effect decreases, the variables are going in the opposite direction. This is represented with a negative sign.

One way to determine loop-polarity is by counting the number of negative signs around the loop. If it's an even number the loop is a positive loop. If it's an odd number it's a negative loop. Positive loops are self-reinforcing. A change in one of the variables would change the other variables in the loop and eventually cause reinforcement of the original change. Negative loops counteract any change and balance the system. Strong negative loops tend to bring a system into equilibrium. Dynamics of any system are produced by the interaction of the positive and negative feedback loops.

[7] This was suggested by Professor Saeed.

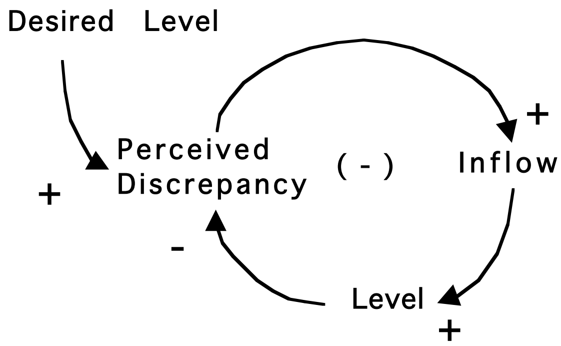

Figure 2.2: Causal loop with polarities

How this assignment was graded.

1. A) One point for identifying the variable correctly as stock or flow; one point for identifying associated flow or stock; divide total by sixteen - eight questions, each with two parts.

1. B) One point for identifying one or more correct flows for each stock; divide total by seven - the number of questions.

2. A) Score by the numbers of correct loop polarity; divide total by five loops. However, if individual link polarity were considered, everyone would receive a zero on this section.

2.3.2 Replicating Drug Model

The students were provided with printouts of a sample computer model's physical structures and mathematical equations (Appendix 7). The purpose of this assignment is to let students familiarize themselves with the software. The student would use the software to build and simulate a model (see Figure 3 for a sample model). After building a model, students were to provide printouts of model diagram, model equations, and graphs of simulation runs.

The greatest part of the work involved is to make a correct duplicate of the model, in terms of model structure, connection between variables, and model equations. Since the correctness of the printout of model equations and simulation graphs depends on the model, equations and graphs are only judged on whether the students provided the printouts.

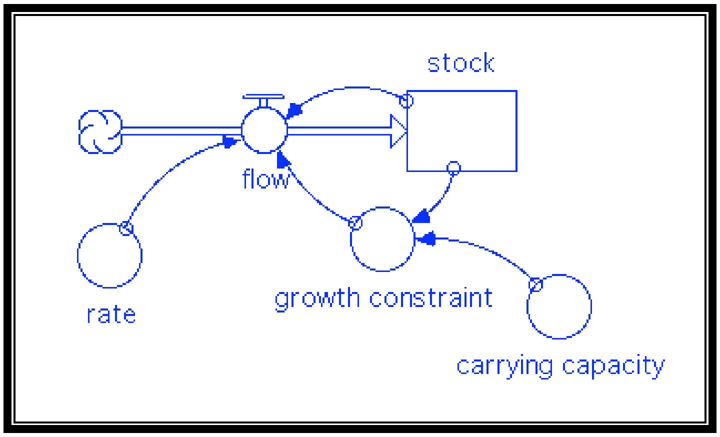

Figure 2.3: Sample system dynamics computer model

```
stock(t) = stock(t - dt) + (flow) * dt
INIT stock = 3

INFLOWS:
flow = stock * rate * growth_constraint
carrying_capacity = 50
growth_constraint = 1- stock/carrying_capacity
rate = .1
```

2.3.3 Article Responses

To determine if students demonstrated improved understanding, students were given an article describing a complex problem and asked to identify the problem and discuss their proposed solution. The article was from the Boston Globe titled "Cape debates impact of rail link." The article is about an entrepreneur's proposal to bring passenger railroad trains back to Cape Cod. The railroad proposal raised many important issues but no clear solution. The students are asked to answer the following two questions: identify and discuss problem, as you understand it, identify and discuss your solution to the problem. Students read the article and responded to these questions (Appendix 3) on two different dates. The first was September 20, before going through the bulk of this class. This is the "before" response. Students responded to the article and the questions again on November 15 (one month after the conclusion of the class). This is the "after" response.

A control group consisting of students not in the class also read the same article and planned to respond to the same questions on two dates similarly apart (however this control group missed the first set of questions).

3 DATA

This section contains the summary of data. The original data can be found in Appendices 10 to 15. For easier cross-referencing of student progress, each student is assigned a number one through nine. The control group had fifteen students. They are assigned c1 through c15.

3.1 Assignment: Beginner Modeling Exercises

Table 3.1: Student Result from Beginner Modeling Exercises

Student	Q 1. A) Score	Common Mistakes	Q 1. B) Score	Q 2. A) Score	Common Mistakes
1	4/16	x	1/7	4/5	b c
2	6/16	y	6/7	5/5	b
3	14/16		6/7	3/5	a d
4	3/16	z	1/7	4/5	a
5	3/16	x	1/7	5/5	a
6*	N/A		NA	NA	
7	9/16	y	5/7	5/5	a
8	3/16	x	6/7	4/5	a
9	16/16		7/7	5/5	a

* N/A: This student did not submit this assignment.
x, y, z, a, b, c, d: See below for detail on Common Mistakes

Results of this assignment are tabulated in Table 3.1. One student did not submit this assignment. The score for that student is indicated with NA. See Appendix 12 for student data, Appendix 5 for correct answers, Appendix 4 for a clean copy of the assignment.

The students made a number of common mistakes. If each of the three sections counted as one third of the total score, only five out of nine students would have received a passing grade on this assignment.

Following are the common mistakes the students made. The explanation of the common mistakes is in analysis section 4.1.

Mistakes made on 1.A:

- x: Eight variables were paired into four groups. (Most common mistake)
- y: Attempted to make a causal loop diagram containing all eight unrelated variables
- z: Did not name associated stock or flow.

In this section, x was the most common mistake, and z was the least common mistake.

Mistakes made on 1.B:

- Three students who received a low grade on this section provided variables that may indirectly change the stock. Those variables are not flows into or out of the stock.

Mistakes made on 2.A:

- a: No link polarity. However, these students provided mostly correct answers on loop polarities.
- b: Misplacement of link polarity. The polarities were placed next to the tail of arrows and next to variables.

- c: Too many link polarities.
- d: All loops were given the same polarity.

In this section, a was the most common mistake, while c and d are the least common mistake.

3.2 Assignment: Replicating Drug Model

Four students submitted this homework assignment. See **Appendix 13** for those printouts.

Table 3.2: Drug model replication results

Student	Overall	Diagram	Equations	Graphs	Notes
1	Excellent	Excellent	Yes	Yes	All details were replicated correctly
2	Good	Good	Yes	Yes	A flow was in the wrong direction
3	Good	Good	No	Yes	A flow as not connected to stock
4	Passing	Ok	No	No	Model was made with Vensim
5	N/A				
6	N/A				
7	N/A				
8	N/A				
9	N/A				

Student 5 through 9 said they had problems downloading the software or accessing the software from the WPI network at the Mass Academy building.

3.3 Problem Analysis: Article Responses

Since the student responses were in essay format, I compared the different responses by identifying important factors and also identifying writing that contained unique and illuminating ideas.

See **Appendix 10** and **Appendix 14** for student responses. The before and after responses are summarized in Table 3.3. The control group is summarized in

Table 3.4.

The categories (in gray) contain important factors that I hoped the students could identify. The factors mentioned in the writing are checked off with "Y." Here is the description of the factors.

- Problem: Traffic jams on the road to Cape Cod.
- Proposed solution: Train is the proposed solution.
- Cost to state and taxpayers: the railroad operator needed state subsidies to run the service.
- Transportation on Hyannis: Trains only go as far as Hyannis. One shortfall is a relative lack of public transportation available to riders arriving in Hyannis.
- Environmental impact: Railroad would affect the fragile ecosystem.
- Development impact: Train service will most likely spawn unwanted development.
- Train may not solve traffic problem: Due to development impact, trains will not solve the traffic problem. A notable alternative proposal is marked with asterisk ("*").

For the category "Use train?" the ideal answer is no, because trains would create more problems in the long term, such as environmental and developmental impact. A question mark was given in this category if the student did not make a decision on whether to recommend a train.

See analysis at section 4.3 and section 4.4 for comparisons and patterns observed in both classes.

Table 3.3: Response from the System Dynamics Class

Student	1=Before 2=After	Problem: traffic	Proposed solution: train	Cost to State (& taxpayers)	Transportation on Hyannis	Environmental impact	Development impact	Train may not solve traffic problem	Use train?	Highlight: short summary of main ideas or arguments
1	1	Y	Y	Y	Y				N	Travel on alternative (non-weekend) days to avoid traffic. Railroad may lead to more problems and more expenses for the state of Massachusetts.
1	2	Y	Y	Y	Y	Y		Y	N	Fundraiser should be held to help pay for the railroad. However, trains may lead to more problems for residents, tourists, and the state government.
2	1	Y	Y		Y	Y	Y		Y	Budd train may work because it's too slow to attract commuters.
2	2	Y	Y		Y	Y	Y	Y	Y	Needs to build a model to study traffic flow.
3	1	Y	Y		Y				Y	Lack of funding may kill the railroad idea.
3	2	Y	Y			Y	Y	*	Y	Limit number of tickets. Use trains also to transport goods.
4	1	Y	Y						Y	U.S. lacks good public transportation system. More public transportation systems should be built to relieve traffic.
4	2	Y	Y			Y			Y	Train would encourage travelers to take public transportation.
5	1	Y	Y						Y	Limit the number of trains so there will be a good balance in relieving the traffic congestion and limiting unwanted industrial growth.
5	2	Y	Y		Y	Y	Y	Y	N	Train may not be the solution. A commuter train may cause area development and have adverse effects on the environment.
6	1	Y	Y			Y	Y		Y	Need to model environmental & financial impact of rail line.
6	2	Y	Y			Y	Y	Y	Y	Put a cap on the number of trains to prevent unwanted development and pollution.
7	1	Y	Y	Y	Y	Y	Y		?	Analysis only: If funding is unavailable, doing nothing is acceptable. If nothing is done, the traffic problem is sustained, but no negative changes will apply either.
7	2	Y	Y	Y	Y	Y	Y		Y	Get car rental agencies and mass transportation to Hyannis. State subsidy should be minimal. The train should connect with Amtrack for convenience.
8	1	Y	Y			Y	Y		Y	Train would cost more than driving and may take longer so trains would not affect growth too much.
8	2	Y	Y			Y	Y	Y	Y	Limit the number of trains. The railroad company should also be forced to maintain environment.
9	1		Y	Y	Y	Y		Y	N	The project would cost the government and hurt the environment. Plus it won't help passengers once they are in Hyannis due to lack of public transportation.
9	2		Y	Y	Y	Y		Y	N	The project would cost the government and hurt the environment. Plus it won't help passengers once they are in Hyannis due to lack of public transportation.

Table 3.4: Response from the Mathematical Modeling Class

Student	1=Before 2=After	Problem: traffic	Proposed solution: train	Cost to State (& taxpayers)	Transportation on Hyannis	Environmental impact	Development impact	Train may not solve traffic problem	Use train?	Highlight: short summary of main ideas or arguments
c1	2	Y	Y	Y					N	Perhaps a more efficient train is needed so it won't lose money. People won't take the current train because the train is too slow.
c2	2	Y	Y	Y	Y				Y	Avoid government subsidies by raising train ticket prices.
c3	2	Y	Y	Y	Y		Y		?	People would not like to pay for the train and car rentals. People will use train if people have access to better public transportation at Hyannis.
c4	2	Y	Y		Y	Y			N	Build a bigger and wider bridge.
c5	2	Y	Y		Y	Y	Y	Y	N	If people are upset about the traffic, then they shouldn't go. A commuter rail would be horrible for the environment; some land should remain undeveloped.
c6	2	Y	Y	Y			Y	Y	N	Set up parking lots around the Cape. Have trolleys/bicycles available in towns. (This will relieve traffic in towns but not to and from the Cape).
c7	2	Y	Y	Y	Y	Y	Y	Y	N	Build a tolled canal tunnel. Cape is slowly being eaten by continually increasing tourist population, development projects, and an increasingly longer tourist season.
c8	2	Y	Y			Y		*	Y	Train would decrease the use of cars; that means less pollution (from cars). Railroad would not impact the environment as much as people living in the environment.
c9	2	Y	Y	Y		Y		Y	N	Let public deal with traffic. Too many tourists will pollute the beaches so much that none would want to go anymore. Charge people a fortune at the tolls to both make money and decrease traffic.
c10	2	Y	Y						Y	Trains would make Cape more accessible to tourists. Although trains did not work before, it may be different now.
c11	2	Y	Y	Y		Y			?	Survey people to see if enough people will use the train. If yes, use the most efficient and environmentally safe trains possible.
c12	2	Y	Y	Y		Y	Y	*	Y	If trains are well used it would cut down pollution from cars, and also cut down development near highway. (Fast food and other development follows highways but not train tracks). Increase public awareness about ecological impact of private vs. public transportation.
c13	2		Y	Y	Y				?	Let the people of Cape Cod vote. If they want the train they will pay for any possible repercussions.
c14	2	Y	Y	Y		Y			?	The traffic is concentrated near the bridge and does not warrant millions of dollars to fix. Yes to train if it does not destroy environment.
c15	2	Y	Y	Y					Y	Tax the residents to pay for the service.

3.4 Problem Analysis from the Mathematical Modeling Class

The railroad article and associated questions were given to fifteen students from the Mathematical Modeling class serving as the control group (non-system dynamics class). See **Appendix 15** for student output. Results compared the same way as the last section (see summary in Table 3.4.) Student responses were not collected in the beginning of the course.

3.5 4th Annual High School Mathematical Contest in Modeling (HiMCM)

This happened after the course was over and the students did this voluntarily. A group of students had System Dynamics in mind when they built a computer model for a mathematical contest in modeling. The model had no stocks or flows and therefore no feedback. The model does seem to make calculations based on a number of variables according to equations these students wrote. The student report included a number of equations, but did not include a complete equation printout from the model (see Appendix 16).

4 ANALYSIS

This section discusses what was learned based on:

- Homework assignments
- Comparison of student responses of an article before and after the class
- Comparison of student responses of an article with another course
- Inference from anecdotes

Each section contains summary of data, interpretation of data, and recommendations.

4.1 Homework Assignments: Beginner Modeling Exercises

One student did not turn in this assignment so I had responses from eight students.

Part 1A

Two students did well and six students failed this section. Those students who did poorly were looking for nonexistent relationships between pairs of individual variables. The cause may be misunderstanding of the assignment's directions.

Part 1B

Five students did well and three students failed this section. The wrong answers given were variables that would affect the stock, instead of giving direct flows. Although those answers were not correct, they show that students were thinking in the context of systems by giving variables that may be relevant in the bigger picture.

Part 2A

The student responses were unusual for this section. In one way everyone failed this section, in another way everyone passed this section. Although every student gave loop polarity, none indicated the polarity of individual links in the correct way. If link polarity were considered, none of the answers would be satisfactory. However, if only loop polarity were used to grade this section, everyone passed.

Did the students know what they were doing or were they just guessing?

Let's use probability to find out. This section contained a set of five loops, each having either positive or loop polarity. If the students were guessing randomly, one out of every thirty-two tries would yield the correct set of five answers [(1/2)^5 = 1/32]. Guessing randomly, there must be thirty-two students to produce one set of five correct answers.

Four out of eight students submitted the correct set of loop polarity. That's sixteen times the occurrence that random guessing would produce. Therefore, it is unlikely that the students got the correct set of answers by guessing. If they did not guess they must have used their knowledge to get to the correct solutions. I will assume that the students derived the loop polarities mentally. (Instead of writing down individual link polarities and then determining loop polarity, the students may have just done the polarity calculations in their heads).

This assignment was fairly simple and I was expecting better results. However, students did show some understanding of the material. Disregarding the lack of link polarity in the last section, five students received passing grades (one excellent, one good and the other three ok). Since the students were able to answer similar questions in class, perhaps students did not understand the written assignment.

In response to the outcome of this assignment, I recommend the following:

- Provide a reading on causal loop diagrams.
- Clarify the assignment by providing one completed example for each section (see **Appendix 5** for completed examples).

4.2 Homework Assignments: Replicating Drug Model

Four out of nine students handed in their models. One of those models is a complete replica. The other two models had minor bugs, which could be easily identified and fixed as the students become more familiar with the software. Another student passed in a model with no equations because the student used Vensim software, which is difficult for beginners.

The other five students said they had problems downloading the software or accessing the software from the WPI network at the Mass Academy building. (although they were supposed to have access from their school building). The ones who completed this assignment successfully downloaded a demo from the software makers. Perhaps the lack of software affected the others ability to complete this assignment.

Recommendations

- Ensure the software is available on the Mass Academy network.
- Provide a simplified guide on how to build models that also mention common problems such as reversed flow, flow not connected.
- Also assign experiments to be performed on the model.

4.3 Problem analysis: before and after

The central problem is "Will the train solve the traffic problem?" I hoped the students could realize that trains may solve some traffic problem in the short term, but having the train may be detrimental in the long term. The train and the traffic combined would eventually bring in more tourists, which could cause more development and pollution on the Cape.

To determine if students changed the way they think as a result of this class, I will compare student writings from "before" and after the class. I hope the "after" writings will demonstrate greater use of systems thinking. The students should think about interactions between different issues (the variables) and the resulting implications in the context of the long term.

Comparing the two writings, the data show that on the second writing:

- Only one person out of nine has changed the solution from using train to not using train. There was no significant change of opinion on whether to use trains.

- Students identified more issues in more details on the second response. This is good because they seemed to see the problem more thoroughly and provide more articulate solutions.

- There is increased understanding that trains may not solve the problem. Originally one out of nine (11%) students identified that trains may not solve traffic problem in the long run. After the class, six out of nine students (66%) said trains might not solve the traffic problem. However, many of those students still suggested using trains, if the numbers of trains is limited.

- One proposal favors the train but gives an alternative solution that would solve multiple problems. The proposal would limit the number of tickets to control growth. The proposal also suggested using the train to transport goods to help pay for some of the costs. This plan sounds feasible.

Question:

Does a person gain a better understanding of an article the second time they read the article? What if a long time passed between the readings? The "before" and "after" student writings were almost two months apart. The research will assume that the students did not remember much of their initial analysis.

Recommendations:

- The first set of responses was collected after the students had been exposed to two classes' worth of System Dynamics. The first part should have been given before they were exposed to any classes.

4.4 Problem Analysis from Control Group: Mathematical Modeling Class

Four out of fifteen students (26%) identified that a train might not solve traffic problem in the long run. Two proposals favored the train but explained systematically why. Six (four plus two train proposals) out of fifteen students demonstrates that they understand the interactions of system elements over time (40%).

I was expecting the percentage of students that identified that train may not solve traffic problem in the long run would be close to the initial percentage of the students who took the system dynamics class. However, the measurement for this class falls right between 11% and 77%.

Question:

Did the members of the class gain increased understanding of mathematical modeling as a result of the mathematical modeling class? Or did their knowledge stay at a constant level, despite the class? The result is inconclusive without a before and after writing from the mathematical modeling class.

4.5 Inference from Anecdotes

Professor Saeed came to the class on October 15 to observe the progress, with very positive reactions. Professor Saeed commented that the students were very responsive and participated well. He observed that although one group had a handle on the problem and one group had lagged behind, by the end of the class everyone seemed to understand the problem. Professor Saeed also described my facilitation process as effective: there was "convergence from various visions to a commonly accepted reference and one dynamic hypothesis."

Last Day of class: A student asked if he could enroll in System Dynamics classes at WPI. The course produced interest in the field of system dynamics, and one student like it enough to ask for more information. There might be others who also like system dynamics but did not ask about WPI's program.

Majors Fair: Students from the class brought their friends to the System Dynamics / SSPS table to see and experiment with the computer models and simulations. The crowd showed overwhelming interest.

Even after the conclusion of the course, a group of students choose to use system dynamics software to build a computer model for a mathematical contest in modeling. This showed their continued interest in system dynamics.

4.6 Other Material: Note Taking Habit

During the lessons there was good participation. This showed good understanding of the material, but I noticed that students did not take many notes during the class. (Maybe because the material seemed easily understandable in class). I did not examine any of students' notes. However, I was concerned after seeing notes from Mr. Barys. His notes only consisted of what I wrote on the board. Perhaps no one realized the importance of the material that I tried to teach orally. Since I spoke the majority of the things I tried to teach the class, I would assume not much of the information was written down and student notes might contain less than Mr. Bary's. The learning should improve with more handouts.

5 CONCLUSION AND RECOMMENDATIONS

This project started with the goal to design, implement, and evaluate teaching material for an eleventh grade high school course. Although most of the time was spent on developing and implementing of the material and the project is not complete, this course has received positive response from all participants.

In term of the class, although student performance on their written assignment could have been better, I believe that the Mass Academy students learned from the course and enjoyed what they learned. Professor Saeed also had the same observation, that the students were very responsive and also that the students participated well. The students showed continued interest, some voluntarily chose to use system dynamics as their modeling method for a mathematics-modeling contest. Judging by the students' continued interest, it seems likely that another system dynamics class should be offered at Mass Academy. I hope this paper can be used as a guide for the next system dynamics class at Mass Academy.

Although this paper and other resources are available to help teach system dynamics to K-12 students, the principal difficulty faced by teachers is that they need to know system dynamics fairly well to apply the material. It does take time to learn the material, so prospective teachers should start early. For those with no prior training in system dynamics I strongly recommend going to one of the training workshops or going through at least one of the resources listed in section 1.5, such as Road Maps.

However, before this document is used toward future classes, there are certain issues for future work (in addition to recommendations made in the previous sections):

- General structure of the course could be improved, perhaps including discussion of model's calculus and higher mathematics aspects.
- Provide more readings. Students seem to need a reading on causal loops.
- Homework assignments may need more clarification. Provide specific examples of expected solutions. This could be accomplished by providing the appropriate handouts.
- Final computer modeling assignment should be on a simpler topic. More information should be provided to students for the modeling assignment.

The measurements of student learning would also need to be studied further. Large class sizes may be needed to obtain a better statistical evaluation of learning. Since Mass Academy classes are relatively small, one way to acquire a larger sample would be to work together with other K-12 educators throughout the country to collect data from their classes.

Appendix 1: Journal and Materials Taught

David Liu

Summary:
This journal includes project background and how the project came about. The course notes section describes how each lesson was conducted and how students reacted. This appendix could be used as a basis to create a similar set of lessons.

Introduction to System Dynamics

Department of Mathematics
Massachusetts Academy of Mathematics and Science
Worcester, MA 01609-2208
A term 2001

Course Description and Objectives
To introduce students to the concepts of system dynamics and dynamic model building.

Co-instructors:	**David Liu**	**email: dave@DayLightPix.com**	
	James Barys	**email: jbarys@wpi.edu**	**Ph: x5941**

Readings and software
1. Selected articles as indicated in this syllabus
2. Software:
    iThink (recommended) for Mac and PC: www.hps-inc.com
    PowerSim Constructor for PC: www.powersim.com
    Vensim (not recommended) for Mac and PC: www.vensim.com

All reading materials will be distributed in class. All three software are available on the school network.

Demo version of software can be downloaded for free from each company. However, the saving feature is disabled on the demo version of iThink.

Grading
Pass or fail basis depending on:
Class participation
Modeling assignments
Homework

Meeting schedule

9-13-02
Introduction to System Dynamics

9-17-02
Modeling Basics and Sample Models

9-20-02
Railroad Article and Questions (Mr. Barys)

9-24-02
Playing the Beverage Game

9-27-02
Quiz on stock, flow, and feedback loops

10-1-02
Debriefing the Beverage Game

10-4-02
Reading: First Three Hours article (Mr. Barys)

10-8-02
Model building process: Identify variables, create reference mode, and develop dynamic hypothesis. Drugs problem.

10-11-02
Model building process: Translate causal loop diagram into a computer model. Drugs problem.

10-15-02
Model building process: Identify variables, create reference mode, and develop dynamic hypothesis. Railroad problem

10-18-02
Student presentations
Conclusion

Journal: Table of Contents

1 PROJECT BACKGROUND

1.1 Genesis of the Idea to Teach System Dynamics at Mass Academy

The project began to form in the fall of 2000 at an annual major's fair where WPI students and faculty members present their departments to WPI undergraduates without majors, prospective undergraduates, secondary school students, and interested high school faculty members.

I was one of a group that presented the SSPS curriculum and highlighted its unique program on the discipline of system dynamics. At the fair, Robert D. Knittle, a visiting teacher from Mass Academy became fascinated with system dynamics. His enthusiasm helped start the discussion about bringing this discipline to Mass Academy. Later in the year Mass Academy invited SSPS students to make further presentations about system dynamics to Mass Academy students.

The presentation took place in the spring of 2001. Although well received, it produced no immediate requests for a course in system dynamics at Mass Academy. I thought the idea for this project had faded back into obscurity.

I was wrong. In September 2001, this discussion not only revived, it acquired a degree of urgency.

1.2 Design and Development of the System Dynamics Course at Mass Academy

Jim Barys, the mathematics instructor at Mass Academy, received the assignment to prepare an elective course in system dynamics to be taught in January and February of 2002. Due to scheduling conflicts beyond his control, however, this course was rescheduled—for September 2001. Although Mr. Barys had entertained an interest in system dynamics for a few years, he was not yet fully prepared to teach the course, so he decided to find a WPI student to assist him. Khalid Saeed, the SSPS department head, announced this opportunity on September 10. I contacted Mr. Barys two days later to express my interest. He invited me to visit the classroom the following morning to meet him and his students. The course would be experimental—an elective graded on a pass/fail basis. I assumed that I would meet the class for a few minutes and then discuss the structure of the class with Mr. Barys in more detail before I start teaching.

2 JOURNAL: COURSE NOTES

2.1 Journal Entry: September 13, 2001: Introduction to System Dynamics

Today I gave a short introduction of system dynamics. Jim Barys introduced me as the WPI student who will help teach the system dynamics course. After Mr. Barys introduced me to the class, I was quite surprised when he said, "the class is yours." There were nine students and they were interested in who I am. None had calculus so I decided not to involve calculus in this course. I briefly introduced myself as a student at WPI majoring in system dynamics. I went on to explain what kinds of opportunities are available in this field and my ideal job in system dynamics:

“System dynamics in brief, is used to build computer simulations to solve problems that change over time. There are applications in many fields, including business, medical, construction, environmental, social science. I find the business field enticing because, as a consultant, I would have the chance to examine different businesses and gain knowledge of what works well and what does not."

I answered a student's question about why I chose the field:

"I took the introductory course by chance and discovered that I really like what the field has to offer. It combines the right proportion of human and computer elements. Problems that seem vast and complex can be represented by computer models, and these can be explored and analyzed on many levels. Unlike computer coding, which uses strange textual codes with strange syntax, a system dynamics model is visually comprehensible to most people.

I especially like the wide range of applications of system dynamics. For example, system dynamics helped raise key issues in Boston's urban renewal project[1] and also brought global attention to the problem of limited petroleum supply and its effect on the world[2]. With system dynamics, it is possible to turn problems that seem far too complex for any individual to investigate or understand into computer simulations that most personal computers can run. In the hands of the right people, those computer models can make a difference."

I went on to explain how the field started: Jay Forrester, a pioneer in the computer field, joined the MIT Sloan School of Management after working on military computer systems designs based in control theory and on computer flight simulations. At the time that Forrester came to MIT, people from General Electric were puzzled about fluctuations in the numbers of employees at their household appliance plants. The business cycle alone could not explain these fluctuations. By examining the business structure and then building a simulation of it, Forrester found out that the structure, not outside influences, was the culprit. Even with a constant order flow, hiring and

[1] Forrester, Jay W., 1969. Urban Dynamics. Pegasus Communications, Waltham MA

[2] Forrester, Jay W., 1971. World Dynamics. Pegasus Communications, Waltham MA

inventory policies were causing employment instability.[3] The idea that structure alone can influence behavior was confirmed by modeling other corporations. Later, system dynamics was applied to a variety of natural and social systems, including biological, environmental, inventory, labor, infrastructure, and urban systems.

A few fundamental concepts in system dynamics make computer simulation possible. The first concept is that everything can be classified as either a stock or flow. A stock is a quantity—also known as a level. A flow is a change in quantity. One example in business is the forms in which investors receive reports of performance. There are two types of accounting sheets: a balance sheet (which lists stock: assets in dollar amounts), and a profit/loss statement (which measures flow, in dollars per report period).

At this point, I asked the students to provide examples of stocks and flows. Initially they asked me to provide more information. After I provided more examples such as the number of students in a classroom as a stock, students volunteered their own. Examples include bank account and homework assignments. Most of these were correct and demonstrated an understanding of the concept of stock and flow.

Another key concept of system dynamics is that structure causes behavior. This means that the structure of a system has an enormous effect on the behavior of everything within the system as well as everything that the system affects. Sometimes these effects have unintended consequences, but most people attribute these consequences external factors, rather than to the system. There would be fewer problems in the world if more people understood systems better.

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[3] Forrester, Jay W., 1989 The Beginning of System Dynamics http://sysdyn.mit.edu/sdep/papers/D-4165-1.pdf

I explained to the students that we would conduct the “Beverage Game”[4] exercise to demonstrate the concept that structure causes behaviors in one of our future sessions. The beverage game is a board game modeled after a supply chain.

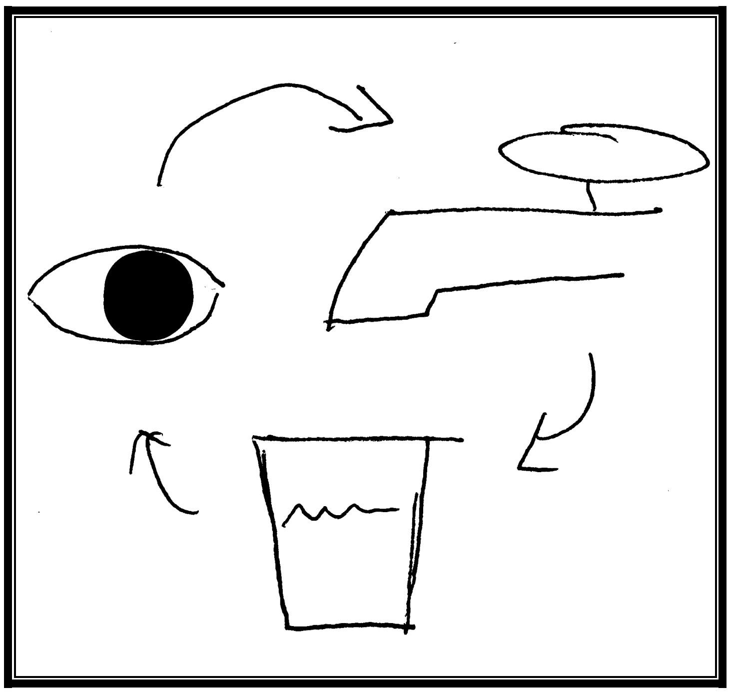

Figure 1: Informal Causal Loop Diagram of Filling a Cup

The final concept in system dynamics is feedback--the interaction between the stocks and flows of a system. To demonstrate this interaction I drew an example of a simple system on the blackboard. The system portrayed a person filling a cup of water (Figure 1).[5] The components of this system are as follows: A person turns on a faucet. Water begins to flow from the faucet into a cup. Over time, the person sees the cup getting full and turns off the faucet.

[4] The "Beverage Game" is commonly known as the "Beer Game" or "Beer Distribution Game" in graduate schools and management circles. The words “Beverage” or “Juice” are more appropriate for younger audiences.

[5] Forrester, Jay W., System Dynamics Seminar with Jay Forrester

All the elements in this activity can be conceptualized as a feedback loop--from the faucet, to the cup, to the person who sees the water level in the cup, to the person's perception that the cup is full, to the person's action (turning off the faucet to prevent the cup from overflowing).

A formal causal loop diagram can portray the action of filling a cup from a faucet. We can call the water from the faucet "inflow," the quantity of water in the cup, "level;" and what the person sees, "perceived discrepancy." Perceived discrepancy is the difference between what one wants (desired level) and what one sees. I drew the components and links of the diagram without the positive or negative signs (Figure 2).

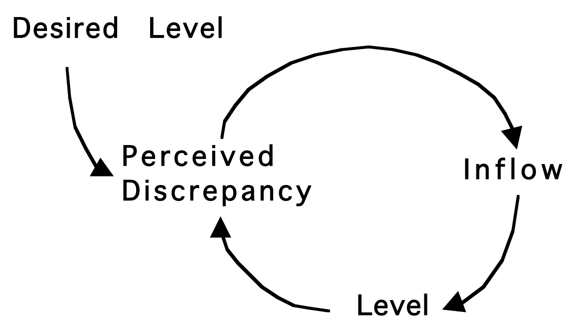

Figure 2: Causal loop diagram of filling a cup without link polarity

I proceed to explain how to determine link polarity in a causal loop diagram. In system dynamics, each link of a causal loop diagram is assigned a polarity. To determine polarity, we examine links between variables one set at a time (temporarily ignoring the other variables) by asking what would happen by increasing a cause while everything else stayed the same. Because confusion may arise in certain situations if one asks: "what would happen if the cause is decreased," link polarity should always be determined by increasing the cause.[6] If the effect increases as the cause increases, the polarity is positive. If the effect decreases as the cause increases, the polarity is negative.

I asked the class what would happen to the level if the inflow increased. Students answered correctly: it would increase. I drew a positive sign at the tip of the arrow from inflow to level. Then I asked the polarity of each of the other links, one at a time. If level increased perceived discrepancy would decrease. At this point some students wanted to determine the effect of *decreased* perceived discrepancy on inflow but I reminded them of the "increase" rule. If the perceived discrepancy is increased (say someone drinks the water), then inflow should be increased. There was some confusion but the students who got it explained to the other students about the reason for that link polarity. Finally, if desired level increased perceived discrepancy would also increase. At this point everyone seemed to understand the completed causal loop diagram (Figure 3).

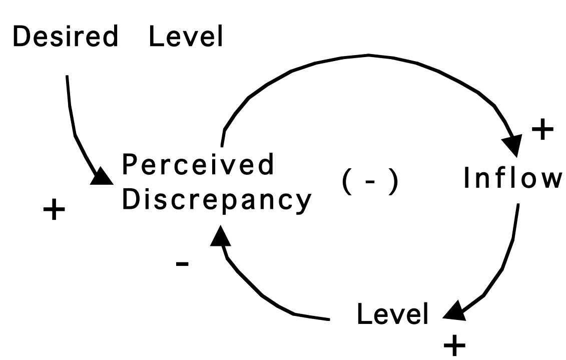

Figure 3: Causal Loop Diagram of Filling a Cup

[6] All else being the same, if birth rate increased, population would increase. However, if the birth rate decreased, population would still increase at a slower rate. In this situation it would be less confusing to determine link polarity between birth rate and population by using the "increase cause" rule.

Before the conclusion of the class, I was able to open a sample iThink model to briefly show the class what a system dynamics computer model looks like.

This concludes the class for today. I was surprised to teach the class so soon but I was prepared partly due to a recent viewing of System Dynamics Seminar with Jay Forrester. I think I did well today since the students participated and answered my oral questions regarding stocks, flows, and causal loop links.

Recommendation: Upon reflection, I realized that the accounting sheet example might not be appropriate for this age group and it may have to be revised.

2.2 Journal Entry: September 14, 2001: meeting with professor Saeed

Professor Saeed suggested that I meet with Professor Jim Doyle who taught psychology to discuss evaluation methods. I went to see Professor Doyle and learned that he was the advisor for five projects this and the next term; therefore he was quite swamped for the next four months.

Professor Saeed became the project advisor. He suggested that student perspective change could be part of the evaluation. I could give an assignment where students were to give assessment of a problem and suggest policies (recommendation to relieve the problem). Later the students could make an assessment of the same problem again and provide a policy. These assessments can be compared to see if perspective changed and how it changed. This can be conducted using any newspaper article. I called this process "student article responses."

2.3 Journal Entry: September 16, 2001: meeting with Mr. Barys

I met with Mr. Barys to plan for the future classes. There are ten more sessions. Mr. Barys will teach three of them, starting from where I left off. We planned the schedule as shown in Table 1 (the dates on which I teach are in bold type.)

Table 1: Informal Syllabus

13-Sep	**Introduction to system dynamics**
17-Sep	**Run the beverage game**
20-Sep	Mr. Barys: article response and more intro to system dynamics Students respond to article
24-Sep	**Debrief beverage game, modeling methods**
27-Sep	Mr. Barys: sample models
1-Oct	**Modeling methods**
4-**O**ct	Mr. Barys will teach from where I left off. Students respond to article
8-Oct	**Modeling methods**
11-Oct	**Building computer model**
15-Oct	**Building computer model**
18-Oct	**Student presentations** Students respond to article.

I mentioned collecting student response to an article and we planned three dates for that. Students were to read an article and to provide written responses to a set of questions regarding the article on September 20, October 4, and October 18.

2.4 Journal Entry: September 17, 2001: Modeling Basics and Sample Models

I did not realize that the copies of beverage game used at WPI belong to Professor Michael Radzicki and are not always obtainable. The game is unavailable today so I asked to borrow the game for next Monday. Instead of the game, I decided to teach modeling method today with examples of basic models.

A computer was ready and a computer projector showed the students what I did on the computer. The computer had iThink on it so I described how to use iThink.[7] I showed them where the stock, flow, converter, and connector are and how to connect the different elements. Converters are just decision rules. I also showed them how to enter data and equations into the model.

I proceeded to demonstrate how to use the software to produce simple computer models. Each model is to produce one of the following behaviors: exponential growth, exponential decay, goal seeking, S shaped growth, and oscillation.

I put a stock, an inflow, and a multiplier on the software, connected as shown in Figure 4. I entered a constant in stock and a constant for the multiplier. The equation of the inflow is the stock multiplied by the multiplier (stock * multiplier). I asked the students to think about what would happen to the stock and to my delight, they answered exponential growth. Running the computer model and graphic, the stock showed exponential growth behavior. A real life example would be money in a savings account earning interest. The more money there is in the account, the account earns more interest.

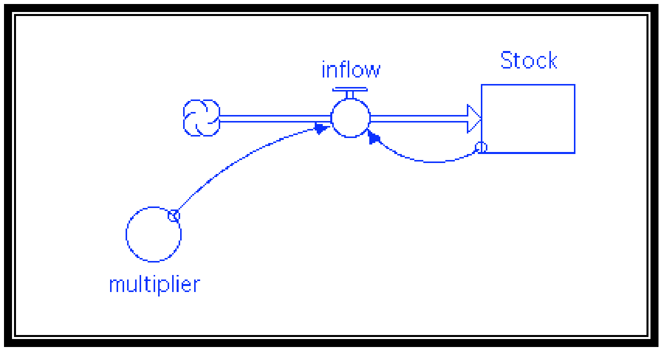

Figure 4: Exponential Growth Model

I proceeded with the next model. This model was similar to the last one except that the flow is coming out of the stock instead of going in (Figure 5). After creating the structure and entering constants and equations, I again asked for mental simulation and the students concluded with exponential decay. The model is then run to show the exponential decay of the stock. An example is radioactive material undergoing exponential decay.

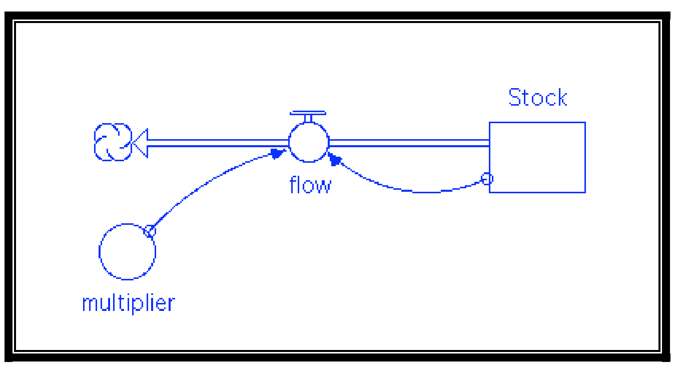

Figure 5: Exponential Decline Model

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[7] The iThink User Manuel provides excellent instruction for using their software and how to use it to build computer models.

The next model was slightly more complicated (Figure 6). There is a stock, a flow into a stock, a rate, and a goal. The equation for the flow is (goal-stock)*rate. I asked them what would be the behavior of the flow over time as the stock gets near the goal. They answered correctly that the flow would decrease over time and eventually stop. So what would happen to the stock? I picked a student to draw a graph on the board. Everyone agreed with the graph and I ran the model. This behavior is called goal seeking.

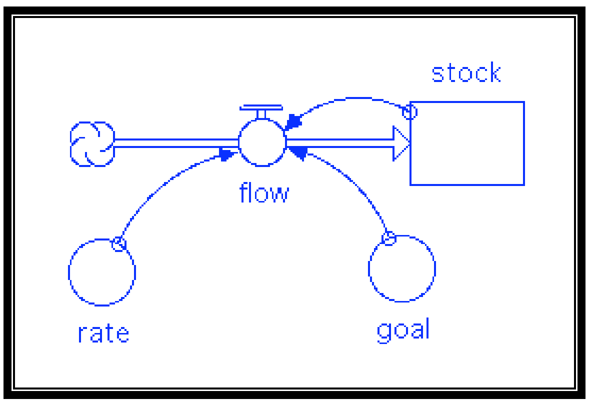

Figure 6: Goal Seeking Model

I built the next model from another blank iThink page. This model contained additional converter and links (Figure 7). The goal is replaced by a "growth constraint," which is determined by the stock and carrying capacity. The equation for growth constraint is 1- stock/carrying_capacity. The students could mentally simulate the behavior of the growth constraint - that initially the growth constraint will have miniscule effect on the flow, but that effect will grow as the stock gets near carrying capacity. As to the behavior of the stock there were disagreements. This time the students voiced a few different outcomes, including the right one. I asked them to think about it again but some students could not decide. One or two of the students voiced: "just run the model." Since the other students seemed stuck, I ran the model. To the satisfaction of those students who shouted, they had the correct outcome. Initially the stock experienced exponential growth since the growth constraint had little effect in the beginning. But as stock grew, the growth constraint eventually caused the flow to slow down. The system would then behave like a goal-seeking model, with the stock reaching the carrying capacity at a decreasing rate. The behavior of this model is called S-shaped growth.

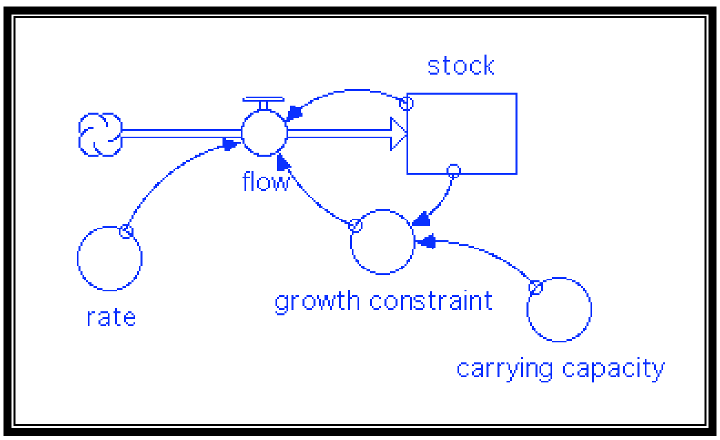

Figure 7: S-shape Growth Model

The previous models only contained one stock. However, one of the fundamental behaviors of a system cannot occur without multiple stocks. This behavior involves time delay. The delay can exist in any part of the system but it can only be modeled using at least one additional stock.[8] I built a goal-seeking model that contained a delay in perception (Figure 8). The delayed perception is the cause of a delay reaction to the situation. I talked the students through the behavior of this system. There is a difference between the stock and the goal called discrepancy.

However, that discrepancy is observed over multiple time periods. In this case, the time period is two. Since the initial perceived discrepancy is slow, the corrective action is slow. Eventually the stock is equal to the goal, but because of the delay in perception, what happens to the system? The perceived discrepancy is delayed so corrective action would continue and cause the stock to keep on going, to overshoot, when it reached the goal. At this time the discrepancy turned to the other direction. The perceived discrepancy will slowly change toward the other direction. The stock would overshoot in the other direction and the cycle continues. I asked, can someone tell me how the graph for the stock would look? A student drew a wave in the air said that it would "go up and down."

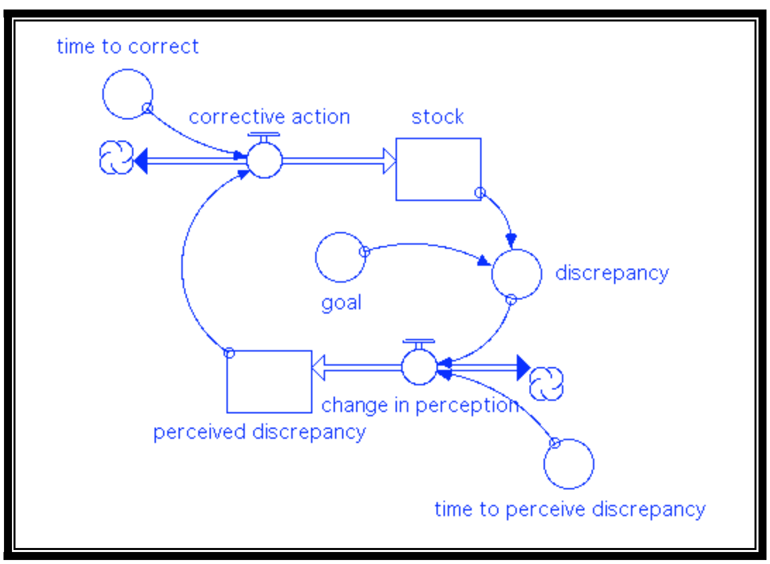

Figure 8: Oscillation Model

[8] The software contains delay functions. The delay functions do not show the structure (of additional stock) required to represent delay, so it's better to build the delay structure.

When I ran the oscillation model something unexpected happened. The stock oscillated but the oscillations gained amplitude with each cycle. At that time I could not identify the problem. Later I realized that the exploding oscillation was caused by the integration method of the computer program. Changing the integration method under "Time Specs" from Euler's Method to Runge-Kutta 2 resulted with continued oscillation of the same height.

Oscillation can be found in many business systems, from the inventory level of an individual store to the business cycle of the overall economy.

I finished my material for the day but there were about ten minutes left in the class. On Mr. Barys' suggestion we took the class to the computer lab. The students were enthusiastic but for some reason the system dynamics software was available only on one computer (we later found that it was due to misinterpretation of software license and fixed the problem). There was a predator and prey model that came with the software. The model has one predator population that feeds on prey population. The prey population is supported by a constant resource. The resource is just a stock with no inflow or outflow. Since the resource cannot be depleted, I thought this model would produce oscillating behavior of the predator and prey population but instead the model showed overshoot and collapse of the predators after it consumed all the prey population. The behavior was undesirable, so I challenged the students to correct the behavior. Students examine the model and offered many suggestions such as changing predator birth rate or consumption rates. However, none of the suggestions helped. I gave it a try but the behavior didn't change either. The class was almost over and there was no time to look at all the equations to find out what's causing the behavior. I explained that the behaviors of some systems are difficult to understand without simulations and in the case of the one we just saw, more time is needed to understand how the behavior occurs.

Today's session accomplished two main tasks. The first is demonstrating how to build simple system dynamic models in iThink. The session also taught the students how to simulate dynamic models mentally. Upon reflection, I should have provided printouts of the computer models built during class and assigned the task of duplicating those models as their homework.

There was a good discussion today. Although a few students are very vocal, the majority of the students are more reserved. For future classes I should encourage more students to participate in the conversation.

2.5 Journal Entry: September 20, 2001: Article response: Initial student responses

Student article responses. Mr. Barys distributed copies of a Boston Globe article "Cape debates impact of rail link[9]" (Appendix 3). The article is about an entrepreneur's proposal to bring passenger railroad trains back to Cape Cod. The railroad proposal raised many important issues but no clear solution. The students are asked to do the following, in writing: Identify and discuss problem, as they understand it. Identify and discuss their solution to the problem (the student writings are in Appendix 10).

The students will be asked to respond to the same article and same set of questions in the future for comparison.

[9] "Cape debates impact of rail link" Boston Globe August 19, 2001. B1, B6

2.6 Journal Entry: September 24, 2001: Playing the Beverage Game

Today we will play the Beverage Game. The debriefing (explanation of game results) is scheduled for the next session. The game usually requires two hours to play but the class was only 90 minutes long so I had to work fast and accelerate the pace of the game (for those who want to learn how to run the game, see Appendix 2 for tips).

I started to set up the game when the classroom became available. Some of the students were already there so they helped me set up two game boards and game pieces. We were quite efficient and the game was ready within five minutes. The students formed themselves into two teams and I asked each team to choose a name.

The Beverage Game is board game. It is a model of a supply chain developed to introduce management students to the concepts of system dynamics. Over the years many people have played the game, including students, teachers, government officials, and business managers. We are playing this game to demonstrate an important concept in system dynamics, which I will explain at the debriefing next session.

Here's how you play the game. Each table is a team working to minimize the overall cost to the team. The team with the lowest combined cost will win.[10] It costs $.50 every week to hold a unit of inventory but it would cost $1.00 a week to have a unit of backlog. I will explain backlog later. For the purpose of the game, there are some rules: The only way you can order something is to write it down on the order slip. There will be no communication about the orders between different positions on the order line. You can talk about the weather but not about the game.

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[10] Some students mentioned later in the game that they did not realize that the objective is to minimize cost. If I run the game again I would write the goal and the costs on the board.

There is also no looking up or down the supply chain. The Retailers please do not tell the others about the customer order pattern. The game won't be as exciting if you break any of these rules. We will have a discussion of the rules at the debriefing.

We will start with a training season of three weeks. Each business on the supply chain has slightly different responsibilities and we are going to train you to run your part of the business during the training season. The bingo pieces represent one case of beverage, the poker chips represents five cases of beverages. We start on week one. I took customer order decks from my pocket. The customer order decks which are all identical, were kept in my pocket so curious participants won't be able to flip through them before game time. I talked them through the steps of the game (Appendix 2). Some mistakes were made but quickly corrected. (During training season all sectors are required to place orders of 4 so mistakes stand out). By the end of the steps everything was in order. I changed the week number on the board to week 2 and again talked them through the process. At the end of week 3 training ceased and the students were freed to make their own decisions.

A few weeks went by and a position could not fulfill its customer orders because the sector did not have enough beverages in its inventory (typically around week 8). At this time I explained how backlog works in the game. The backlog is essential negative inventory. If order exceeds inventory, the sector will ship its entire inventory and record the difference between the backlog and inventory. For example, if the inventory is 5 but the order is 7 cases, the sector will ship 5 and record a backlog of 2. That backlog will have to be shipped when inventory arrives. Say if next week 6 cases arrived but there is an order for 3 more, the sector would have to ship 5 cases to fulfill its backlog and new orders and the inventory count would be 1 case of beverage [-2 (backlog) +6 (arrival) -3 (new order) = 1]. If there is nothing to ship, the team must ship a piece of paper with zero written on it so there won't be an empty spot (it’s confusing to have an empty spot).

As the game continued and the pace increased the usual problems emerged. Some students knew the steps well and tried to go ahead of the announced steps. Since out-of-sync steps could confuse the other students I reminded them to wait until the step was called. One sector kept concurrent inventory and backlog and that problem was corrected. At another point a student realized that his sector lagged behind the game by a week, so I had to fix it up quickly. It was more important to keep the game going. The seemingly simple game was not behaving as the students expected. In the beginning there seems to be plenty of demand but not enough inventory and deliveries to cover the demand. Later in the game the sectors are inundated with large deliveries while the demand seems to have evaporated. Nothing was happening as students planned. As expected, besides laughs about the situation, the students were blaming each other for their misfortunes. I will describe this in more detail during debriefing.

I stopped the game on week 36 with less than ten minutes left in the class. The students thought the game would run to week 50 and they were disappointed. They wanted to continue playing. But besides the need to finish a few more tasks there was a good reason for stopping the game. The recording sheets contain spaces for 50 weeks of records to mislead the participants into thinking that the game would run to week 50. Why is the illusion necessary? Studies show that game participants tend to explore experimental, sometimes irrational behavior as they see the ending of a game is imminent. To prevent participants from doing anything unrealistic such as running down inventory, it is necessary to stop the Beverage Game early (typically around week 36), before the perceived ending of the game.

I took the secret customer order decks and I reminded retailers not to tell the others about the customer order pattern. Too late. The retailers mentioned that they had already told the order pattern to a few curious students. Oh well, it will give them time to think about the game.

The first task was to calculate the total costs of each team. This is the total over the span of the game. For each sector, after the total quantity of inventory and backlog over the duration of the game was added, students calculate their sector cost according to the cost structure of $0.50 for each case inventory and $1.00 for each case of backlog. Summing the cost from the four sectors of a team produced the team cost.

The rest of the tasks include graphing variables over time. These graphs will be used for debriefing. For the first graph the students were asked to articulate their mental model of retailer's customer order pattern over time (as in what they think the deck of cards contained). Retailers do not draw this because they knew the customer order pattern. (For those students in non-retailer positions who already knew the order pattern I asked them to graph what they think before they found out what the order pattern was).

The next two graphs involve graphing from their record sheets. One is a graph of inventory level of the sector over time. The other is a graph of the orders they placed over time. There was a problem that seemed minor at the time. A number of graphs needed ranges beyond what was provided on the graph papers. We used extra paper for one graph and a student changed the scale on another graph.

As the students prepared to exit the class, (I guessed some might be bothered by the outcome of the game) I told them that there are reasons why things happened the way they did in this game. I will explain during the game debriefing.

The day was a success. I was able to compress the game from two hours to ninety minutes without cutting it short. Considered the accelerated pace, the game ran smoothly.
The students demonstrated a good understanding of the rules and instructions. There were the anticipated minor screw-ups but the supply chain behaved as it was supposed to. I guessed the game ran smoothly because the group size was small. I would prefer to have at least one other facilitator to look after the game, but it may be unnecessary because the group was small.

The student graphs were mostly sloppy. One problem was that students did not plot every week. Many more graphs had amplitudes that exceeded the given Y-axis, but the graphs made no mention of it. One graph was completely out of scale. Maybe the graphing part should be assigned as homework so students can spend more time on it. Nevertheless I taped the graphs together in vertical groups in preparation for the presentation. See Appendix 11 for game results.

2.7 Journal Entry: September 27, 2001: Quiz on stock, flow, and feedback loops

Mr. Barys gave his class a quiz on stock, flows, and feedback loops. (Beginner's modeling exercises, Appendix 4). See Appendix 12 for student results.

2.8 Journal Entry: October 1, 2001: Debriefing the Beverage Game

Today's task is to debrief the Beverage Game and to get students to share their thoughts. Recently I attended John Sterman's beverage game debriefing session to Sloan freshmen and I modeled today's session after that.

I started by asking the students what they thought of the Beverage Game. Their responses were enthusiastic; they enjoyed the game very much.

I continued. The game's structure and rules incorporated many simplifying assumptions. I asked the students if they could tell me some of the simplifying assumptions that the game made. The first answer referred to the communication between the sectors. Besides the ordering slip, game participants cannot talk to others about their knowledge or assumptions, including the customer order pattern. They said that knowing the customer order pattern would have helped and I agreed.

One student mentioned that the factory was extremely simplified. For example there was no restraint on factory capacity. In the game the factory was able to produce as much as it wanted at any time. It's unrealistic because it takes time to change capacity in real life. The factory in the game also didn't need raw materials to process.

The next student mentioned that there were no sales or marketing efforts in the game. In reality people are bombarded with advertisements. I explained that it's one less factor to affect customer demand.

The factory response seemed to have struck a chord. Another student mentioned that in reality the factory would need raw material and the price of raw material would fluctuate with demand. In real life the price of raw material is build into the cost of the product.

The next student mentioned the timing of when orders were made. If orders were made on a weekly basis, the distributor would probably wait for the retailers to make their orders before making their own orders, wholesaler would wait for the distributor's order and so forth up the supply chain.

Someone said that there was no limit to storage capacity at the sectors. The sectors were able to take in the flood of deliveries without restriction. In reality, there may not be enough room for the extra inventory. I added that over time the stockpile of inventory could expire but that it was left out of this game.

I continued to explain why the simplification assumptions were made. The main reason is to demonstrate that sometimes it is difficult to understand even a simple system. This game was designed to be as simple as possible. There were minimum variables and the structure and mechanics of the game are on the board for everyone to see. Think about this. If people do poorly in a simple game, what would happen in real businesses with many more factors and variables? A student mentioned that the lack of communication was unrealistic. I said that the game did simulated communications, since in real life people do not believe everything other people say. For example, would you believe everything another person said?

I asked the class what happened. I went from student to student and they provided many accounts, including: overproduction, over-order, "you people panicked," lack of communication, "I messed up," "we screwed up," and "he was screwing with me." There were plenty of theories but no one seemed to realize that the system was at fault. There was a general agreement that the players were at fault.

I proceed to present their results. These were taped together vertically by team with retailer on the top, then wholesaler, distributor, and factory at the bottom. The results were taped on walls. I asked the students to gather around the graphs so they could see the graphs better.

The effective inventory graphs show the inventory or backlog over the duration of the game. Initially there was a dip in the inventory and it developed into a backlog situation. Later the backlog was relieved by large shipments. However the shipments continued and most sectors ended up with stockpiles of inventory.

The graphs of Orders Made showed that there is gradual increase over time. In fact, the height of some of these orders jumped off the charts. Later, participants all dropped their orders to near zero.

On the first glance, the graphs are very similar to others but their differences would provide some insight into the system. I explained that the amplitude of the graphs was exaggerated as we go from retailer to wholesaler, distributor, and to factory, with the factory inventory level suffering the worst swing. I mentioned that the pattern is supposed to be delayed (a phase shift) as we compare retailer to wholesaler, distributor, and to factory, with the factory the most delayed. However, these graphs did not show it. I showed them a page from Sterman's book of typical results of Beverage Game to show examples of phase shift and magnification of amplitude. Those graphs also show oscillation in the supply chain.

We looked the graphs that contained students' perceived customer order patterns. They are the students' mental models of customer orders. These graphs are again similar to each other. All contained a rise and fall. That meant everyone thought customer orders rose then fell. But the students were not the only ones who thought that way. I told them that a partner at a major consulting company drew something similar to Figure 9:

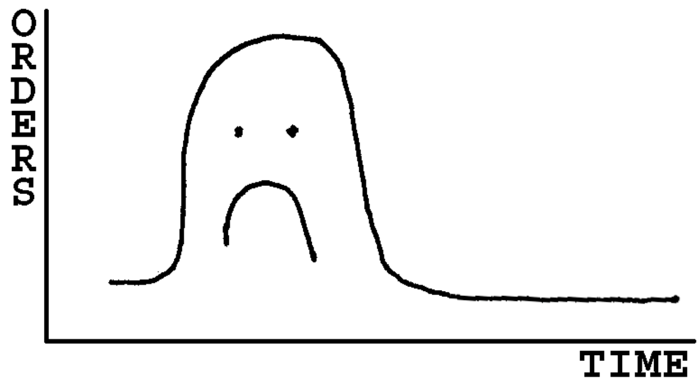

Figure 9: Customer Order Pattern as perceived by a partner at a major consulting company[11]

I finally revealed the customer order pattern. The only change in the pattern was that it jumped from initial demand of four a week to eight a week. And it stays at eight per week for the rest of the game. It doesn't fit the disorder experienced by every part of the supply chain. The students were surprised (those who hadn't found out). They wanted to know why.

All who played the game are individuals free to make their own decisions, but they all produced the same behavior (to a greater or lesser degree). Why? Structure caused this behavior. Imagine what would happen if you were hired as the manager to run this business? Initially the boss would ask you to try harder. But as time goes on and matters became worse, the boss might have a talk with you. "We're sorry to fire you, but it seems that you are not able to do your job so we have to let you go."

So who won? I announced the winning team. Their cost for the duration of the game was $4279.50. The other team had a cost of $5764.50.

I explained that some teams do better than the others, but no one group gets close to the optimal. The optimal cost was in the hundreds. The average cost for teams are typically about $1,500. You may think that it's fine as long as you are the best among humans, but think about the savings if this is a big complex corporation with billions of dollars in revenues. The saving would be in the hundreds of millions.

So what can you change to improve this system? One, you can change physics. You can try to change the physical structure of the game. Shipping delay can be minimized but it cannot be eliminated. Two, you can change the information flow. For example the retailer could send the customer order pattern to the other businesses in the supply chain. But would you believe everything another person said? Third, you can try to change mental models. The other players on your team did not try to sabotage your job.

You may be thinking this is only a game and situations like this don't happen in real life. Well, it does happen in real life. An example is the Italian pasta industry. A person may eat spaghetti one day and ravioli another day. But overall it's all pasta. Do you know what their demand for pasta is? It is constant and it is high.

Their supply chain has manufacturers with more distributors than manufacturers and more retailers than distributors. They suffer oscillation in their supply chain. The manufacturers would sometimes need to hire workers and have all the workers work overtime. At other times they have to fire workers because they did not receive any orders.

It turned out whenever retailers had a sale on pasta, customers would stock up with pasta for the future. The store would sell a lot so they would place big orders to restock their inventory. But

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[11] I saw this at John Sterman's beverage game presentation. I liked its comic relief aspect.

customers don't buy much more when the price is back to normal. Meanwhile, the retailer's orders arrived at a greater rate than the customer's rate of purchases. Inventory would build up and retailers would stop ordering from distributors. In time, to reduce the inventory, the retailers would have another sale, and the cycle continues. The supply chain amplified this swing so it' s much worse for the manufacturers.

Situations similar to the beverage game happen in real life but we are not helpless. Although real life situations are often too complicated to run "mental simulations," computer simulation can help. A model everyone can see, agree upon, and experiment with can help tremendously with people's ability to make better decisions.

Today's lesson went well. For comparison, I should have brought graphs that were made by other players of the beverage game. Those graphs would be larger and more personal than graphs in a textbook.

To encourage participation I brought a bag of candy to class. After the first student who answered a question received a piece of candy the students became more enthusiastic than usual to respond to my questions. Although students don't get any more candy after getting one piece, the students continue to participate with great enthusiasm. By the end of the class everyone had spoken out at least once.

2.9 Journal Entry: October 4, 2001: The First Three Hours Article

Mr. Barys led the students to read and discuss the first three hours article (Appendix 8). This session was undocumented.

2.10 Journal Entry: October 8, 2001: Model Building Process: Identify variables, create reference mode, and develop dynamic hypothesis

Today I will explain the computer model building process. The model will be based on an article about drugs. The article is about a study that disputes the conventional wisdom that reducing drugs would reduce crime.

Students received a copy of the article "When heroin supply cut, crime rises, says report" (Appendix 6). It is a short article and students finished reading in a few minutes. I asked them to tell me what the article talked about. Someone gave a concise summary.

This article said busting drug dealers would actually increase the crime rate. Because the drug prices would increase, addicts would commit more crimes to raise money to buy drugs.

I asked students around the room to name the variables involved. I wrote them on the board and asked for input from everyone around the room. The list included price, customers, suppliers, busts, crime rate, income, addiction rate, population, rehab, trafficking.

In system dynamics we don't model everything. We model a problem. The reference mode is the first step to building a computer model. The reference mode is a visual definition of a problem. It involves graphing variables that are important to the problem over time.

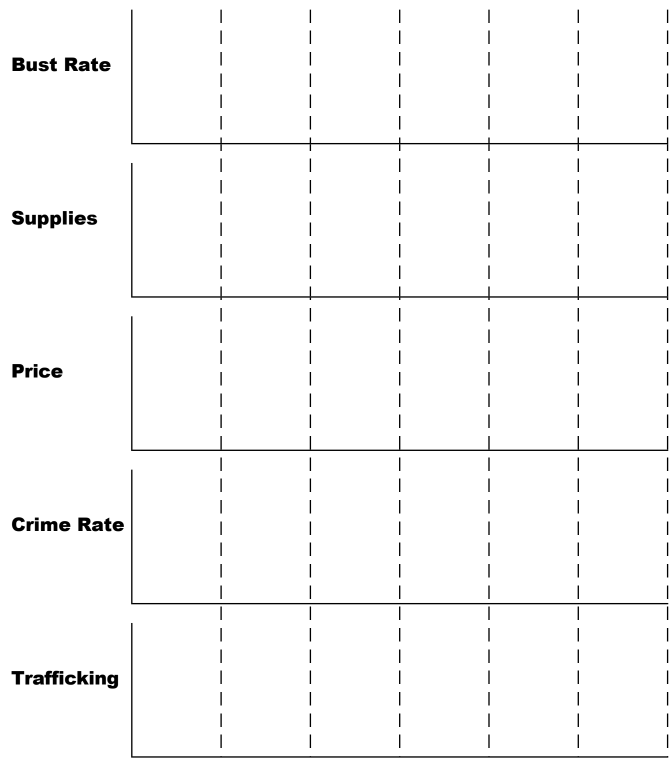


Figure 10: Blank reference mode

To develop the reference mode, I narrowed down the variables to bust rate, supplies, price, crime rate, and trafficking. The graphs are vertically aligned to show correlation of variables. I drew on the board five L shaped graph axes for the variables. I drew vertical dotted lines to divide the x-axes into equal sections. The x-axes represents units of time (Figure 10).

We started this off with equilibrium for the first time period. To simplify the problem, we assumed that addicts would not quit the drug.

Time period 1 to 2. The equilibrium was disturbed with an increase in bust rate to simulate police busts. I asked the students what would happen to the supplies (city's total drug inventory) and they answer that the supplies would decrease. With a decrease in supplies price would increase.

And with the increase of drug prices revenue-raising crimes would increase (slightly for this time period while others think about committing crimes). Since it takes time to increase drug trafficking, there is no change in trafficking at this time.

Time period 2 to 3. At this time the police busts returned to normal. The supplies would level off. The price would plateau at a higher level than before. The addicts would need to commit more crimes for drug money. Extra money from the crimes begins to increase trafficking.

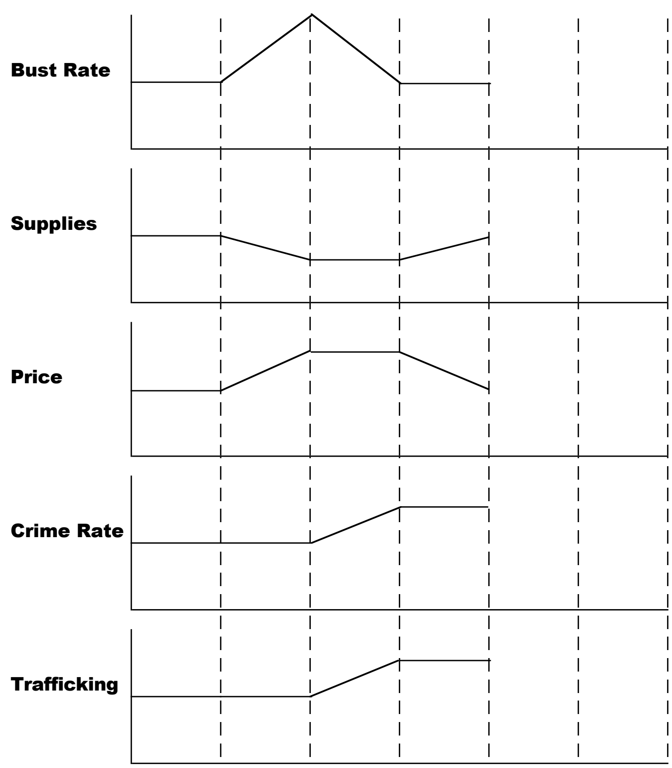


Figure 11: Drug Article Reference Mode

Time period 3 to 4. Due to the increase in trafficking the supplies finally increase. Price would decrease. Crime rate and trafficking would plateau. Without a computer simulation it is difficult to determine what happens next (see Figure 11 for the reference mode).

The next step involves drawing causal loops to describe the problem. Using what is sometimes called the dynamic hypothesis, we determined how different factors affect each other. I asked the students to recommend links and tell me the polarity of those links. To determine polarity of individual links, we look at each link independently, assume all other variables are constant. If the cause is increased and the effect increases, the variables are going in the same direction. This is represented with a positive sign at the head of the arrow. If the cause is increased and the effect decreases, the variables are going in the opposite direction. This is represented with a negative sign.

One way to determine loop-polarity is by counting the number of negative signs around the loop. If it's an even number, the loop is positive. If it's an odd number it's a negative loop. Positive loops are self-reinforcing. A change in one of the variables would change the other variables in the loop and eventually reinforce the original change. Negative loops counteract any change and balance the system. Strong negative loops tend to bring the system into equilibrium. The dynamics of any system are produced by the interaction of the positive and negative feedback loops.

One of the first loops linked supply to price to consumption and back to supply. Since an increase in supply would decrease the price, that link is negative. An increase in price would decrease consumption. This link is again negative. An increase in consumption would lead to a decrease in supply (negative link). This is a negative loop.

We worked to create a new loop. Drug price would also affect trafficking. An increase in price would lead to an increase of drug trafficking. If trafficking increased, supply would also increase. Since an increase in supply would reduce price, the loop is again negative.

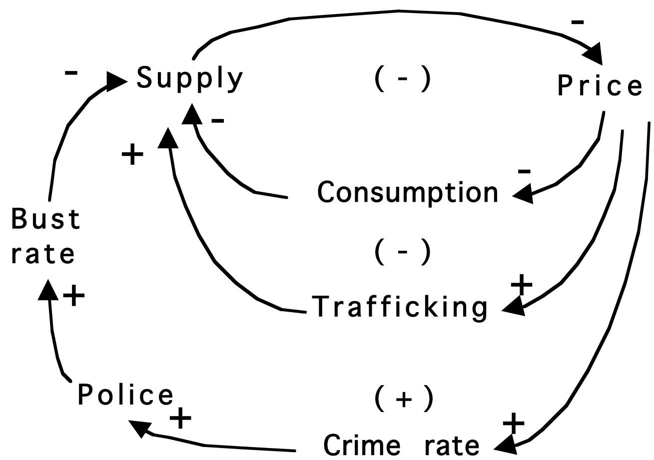


Figure 12: Drug Article Causal Loop

We produced a final loop to include crime rate. After we determined that an increase in price would increase crime rate we were stuck for a moment. Someone mentioned that increase in crime rate would lead to an increase in policing (due to citizen complaints). The class was almost over. In the interest of time, I took up the next student's idea to close the loop. An increase in policing would lead to an increased bust rate. An increase in bust rate would lead to a decrease in supply. This loop completed with a positive polarity.

As we developed the different loops they were added to the loops that already existed. The final causal loop on the board was quite messy. Some links crisscrossed other links. I redrew the diagram (see Figure 12) to make it more orderly.

The students had many ideas and today I mainly facilitated their exchange of different ideas and theories. The students addressed and agreed to the reference mode and the causal loops. I noticed that not many were taking notes because they were busy speaking out, expressing their ideas, or listening.

Upon reflection, I think that, the causal loop diagram we developed today has two problems. As we analyzed the crime rate, it did not lead to the exchange of crime money with drug dealers. At least in the context of the article, the police bust rate seemed like an external decision and did not appear as part of a loop. This suggests that the crime rate loop should be revised. Perhaps additional information on drugs and crimes is needed.

2.11 Journal Entry: October 11, 2001: Model building process: Translate dynamics hypothesis into a computer model

Today we will continue building a computer model based on the drug article. In the previous session we painted a picture of the drug problem. The goal of today's session is to translate our causal loop diagram into a working computer model. The computer model should exhibit behaviors similar to the reference mode.

I drew the causal loop diagram of the drug problem from the last session. I started to build a model from this causal loop diagram but did not complete a working model. For this, I used a WPI professor's model (professor Saeed's model on drugs can be found in Appendix 7). This model differed from the class’s causal loop diagram because it makes many more simplifying assumptions.

I have a copy of the professor's model on disc, but I proceeded to build it from scratch for the students. I started with a stock called drug inventory and a flow of drug consumption rate. Consumption rate depended on the number of total addicts and the drug consumption per addict. To simplify things, the model assumed that the number of addicts and the amount of drugs they consume stays constant. This leads to a constant drug consumption rate.

The next variable I created was drug price. This is a ratio between desired drug inventory and existing drug inventory. If drug inventory increases but desired drug inventory stays constant, the price would fall. If drug inventory decreases, drug price would increase. Most businesses set an inventory coverage time to keep inventory on hand to fulfill demand for a certain amount of time. I utilized the same structure. Desired drug inventory depends on drug consumption rate and inventory coverage time. Inventory coverage is a constant.

In this model, the next links factors in crime. The potential to commit drug-related crime ("drug related crime potential") is determined by the drug price and the normal drug-related crime potential. Normal drug-related crime potential is determined by normal crime per addict and the number of addicts. Normal crime per addict is a constant. After a delay, the drug-related crime potential becomes drug-related crime. For drug-related crime a smooth function is used, I presume for simplicity.

The drug supply rate is an inflow into drug inventory. The drug supply rate is determined by drug-related crime and average drug supplied per crime. The best explanation I have for this is that the proceeds of the crimes were used to buy drugs. That money is passed on to the drug dealers, who in turn, use it to supply more drugs.

Finally, there is an outflow from drug inventory called “busts.” This is an external policy to represent drug busts made by the police. "Busts" used a step function. A step function changes by the "step" amount at a predetermined time. In this case, it would increase busts to 10% of drug inventory on the fifth time unit of the simulation.

For the first run, I switched drug busts off (by multiplying it by zero) to ensure that the model would run at equilibrium. I explained that an equilibrium run is one of the tests to decrease the chance of having bugs in the model.

I then activated drug busts to bump the model up from equilibrium.

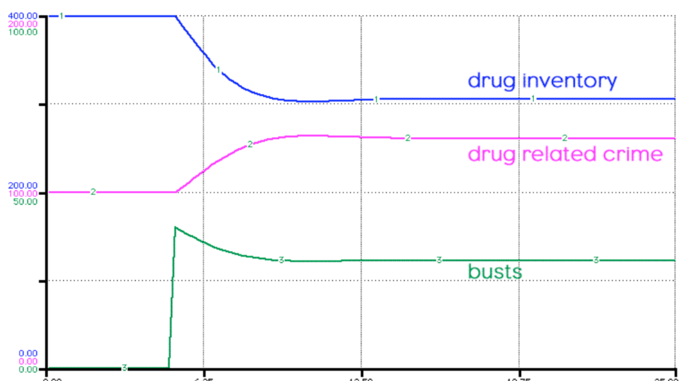


Figure 13: Drug Model with Drug Busts

Figure 13 shows that an increase in drug busts resulted in a decrease in drug inventory and an increase in drug related crime. Drug busts dropped after an initial high, because as there are fewer drugs on the market, it becomes harder to make busts. The model arrived at a new equilibrium with a lower drug inventory but with a higher crime rate. The model did not go back to the initial equilibrium, because drug busts continued throughout the rest of the simulation run.

Some students wanted to see a run comparable with the reference mode we developed at the previous class. That reference mode had drug busts that were turned off after some time. To do that I inserted another step function [STEP(-.1,10)] that would activate to drop busts from 10% back to 0% of drug inventory.[12] Figure 14 shows that the model slowly went back to initial equilibrium as drug inventory was replenished by drug crimes.

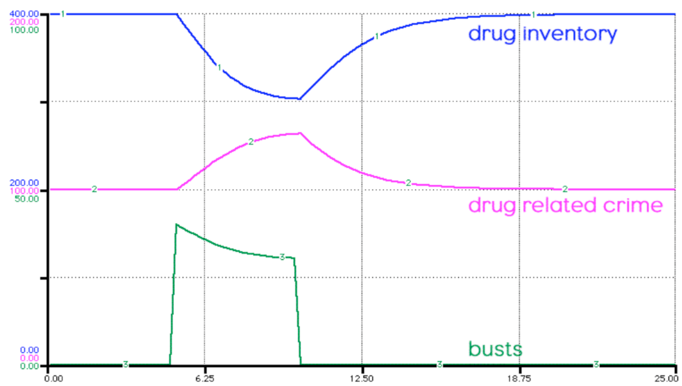


Figure 14: Drug Model with Drug Busts for a limited amount of time

So what's next? To determine a policy that can help the system. If busts increase crime, what would be the outcome if the reverse happened? Let's see what happens if, instead of taking drugs away, more drugs were introduced into the system. To do that I removed the busts outflow and introduced an inflow call "free drugs" with equation of STEP(20, 5). The outcome of this policy was predictable. With more drugs in inventory, the price of drugs fell. With a lower drug price, addicts do not need to commit as many crimes to get their fix; crime rate decreased (see Figure 15).

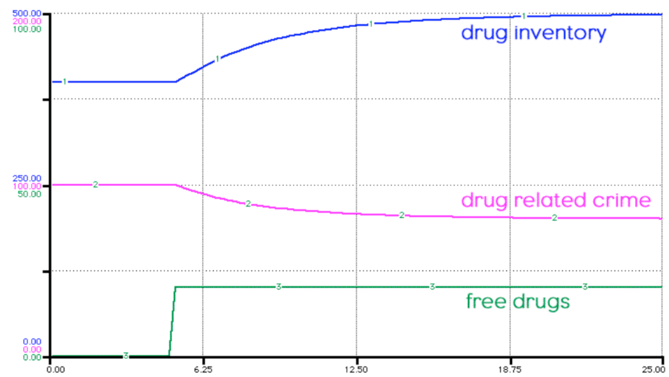


Figure 15: Drug Model with Subsidized Drugs

It seemed such a simple solution. But does it work in real life? Methadone clinics are the real-life incarnation of this idea. Although these clinics do not give away heroin, they offer methadone that is taken orally by recovering addicts to subdue the desire for heroin. These clinics in effect offer a controlled but free alternative to buying heroin, reducing the need for heroin and the need to commit crimes for heroin.

I assigned homework to replicate the model that was built today. Students receive a copy of the visual structure along with equations of the model. They will have to bring a printed copy of the replicated model, the equations, and the simulation graphs to our next meeting. I told them that the software is available on WPI computer labs. If they want to work at home, they will have to download a demo.

I explained that there are three main software packages for system dynamics. High Performance Systems makes iThink. It will work on both Mac and PC, but the demo does not allow models to be saved. PowerSim makes PowerSim Constructor. It only works on PCs. Vensim makes Vensim, which will work on both Mac and PC, but I recommend against using Vensim because

[12] Busts = drug_inventory * (0+STEP(.1,5)+STEP(-.1,10))

it's difficult for beginners. I pointed out that the students can find download links on the web site of WPI's System Dynamics Club at www.wpi.edu/~sdclub.

There was some disappointment today because there were significant differences between the model and the causal loop diagram. Maybe I should have created a model from the causal loop diagram. I could also have steered creation of the causal loop diagram so the result would resemble the model that was built today.

2.12 Journal Entry: October 15, 2001: Model building process

Today's session will be comparable to the class on October 8. The product of today's class will be a reference mode and causal loop diagram of a problem. Today's discussions will be based on the Cape Cod railroad article (Appendix 3). We have Professor Saeed from WPI as our guest today.

Students mentioned that they still had problems accessing the software at the Mass Academy building. As I collected the homework assignment, Professor Saeed answered a few questions about the drug model.

After the students took a few minutes to read the railroad article I asked them to provide variables. The list included train, tourists, residence, development, cost for train service, cost to build railroads, ticket prices, speed of train, (automobile) traffic, government subsidies, desirability of the destination, and travel time.

I divided the students into three teams. Each team will pick between three and five variables and graph a reference mode. They will then present it to the class. Professor Saeed suggested that student keep a specific client in mind as they develop their reference mode, since different clients would have different needs and different models. For example the railroad operator would look for ways to optimize profit, while the local government would study the economic and environmental effect of the railroad on local communities.

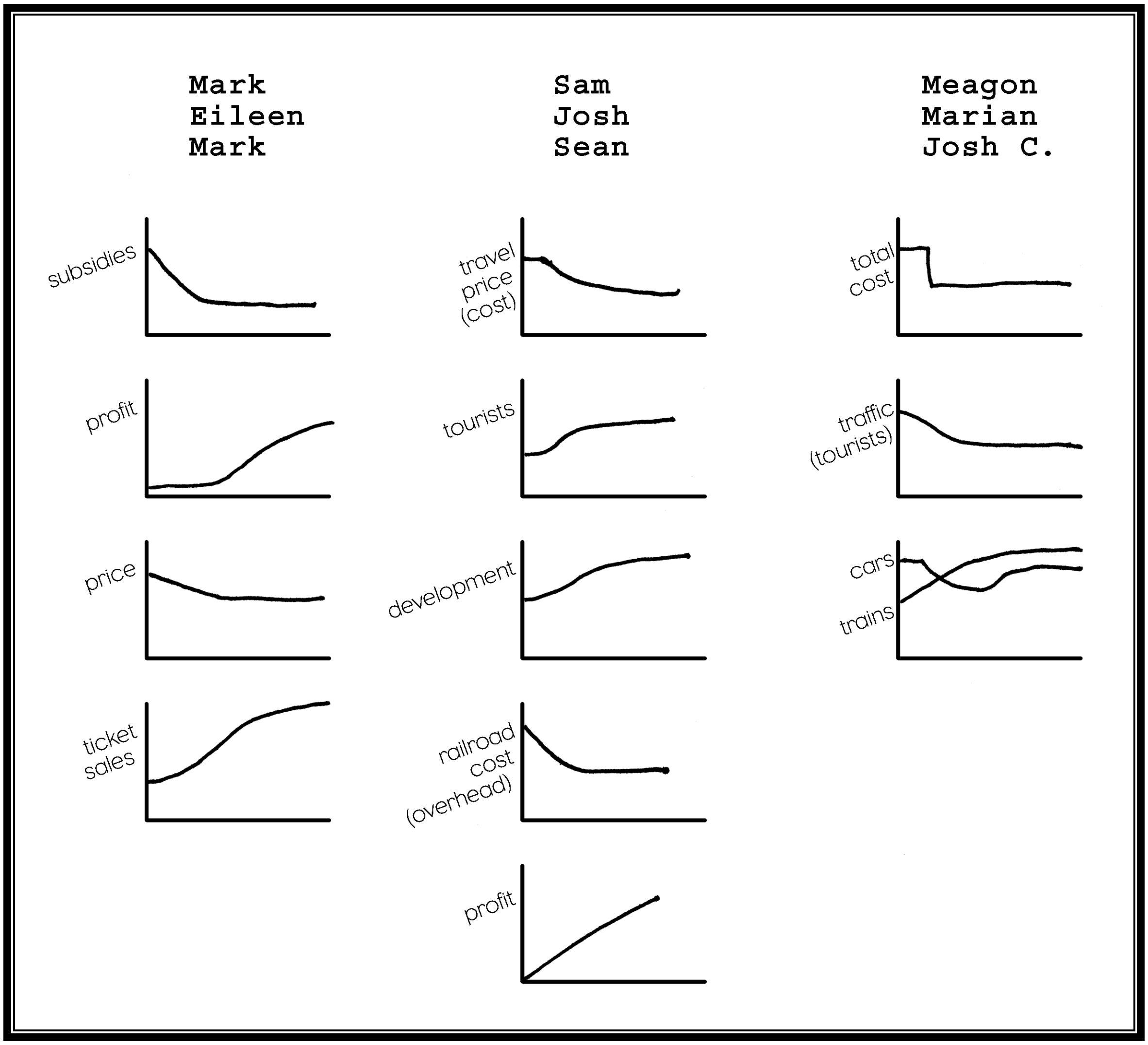


Figure 16: Railroad Reference Modes by Students

I walked around to observe the students' progress. After five minutes I stopped the groups and let them present their reference modes. Student reference modes are combined in Figure 16.

First group (Mark, Eileen, and Mark): After initial subsidies there will be no profit for a period of time as the railroad service slowly gains customers. As ticket sale increase, the profit would increase. With increased profit the railroad operator can then cut ticket price to gain more customers. Eventually ticket sales and profit would reach a plateau and stay there.

Second Group (Sam, Josh, and Sean): After initial investment into railroad, the overhead for running railroad would decrease. Ticket price could decrease as more tourists take the train. As the number of tourists increases there will be a rise of economic development to provide services to the tourists. Railroad profit would increase.

Third group (Meagon, Marian, and Josh C.): The initial cost would be high for the railroad operator. But once the railroad was completed the operating cost of railroad would drop to a lower level. The heavy automobile traffic could drive some tourists to take the train. As more tourists took the trains there would be fewer cars and less traffic. Eventually it will be appealing to some people to drive again because of the lower level of traffic on the road, as more people take trains. The amount of automobile traffic could increase slightly, and as the desirability of trains and driving stabilized, there would be a new equilibrium, with less traffic than before and good number of people taking trains.

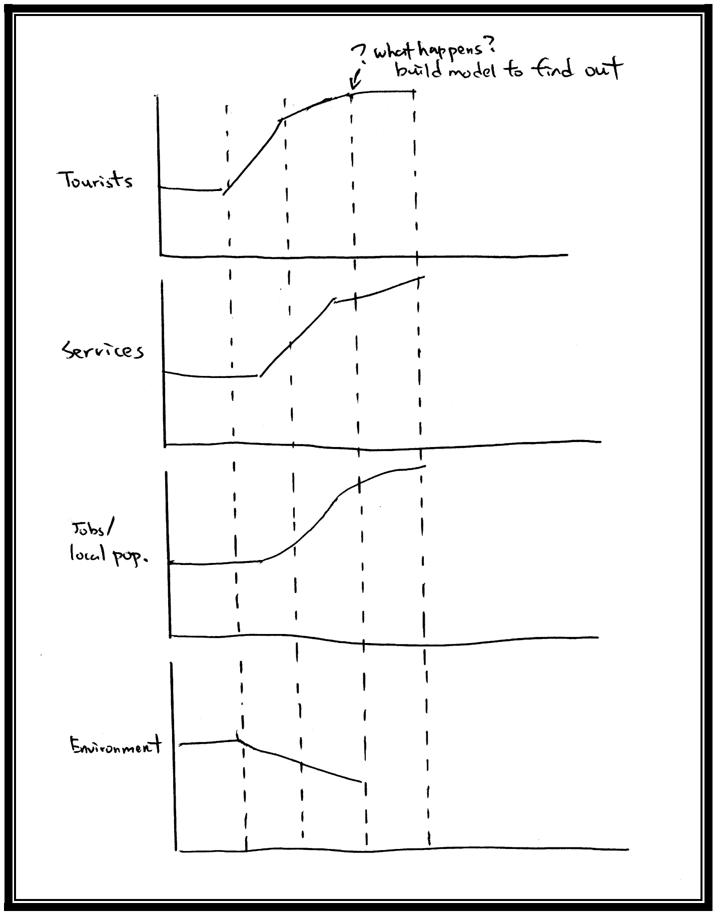


Figure 17: Railroad Reference Mode

With Professor Saeed's expertise we combined different perspectives into one (Figure 17). Train service would certainly increase the number of tourists but what will happen with more tourists? An increase in tourist would result in an addition of tourist services. This would result in an increase of jobs and higher local population. However, an increase in local population and businesses would certainly degrade the environment. What would happen if the environment deteriorated enough that it might no longer be desirable to go the Cape?

With the railroad's effect on the environment in mind I helped the class construct a causal loop diagram to combine various ideas discussed today.

We started with the tourists at the first variable. The first loop covered railroad. An increase in the number of tourists would increase railroad operator's profit. With more profit, the railroad operator could increase railroad capacity. An increase in railroad capacity could lead to more tourists. This is a self-reinforcing loop.

A second loop considered services. More tourists could result in an increase of services for tourists (shops, restaurants, hotels, etc.). An increase in services would in turn bring more tourists. This is also a self-reinforcing loop.

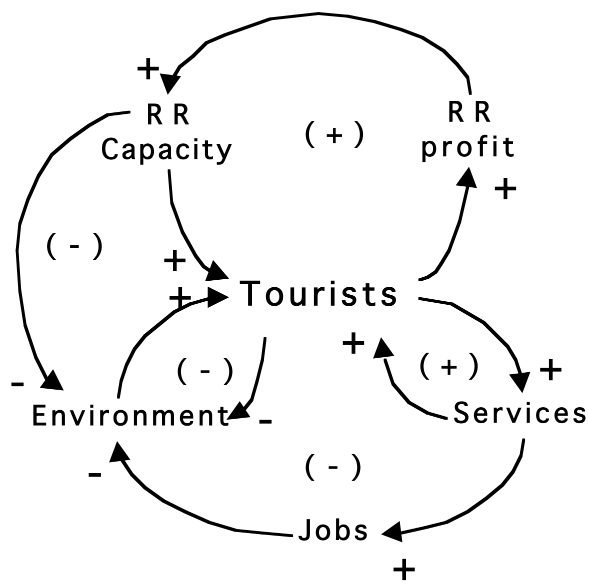


Figure 18: Railroad Causal Loop Diagram

The next loop added environmental conditions to the system. Tourists have a negative effect on the environment; more tourists are likely to cause more damage. However, the environment has a positive effect on tourists; better environments will attract more tourists.

Other factors also affected the environment. Railroad capacity has a negative effect. Tourist services also have an effect. An increase in tourist services would lead to increase in local jobs (and population). That in turn will have a negative effect on the environment (see Figure 18 for the Cape Cod railroad dynamic hypothesis).

As homework the students are to continue working in groups to develop stock and flow models from the reference mode and causal loop diagram. Each team will present its model and findings at the next session.

Things went smoothly today. There were plenty of discussions and a lot of participation. A student had a funny comment: "Are you going to give us candy?" As to the assignment, I know building a model for homework is an ambitious goal, but I was curious to see how much we could accomplish.

Professor Saeed commented that the students were very responsive and that they participated well. He observed that although one group had a handle on the problem and another group had lagged behind, by the end of the class everyone seemed to understand the problem. Professor Saeed also noted, a convergence from various visions to a commonly accepted reference and one dynamic hypothesis.

Four students submitted their homework assignments that were due today. One model was built in Vensim. It didn't come with equations or graphs. I assumed that this student could not figure out how to enter equations into Vensim. The other three were built in iThink and included graphs of simulation runs. One model was built correctly. The other two running models came very close. Each contained a different bug. One model did not connect a flow; the other model reversed the flow of drug busts. Although these bugs can be fixed in seconds they may be difficult for beginners to find.

2.13 Journal Entry: October 18, 2001: Student Presentations, Course Conclusion

Today is our last session. Students will present their computer model and findings.

The students did not have much to present. One group said they had an iThink model but couldn't save it because they used a demo version of the software. One group had a model that won't run because it lacked equations. One group had a working model in PowerSim. The model showed an initial decrease in traffic, then traffic increased to above starting level.

We discussed the models. They did not contain enough feedback; and some components were constants not affected by the system. The relationships between some model variables were not clear (unit conversion problems). The students seemed to have tried hard to create working models, and I realized that the assignment should have been much simpler. The students would need much more instruction in order to build a complex computer model.

I drew the causal loop diagram on the board. For the rest of the class I tried to build a working problem from the causal loop diagram. There wasn't much time and I could not get the model to run in equilibrium. As the class neared its end, I told the students that I am glad to have had the opportunity to introduce system dynamics to them. The material I taught is only meant as an introduction; more training is necessary to make complex models. However, many of the concepts from the class could be applied to look at the world with a different perspective.

After the class a student expressed interest in taking more system dynamics classes. Mr. Barys said he couldn't see why not. The student could take the system dynamics classes offered at WPI as his senior project.

2.14 Journal Entry: November 16, 2001: Article response: Final student response and Control group response

Students who took this class and the student who took a math-modeling course responded to questions about the railroad article. The students who took the math-modeling course serve as the control group for learning.

3 JOURNAL: OF EVENTS AFTER COURSE CONCLUSION

3.1 Journal Entry: November 14, 2001: Entry into a Mathematical Contest Using System Dynamics

Mr. Barys mentioned that three students from the class just finished the Mathematical Contest in Modeling in which they used PowerSim to model the evacuation time of a tall building. I think it was notable that these students would voluntarily choose to use system dynamics software to tackle the contest. I guess the class made an impression. See Appendix 16.

3.2 Journal Entry: November 15, 2001: Attendance at WPI Major's Fair

Today was WPI Majors Fair. It's been a month from the conclusion of the class at Mass Academy. I was a representative of the Social Science and Policy Studies department. The SSPS department brought three laptop computers with system dynamics computer simulations.

The Mass Academy students came as a group. Students who took the class enthusiastically brought their friends to the SSPS table. They showed much interest and they asked me many questions. The table was literally swamped. The students were able to explore and run the computer simulations. Many were amazed at the complexity of one of the computer models.

Referring to the impact of the class, one student commented: "We're thinking differently."

Appendix 2: How to Run the Beverage Game

David Liu

Summary:
This guide is designed to improve the facilitation of the game. Most of this guide came from my notes of the Beverage Game facilitation training at MIT.

Notes:
The Beverage Game (or more commonly known as Beer Game) can be purchased from the System Dynamics Society. http://www.systemdynamics.org/Beer.htm

How to Run the Beverage Game

Facilitation Tips

- Do not move chips or slips for the player. Tell them what to do.
- Keep the order deck hidden, until the appropriate time (to keep participants from flipping through the deck).
- Make sure team name and position are on sheets (for record keeping purposes).
- Make sure the participants do not go ahead of the facilitator. (Going ahead may confuse other players).
- Some conversations will be colorful, especially the blame game. Quote those conversations for use in debriefing.

Steps of the game. (I have combined "fill orders" and "record inventory or backlog" because I found myself doing both steps at the same time when I played).

	Steps description	Verbal Command	Facilitator Check
1	**Receive inventory and advance shipping delays**	Take both hands and put them in both positions to your right. Move them one spot to the left.	• Both hands are in the right positions • Pieces moved to the right direction.
2	**Fill orders and record inventory or backlog**	Retailer first. Take top card from the customer order deck, do not show anyone except your partner. Place card facing down and fill your order. Other positions take the order slip at your 11 o'clock position, show your partner and put the slip under the game board. Fill the order by moving the proper amount of chips out of your inventory. Record your position's inventory or backlog.	See if retailer did the shipping Card placed face down Other positions are using the right order slip • See if the other positions did the shipping
3	**Advance order slips, factories produce**	Every position except factory, take the order slip at your 1 o'clock and move it one position to the right. Factories take the production slip and move the correct number of chips into the supply chain. Put the slip of paper under the game board.	• Make sure order slips are moved by the correct position • Make sure factory produces
4	**Place and record your orders**	Decide how many cases of beverage you want, record your order on both the order slip (place your order slip face down) and order sheet.	• Make sure order gets placed

Tell participants that the game will be run for 50 turns. However, stop the game at or before turn 36. This is to prevent participants from doing unrealistic things toward their perceived ending of the game (such as running down the inventory level or placing unrealistic orders).

Appendix 3: Article: Cape Debates Impact of Rail Link Questions by Jim Barys

Summary:
Student responses to this article and accompanied questions were collected in the beginning of the course (September 20) and after the course were over (November 16). Also given out to a control group of students on November 16, the responses would be used to determine whether the course made any impact on the detail level of student response and student reasoning between the students who took the system dynamics class and the control group.

City/Region News B1-6, B12
Starts & Stops B2
New England News Briefs B2

City&Region

BOSTON SUNDAY GLOBE AUGUST 19, 2001

Cape debates impact of rail link

Critics say trains could add to growing pains

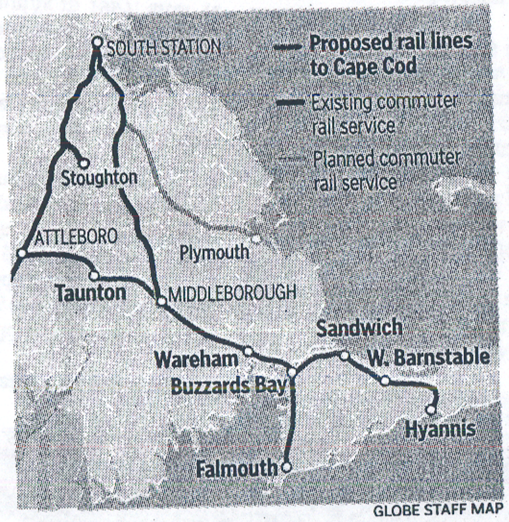
By Raphael Lewis
GLOBE STAFF

HYANNIS — Stewing in the endless, inevitable traffic jams that clog the banks of the Cape Cod Canal each summer weekend, drivers have long cast a hungry eye toward the mysterious, twin-towered bridge looming to the south, its 544-foot span unencumbered by a single car, bus, or truck.

Once a testament to ingenuity, the 65-year-old Buzzards Bay Railroad Bridge and its moveable deck is now a monument to inactivity, lowering just twice a day for the past three years for garbage trains carting refuse from Cape Cod to an inland incinerator.

Now, as the Army Corps of Engineers works to complete a $30 million restoration of the stately span — one of just three across the canal — a campaign to open the bridge to passenger trains is picking up steam.

But as the movement chugs forward like the locomotives of old, some say the revival of train service on the Cape could derail years of careful planning and land management by creating a speedier trip to and from Boston that would spawn u[illegible]ted development. And that, they say, would only worsen traffic in an already fragile environment.

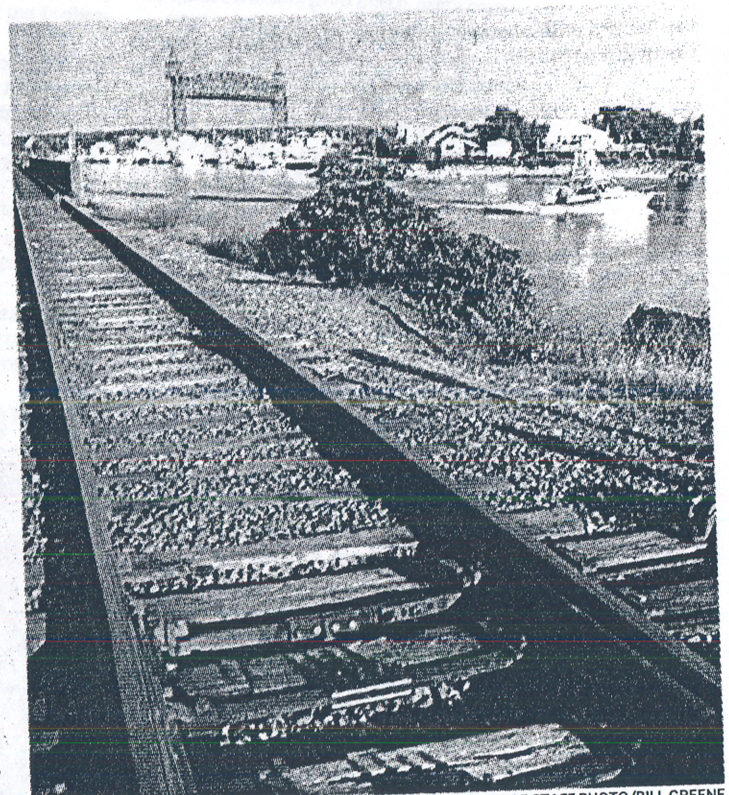


GLOBE STAFF MAP

Like the bridge itself, one Hyannis entrepreneur hopes to bring together the opposing sides — and usher in a new era of rail service to an area choking on its own popularity.

"I've been convinced for a decade that the Cape is right for low-key, environmentally benign rail service, something that would fit in with the landscape," said John Kennedy, 39, whose passenger train proposal has emerged as

TRAIN, Page B6


GLOBE STAFF PHOTO/BILL GREENE

A railway line near the Cape Cod Canal in Bourne, with the old Buzzards Bay Railroad Bridge in the background.

…ed from Page B1

…eader among three such plans.

Kennedy, president of the Cape Cod Central Railroad, which runs tourist trains of refurbished rail cars from Hyannis to the banks of the canal, knows firsthand of the public's desire to ride historic railways. In its third year of operation, the Cape Cod Central is on a pace to serve 60,000 passengers, 25,000 more than last year, and 43,000 more than its first year.

Seeing such a market, Kennedy's company has purchased seven self-propelled train cars built in the 1950s. The Budd cars, so named for their manufacturer, marry the needs of a modern traveling public with the aesthetic, nostalgic requirements of Cape Codders, he says — all at a fraction of what it would cost the state to bring back rail service.

Under his multiphased proposal, Kennedy would deploy trains as small as one car, depending on ridership, to carry tourists and commuters from the MBTA's Middleborough rail station to Hyannis, home to a ferry port, an airport, and next spring, a $5.6 million transportation center that will house intercity and local buses, and shuttle services.

The Budd cars, each powered with a diesel engine, would be allowed to travel only 40 miles per hour on the Cape, and 60 m.p.h. once across the canal, which means the trip to Boston would take about 2½ hours, if the connection at Middleborough were seamless. Currently, bus services make the trip in about 1 hour and 45 minutes, when they're not stuck in traffic.

Because of that long journey — one commuters would likely think twice about — Kennedy's proposal is attractive to many state and local leaders, who fear a high-speed commuter rail line would trigger even more development.

Among those who say they like Kennedy's plan are state Transportation Secretary Kevin Sullivan, former governor Michael S. Dukakis, who is cochairman of Amtrak's board of directors, and several members of the Cape Cod Commission.

"I don't believe this proposal will be a successful commuter service, and for that reason, I don't have any concerns," said Clay Schofield, transportation engineer for the Cape Cod Commission. "I think it's a service that would be attractive to tourists in the summer, and that's a good thing because they wouldn't drive here."

GLOBE PHOTO/STEPHEN ROSE

John Kennedy near the 1950s trains that he envisions as a key to his plan.

But making a profit solely from tourists may be tough. In just the past few weeks, two other proposals that would cater to the tourist market have fallen off the table.

One plan examined by the Cape Cod Transit Task Force, a group assembled last year by Sullivan, called for Amtrak to restore the Cape Codder, — a summer tourist train from Washington D.C. to Hyannis that stopped running in 1997, after 11 years of highly subsidized service.

But last week, Dukakis said the national railroad could never contemplate resuming such a service, given Amtrak's financial problems.

"The Cape Codder was a great train, but we simply can't afford it," said Dukakis, who has thrown his support behind Kennedy. "We cannot inaugurate a new service that doesn't at a minimum break even. If the states [where it would travel] want to subsidize it to make it break even, that's different, but I don't hear anyone from New York, Connecticut, Rhode Island, or Massachusetts saying they would do that. This has got to be a state-supported service."

Another plan, floated by the Cape Cod Regional Transit Authority, would run MBTA commuter trains on weekends to connect the Cape to Amtrak's high-speed corridor in Providence. But last week, Joseph Potzka, the transit authority's administrator, told the Globe that his agency has quietly decided to back away from that plan.

"We still think it's an excellent proposal," Potzka said. "But we're not a rail agency. We think the state should pick up the ball and run with it."

Although the state's Executive Office of Transportation and Construction has voiced approval for the restoration of rail service to and from the Cape, no plan, including Kennedy's, appears to have any immediate priority.

That agency must request bid proposals for such service, but none is planned any time soon, officials said.

"I think it definitely is for real. It's going to happen," Sullivan said in a recent interview. "One of the things we're looking at is the crowded situation we already have in Middleborough, so we have to have a real good understanding of what the demand will be, and how we can do this logistically."

Another problem is the relative lack of public transportation available to riders arriving in Hyannis. Although commuters would return to a parked car or a waiting family member, tourists would arrive to a peninsula largely inaccessible by the Cape transit authority's 11 bus lines.

And curiously, plans for the Hyannis Transportation Center do not include car rental agency services.

Money, too, could derail plans for rail service. Kennedy, who has spent the past year selling his proposal to boards of selectmen, chambers of commerce, and even individual homeowners along the right-of-way, says he would need up to $2 million a year in state subsidies to run his service.

He would also need the state's help to refurbish stations and rails, a cost he says would run no higher than $500,000. But, Kennedy adds, the Cape's residents would not have to pay taxes that other communities served by the MBTA pay, because his would be a privately run service.

But not everyone is ready to embrace Kennedy's plan. State Representative Eric Turkington, a Falmouth Democrat who has emerged as the most vociferous and powerful opponent yet to the resumption of rail service, says Kennedy has grossly understated the costs of his proposal.

The capital expenditure necessary to refurbish rails and stations could run as high as $20 million, Turkington says, and the cost to the landscape and the fragile ecosystem where the trains run would be astronomical.

In a series of op-ed pieces in the local press, he said Kennedy's plans remind him of "a rogue's gallery of past private operators who have stolen state property, defaulted on their lease payments, illegally dumped septic waste onto the rail beds, and enriched themselves with literally millions of dollars in public money."

Asked why Kennedy has received overwhelming support from nearly every commercial and political body along the right-of-way, Turkington said, "If you walk in and say, 'It won't cost you anything,' of course they will endorse it. I don't think the Cape has thought very hard about this. Our experience with rail has been disastrous. I'm not saying Mr. Kennedy would be like that, but experience tells us to use caution."

But Kennedy, whose doctors once said he would die from an esophageal tumor, said he knows something about perseverance, and plans to keep fighting.

"Actually, I don't have to do very much," Kennedy said with a grin, looking at one of his rail cars in the Hyannis train yard. "This proposal sells itself."

Raphael Lewis can be reached by e-mail at rlewis@globe.com.

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

85

JB

Appendix 4: Assignment: Beginning Modeling Exercises

System Dynamics in Education Project

Summary:
Used on September 27 to determine student understanding of the concepts of Stock, Flow, and Casual Loops.

Beginner Modeling Exercises

System Dynamics In Education Project
System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

Michael Shayne Gary
with help from
William A. Glass

March 8, 1993

Everything in the world around us can be represented by either a stock or a flow. As an exercise to help you begin identifying things around you as stocks and flows, the following problems should be completed.

1. A) *Indicate whether the following variables are stocks or flows. Identify the associated flow or stock, that corresponds to each variable and draw a stock and flow diagram that represents the system you have in mind. Some of the variables can be either a stock or a flow, but the stock/flow diagram must be consistent with your choice of answers.*

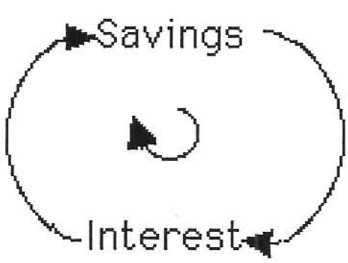
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

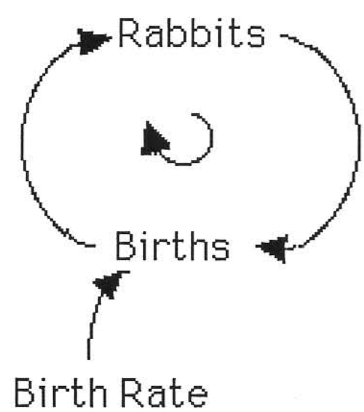
87

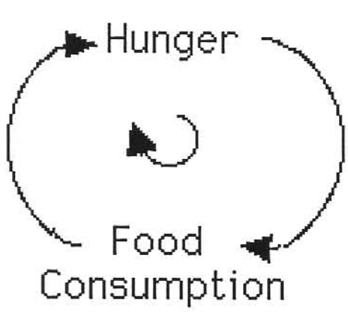
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

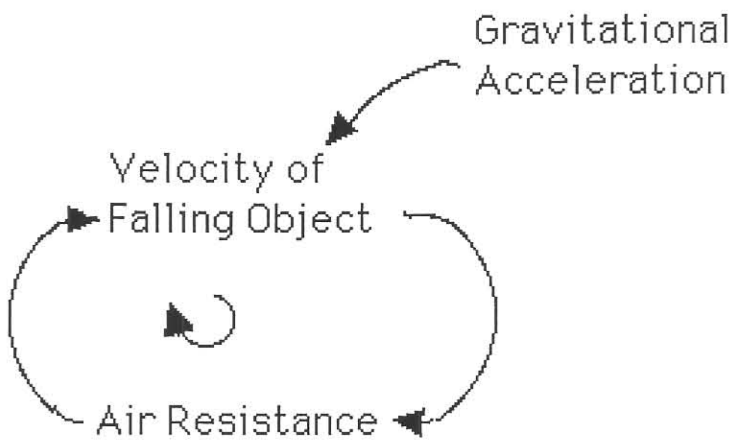
computers in a store
nuclear weapons
books in a library
trees in a forest
heat
distance
velocity

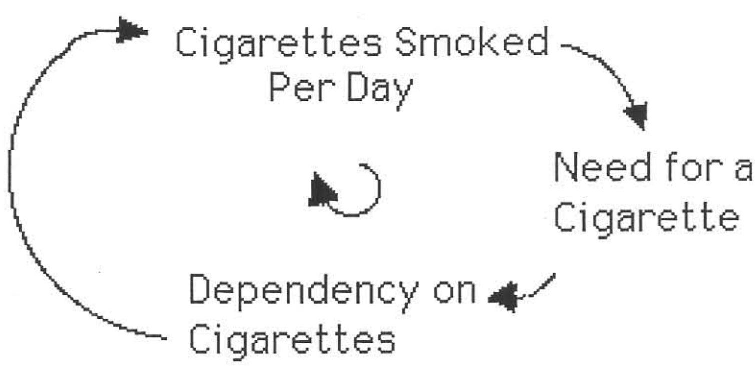
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational
Acceleration
Velocity of
Falling Object
Air Resistance


Cigarettes Smoked
Per Day
Need for a
Cigarette
Dependency on
Cigarettes

Appendix 5: (Solution) Beginner Modeling Exercises

David Liu

Summary:
This is a sample set of correct answers. A wide range of correct answers are possible for section 1; those answers can differ from this set of sample answers.

Beginner Modeling Exercises

David Liu

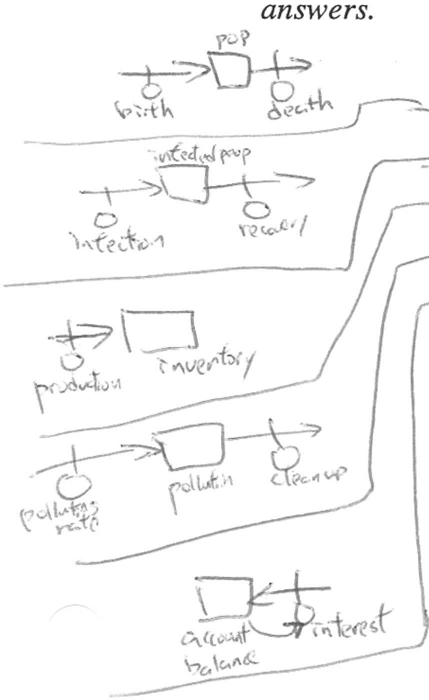
System Dynamics In Education Project
System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

Michael Shayne Gary
with help from
William A. Glass

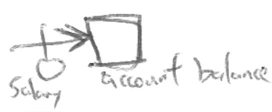
March 8, 1993

Everything in the world around us can be represented by either a stock or a flow. As an exercise to help you begin identifying things around you as stocks and flows, the following problems should be completed.

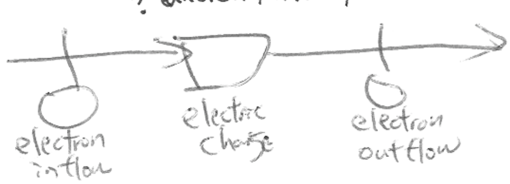
1. A) *Indicate whether the following variables are stocks or flows. Identify the associated flow or stock, that corresponds to each variable and draw a stock and flow diagram that represents the system you have in mind. Some of the variables can be either a stock or a flow, but the stock/flow diagram must be consistent with your choice of answers.*



population	stock flow	births, deaths
infected people	stock flow	infection, recovery
factory production	stock flow	~~Product~~ inventory
pollution	stock flow	polluting rate, clean up
interest	stock flow	account balance
salary	stock flow	account balance
distance	stock flow	speed
electric charge	stock flow	



? unclear, here's my interpretation

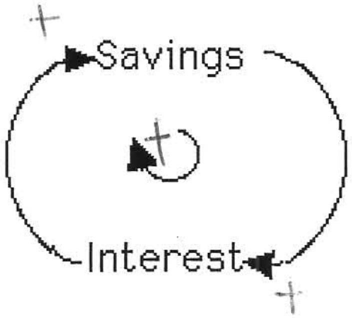


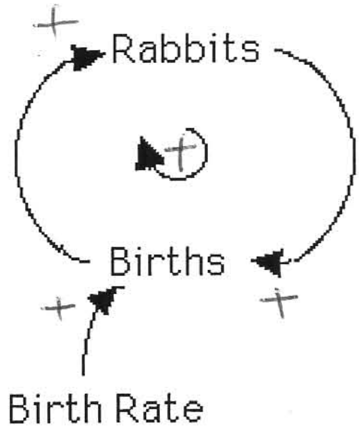
David Liu

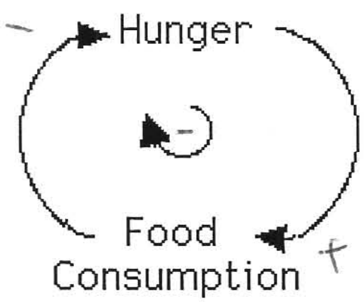
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

stock	stock unit.	flow	flow unit
computers in a store	computers	computer sales	computers/time
nuclear weapons	warheads	disarmament	warhead / time
books in a library	books	borrowing	books / time
trees in a forest	trees	deforesation	trees / time
heat	temperature	cooling	temperature / time
distance	miles	speed	~~distance~~ miles / time
velocity	Velocity	acceleration	V/time

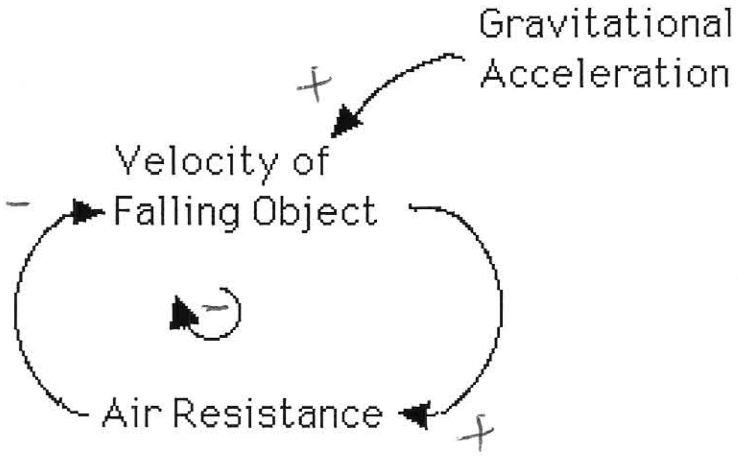
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*

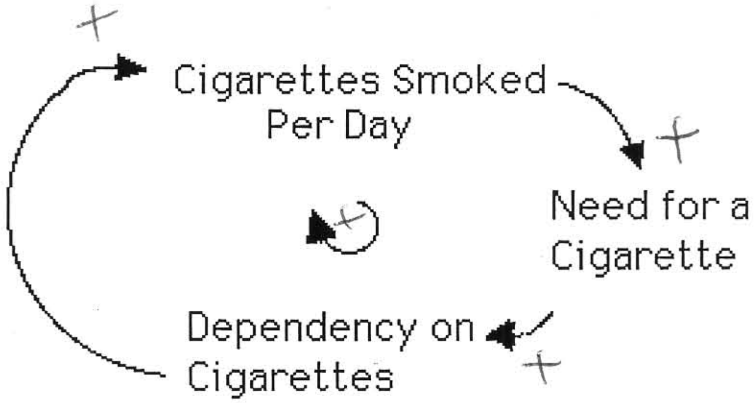






David Liu


Gravitational
Acceleration
+
Velocity of
Falling Object
−
−
Air Resistance
+


+
Cigarettes Smoked
Per Day
+
Need for a
Cigarette
+
Dependency on
Cigarettes
+

Appendix 6: Article: When Heroin Supply Cut, Crime Rises

Summary:
This article is provided for student reading and discussion on October 8, leading to creation of a formal computer model (see Appendix 7 for model)

When heroin supply cut, crime rises, says report

By Saul Friedman
Knight News Wire

WASHINGTON—The next time you hear of a big drug bust and the seizure of large quantities of heroin, don't go believing that your city's streets are necessarily any safer.

In fact, a new study of heroin traffic in Detroit has concluded that the tighter the heroin market, the more likely you will become a victim of a robbery or a burglary by an addict in need of a fix.

The study, which is to be released in a week by the privately funded Drug Abuse Council, is in the hands of Detroit officials. But it has implications beyond Detroit.

It supplies the first substantial statistical evidence challenging the conventional assumption that law enforcement campaigns to reduce the supplies of heroin will lead to a reduction of crime.

On the contrary, the study found that drug seizures lead only to higher heroin prices. And higher heroin prices result in an increase in "revenue-raising" crimes, such as robbery, burglary and theft.

The Detroit figures showed that crimes directly related to heroin climbed three percent, citywide, and much higher in poverty stricken areas — among whites as well as blacks — when the price of heroin rose by ten percent.

"If the price of a bag of street heroin increased from $7 to $9 in any given month," the Drug Abuse Council said, "the number of revenue-raising crimes which occurred at the rate of about 11,000 a month would increase to almost 12,000 a month because of heroin alone."

Furthermore, "reports of specific offenses increased when heroin prices increased ten percent. Citywide, the greatest increase seemed to be in three crimes often associ-

HEROIN, Page 13

Globe, 22 Apr 76.

★ HEROIN
Continued from Page 1

ated with heroin use in Detroit: Armed and unarmed robberies and burglaries of residences. Reports of armed robberies increased by 6.4 percent when heroin prices increased 10 percent."

Focusing on the crime of residential burglary, the study team of statisticians and economists found that "people living in poor neighborhoods were the most frequent victims "of the addict squeezed by higher heroin prices.

The study was based on an analysis of heroin prices and crime rates in Detroit for a 40-month period from June 1970 through September 1973. Drug prices were obtained from government narcotics agencies and the crime statistics came from the computers of the Detroit Police Department.

The Drug Abuse Council acknowledged that "any community that succeeds in eliminating or virtually eliminating its heroin supply could solve its heroin-related crime problem in fairly short order."

But while no community has been able to do so, many police departments, including the one in Detroit, have made large seizures and have temporarily reduced the heroin supply.

"Although conventional wisdom holds that such efforts lead to a reduction in heroin-related crime," the study said, "some people closer to the heroin scene, such as experienced law enforcement officials, believe the opposite occurs. In their judgment, marginally successful efforts at reducing heroin supplies result in more, not fewer, heroin-related crimes."

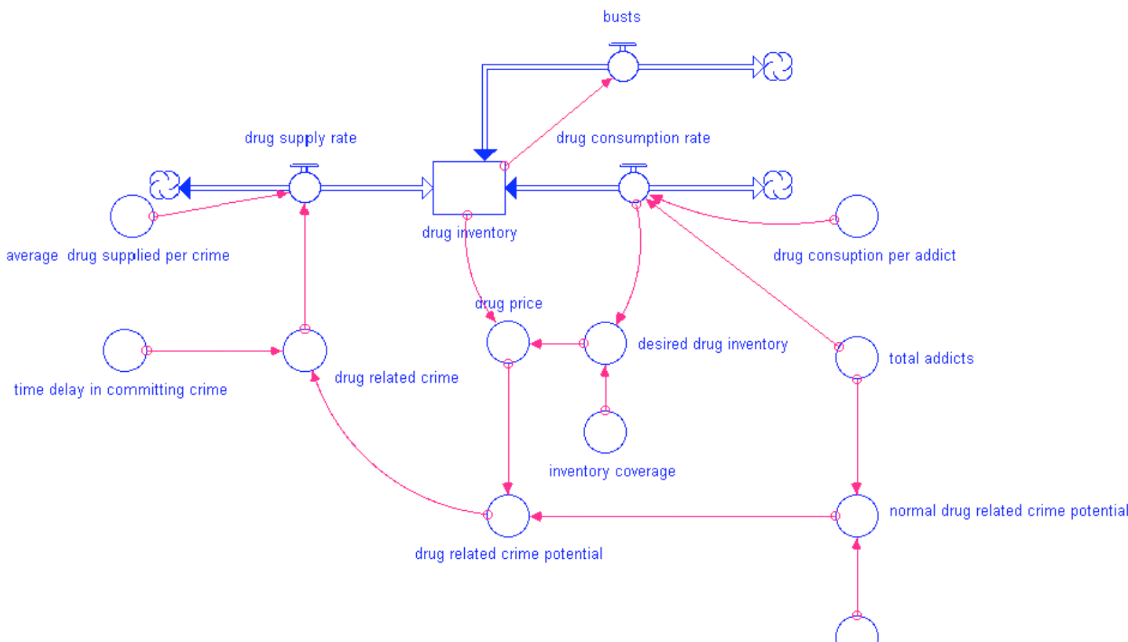
The Drug Abuse Council concluded that its study of Detroit heroin traffic and crime "suggests that the conventional wisdom is wrong and the people more familiar with the heroin scene are correct. That is, slight and temporary reductions in the supply and availability of heoin do not produce the reduction in heroin related crime policy-makers and the public alike want. Such efforts produce the increase in these crimes nobody wants."

Appendix 7: Model: Drug Inventory

Khalid Saeed

Summary:
This model was used to demonstrate a functioning system dynamics model and how policies affect the model simulations.

This model was explained in class and also used as for homework assigned on October 11 where the students were asked to duplicate this model.



Drug Model Equations:

drug_inventory(t) = drug_inventory(t - dt) + (drug_supply_rate - drug_consumption_rate - busts) * dt
INIT drug_inventory = 400
INFLOWS:
drug_supply_rate = drug_related_crime*average__drug_supplied_per_crime
OUTFLOWS:

drug_consumption_rate = total_addicts*drug_consuption_per_addict
busts = drug_inventory*(0+STEP(.1,5))*1
average__drug_supplied_per_crime = 1
desired_drug_inventory = drug_consumption_rate*inventory_coverage
drug_consuption_per_addict = 1
drug_price = desired_drug_inventory/drug_inventory
drug_related_crime =
SMTH1(drug_related_crime_potential,time_delay_in_committing_crime)
drug_related_crime_potential = normal_drug_related_crime_potential*drug_price
inventory_coverage = 4
normal_crime_per_addict = 1
normal_drug_related_crime_potential = normal_crime_per_addict*total_addicts
time_delay_in_committing_crime = 1
total_addicts = 100

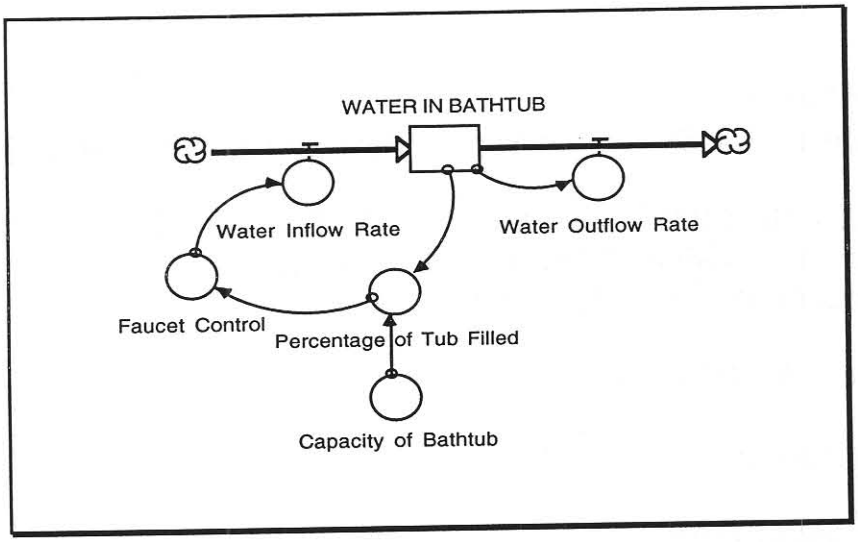
Appendix 8: Article: The First Three Hours

System Dynamics in Education Project

Summary:
This article describes is a good introduction to system dynamics and how to make basic system dynamics computer models.

The First Three Hours

An Introduction to System Dynamics Through Computer Modeling



Matthew C. Halbower
System Dynamics in Education Project

NOTE: This paper is meant to accompany the First Three Hours Disk or the Road Maps' Models Disk.

The First Three Hours
An Introduction to System Dynamics Through Computer Modeling

Prepared for the MIT System Dynamics in Education Project
Under the Supervision of Dr. Jay W. Forrester
Germeshausen Professor Emeritus

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May 1991
Revised December 1994

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ABSTRACT

It can be argued that current primary and secondary school educational systems are serving students poorly in the United States. The result has been a great outcry to improve America's educational system. Unfortunately, many plans aimed at improving education are misguided efforts calling for more of what is already not working, rather than seeking fundamentally new and more effective approaches to education. System dynamics and learner-centered learning are alternative approaches to the status quo of strict factual education that currently dominates America's primary and secondary schools.

The following tutorial is meant to serve as a hands-on introduction to system dynamics and learner-centered learning for educators and others interested in learning the basics of system dynamics through computer modeling. The tutorial sets forth some of the principles of system dynamics and learner-centered learning and escorts the reader through a series of system dynamics computer simulation models applied to physical systems. It is hoped that the skills gained from this tutorial will serve as a basis for continued learning as well as education based on system dynamics and learner-centered learning.

Document Organization

This document was conceptualized as “the first three hours” of a hands-on introduction to system dynamics. In this spirit, try to set aside about three hours of time for exploration. As stated in the abstract, this document is meant to serve as an introduction to system dynamics through an interactive tutorial on computer modeling. Using a Macintosh computer and STELLA modeling software, you will use basic system dynamics concepts to create your own models of Newtonian mechanics.

While this tutorial emphasizes concepts from physics, the general modeling and systems concepts can be applied to everything from physics to literature. If your bent is not toward physics, go through the exercises with your attention focused on the modeling concepts. Future readings and exercises will provide examples from other disciplines.

In addition to setting aside three hours, the reader should have access to the following materials:

<u>Hardware:</u> Macintosh[1] computer with 2 MB RAM if running System 6.0.4 and 4 MB RAM if running System 7 or higher.
<u>Software:</u> STELLA, STELLA II or ithink software package [2].
Disk labeled "First Three Hours" (comes with document)

<u>Required Familiarity with STELLA or the Macintosh:</u> **None**
*Note: Explicit instructions are provided for readers unfamiliar with the software. The instructions utilize specific commands from STELLA II v. 2.2.1 and ithink v. 2.2.1. Therefore, readers unfamiliar with the software should use these versions. For those familiar with earlier versions of STELLA or ithink, it is assumed that you will be able to follow along. Any version after STELLA v. 2.1 or ithink v. 2.1 will work.

If you do not have the hardware or software required to follow along with the tutorial, all is not lost. The beginning portion of the document does not require any interaction with a computer, and the tutorial can be completed without the use of a computer. Computer simulation is merely a

[1] Macintosh is a trademark of Apple Computer, Inc.
[2] STELLA and ithink are registered trademarks of High Performance Systems, Inc.

vehicle to enhance the educational experience.

If access to the STELLA software is a problem, High Performance Systems (manufacturer of STELLA and ithink) can be contacted at the following address:

High Performance Systems
45 Lyme Road
Hanover, NH 03755
(603) 643-9636

System Dynamics

System dynamics can provide a common language for mathematics, biology, ecology, physics, history and literature.

System dynamics is an academic discipline created in the 1960s by Dr. Jay Forrester of the Massachusetts Institute of Technology. System dynamics was originally rooted in the management and engineering sciences but has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological and ecological systems.

In the field of system dynamics, a **system** is defined as a collection of elements which continually interact over time to form a unified whole. The underlying pattern of interactions between the elements of a system is called the **structure** of the system. One familiar example of a system is an ecosystem. The structure of an ecosystem is defined by the interactions between animal populations, birth and death rates, quantities of food, and other variables specific to a particular ecosystem. The structure of the ecosystem includes the variables important in influencing the system.

The term **dynamics** refers to change over time. If something is dynamic, it is constantly changing in response to the stimuli influencing it. A dynamic system is thus a system in which the variables interact to stimulate changes over time. **System dynamics** is a methodology used to understand how systems change over time. The way in which the elements or variables composing a system vary over time is referred to as the **behavior** of the system. In the ecosystem example, the behavior is described by the dynamics of population growth and decline. This behavior is due to the influences of food supply, predators, and environment, which are elements of the system.

One feature which is common to all systems is that a system's structure determines the system's behavior. System dynamics links the behavior of a system to its underlying structure. System dynamics can be used to analyze how the structure of a physical, biological, or literary system can lead to the behavior which the system exhibits. By defining the structure of an ecosystem, it is possible to use system dynamics analysis to trace out the behavior over time of the ecosystem based upon its structure.

The diagram in Figure 1 indicates that the underlying structure of a system determines that system's behavior. The upward-pointing arrow on the left symbolizes this relationship. On the right, the downward-pointing arrow indicates the deeper understanding which is gained from analyzing a system structure. Full understanding can only come when one dives beneath the behavior to understand the structure causing the behavior.

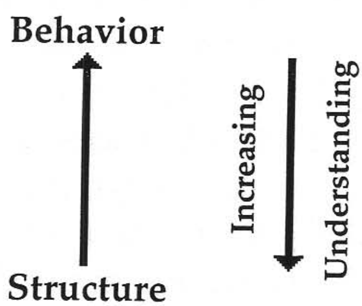

Figure 1: The Link Between Structure and Behavior

The structure-behavior link need not be limited to systems which are well defined historically or analytically. System dynamics can also be used to analyze how structural changes in one part of a system might affect the behavior of the system as a whole. Perturbing a system allows one to test how the system will respond under varying sets of conditions. Once again referring to an ecosystem, someone can test the impact of a drought on the ecosystem or analyze the impact of the elimination of a particular animal species on the behavior of the entire system.

In addition to relating system structure to system behavior and providing students a tool for testing the sensitivity of a system to structural changes, system dynamics requires a person to partake in the rigorous process of modeling system structure. Modeling a system structure forces a student to consider details typically glossed over within a mental model.

In a book examining the historical development of the earth's ecosystem, J.E. Lovelock has the following to say about system analysis:

> "Think about a temperature controlled oven. Is it the supply of power that keeps it at the right temperature? Is it the thermostat, or the switch that the thermostat controls? Or is it the goal that we established when we turned the dial to the required cooking temperature? Even with this very primitive control system, little or no insight into its mode of action or performance can come from analysis, by separating its component parts and considering each in turn, which is the essence of thinking logically in terms of cause and effect. The key to understanding systems is that, like life itself, they are always more than merely the assembly of constituent parts. They can only be considered and understood as operating systems ... whereby the behavior of the system is analyzed in terms of its underlying structure."[3]

Systems dynamics provides a common communication tool connecting many academic disciplines. System dynamics forces people to think critically about problems because of the process they must go through to develop and analyze system structure. Most importantly, with system dynamics, one can make the mental link between the structure of a system and the behavior which the system produces.

Computer Simulation

Tell me and I will forget.
Show me and I may remember.
Involve me and I will understand.

One of the best ways to learn is to participate in a project. Educators can stand in front of students all day long and lecture on how to hit a tennis

[3] Lovelock, J.E., 1979. "Gaia: A New Look at Planet Earth." Oxford University Press, p.52.

ball, change the oil in a car, or run a corporation. However, once a student is in the position where it is necessary to complete one of these tasks, the student often cannot. The reason that a student cannot complete the task is because the mental model of the system he has created based on lecturing or reading does not fit reality. A **mental model** is one's mental perception or representation of system interactions and the behavior those interactions produce. Because of an incomplete or incorrect mental model, a student cannot apply the principles taught in lectures to tasks in life.

How can educators improve students' mental models of systems? How can students be taught to achieve a greater understanding of a problem or phenomenon and the structure of the system which produces the problem or phenomenon? Just as toddlers learn not to touch a hot stove by the direct feedback signal they receive from touching one, educational systems should incorporate direct feedback between the student and the subject being taught.

System dynamics offers a source of direct and immediate feedback for students to test assumptions about their mental models of reality through the use of computer simulation. **Computer simulation** is the imitation of system behavior through numerical calculations performed on a system dynamics model. A **system dynamics model** is the representation of the structure of a system. Once a system dynamics model is constructed and the initial conditions are specified, a computer can simulate the behavior of the different model variables over time.

A good model attempts to imitate some aspect of real life. However, whereas real life does not allow one to go back in time and change the system structure, simulation gives students the power to change system structure and analyze the behavior of the system under many different conditions.

With simulation, students do not have to fly to a Brazilian rain forest and record careful observations for many years to experience how that ecosystem reacts to changes over time. Students can repeatedly simulate the Brazilian ecosystem at home or in the classroom based on varying sets of assumptions about the ecosystem. The idea that one can simulate the experiences of real life is a very powerful concept. Just as jet pilots train on aircraft simulators, so can ecology students gain equivalent experience by training on different ecosystem simulators.

Simulation is not only useful for modeling systems that are difficult for students to observe in real life. Computer simulation is more powerful in influencing the learning process when it is combined with real experimentation. An ideal learning environment would include discussion of a topic, student-directed research, laboratory experimentation, model building and exploration, and computer simulation to verify the link between model behavior and experimental observations. The overall goal is to teach students critical thinking skills and a methodology for dealing with complex problems that they can use later in life as managers, company presidents, journalists, generals, pilots, and engineers. The process of modeling is a continuing companion to the improvement of judgment and human decision making.

STELLA

Systems Thinking Educational Learning Laboratory with Animation

STELLA[4] is a computer simulation program which provides a framework and easily-understandable graphical interface for observing the quantitative interaction of variables within a system. This interface can be used to describe and analyze very complex physical, chemical, biological, and social systems. However, model builders and users are not overburdened with complexity because all STELLA models are made up of only four building blocks:

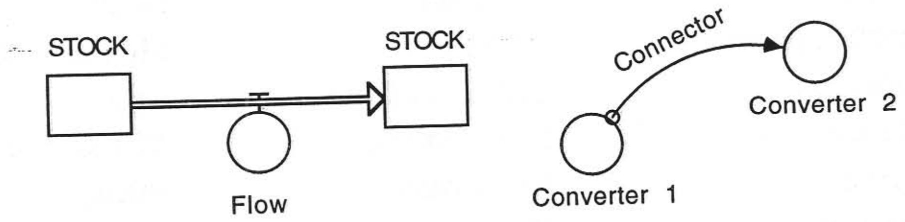

Figure 2: Representations of stock, flow, converter, and connector

[4]All references to STELLA in this paper also apply to ithink as they are essentially the same program.

Stock—A stock is a generic symbol for anything that accumulates or drains. For example, water accumulates in your bathtub. At any point in time, the amount of water in the bathtub reflects the accumulation of what has flowed in from the faucet, minus what has flowed out down the drain. The amount of water in the bathtub is the stock of water.

Flow—A flow is the rate of change of a stock. In the bathtub example, the flows are the water coming into the bathtub through the faucet and the water leaving the bathtub through the drain.

Converter—A converter is used to take input data and manipulate or convert that input into some output signal. In our example, if you were to turn the valve which controls the water flow in your bathtub, the converter would take as an input your action on the valve and convert that signal into an output reflecting the flow of water.

Connector—A connector is an arrow which allows information to pass between converters and converters, stocks and converters, stocks and flows, and converters and flows. In Figure 2 above, the connector from converter 1 to converter 2 means that converter 2 is a function of converter 1; in other words, converter 1 affects converter 2.

The following table provides some examples of variables which might be classified as stocks and flows:

Inflows	Stocks	Outflows
Births	Population	Deaths
Production Rate	Inventory	Shipment Rate
Bookings	Order Backlog	Sales
Interest	Bank Balance	Withdrawal Rate
Hiring	Employees	Firing
Learning	Knowledge	Forgetting
Construction	Buildings	Demolition
Increase	Self-Esteem	Decrease

Figure 3: Table of Stock and Flow Examples

To represent the STELLA structure describing the level of water in a bathtub, one would begin with the stock of water in the bathtub as shown in Figure 4a.

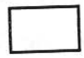

Figure 4a: STELLA Diagram of Stock Describing Water in a Bathtub

The next step would be to connect flows into (inflow) and out of (outflow) the bathtub in order to model how the level of water in the bathtub increases and decreases over time. This is shown in Figure 4b.

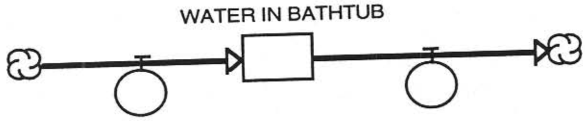

Figure 4b: STELLA Diagram of Stock and Flow Structure Describing Water in a Bathtub

There is a stock of water in the bathtub which accumulates or drains at a rate determined by the flows of water into and out of the stock. The arrow pointing into the stock of water symbolizes a flow of water into the bathtub. This flow comes from the faucet and is measured in amount of water per unit of time. The same relationship is true for the arrow representing the flow out of the bathtub. This flow is a representation of the water moving down the drain, and it is again measured in amount of water per unit time.

Both the inflow and outflow are connected to **clouds**. A cloud represents the system boundary. In the bathtub model, the cloud means that for the purposes of this model, it is unnecessary to know where the water flowing into the bathtub comes from or where it goes after it leaves the bathtub.

Constructing the system structure of the model is commonly known as laying out the plumbing of the system. This nickname evolved from visualizing all stock-and-flow systems as a series of pipes (flows) and basins (stocks) which can transport and hold material. Laying out the plumbing of a bathtub model is fairly zero. Modeling the control structure for the water inflow and outflow is slightly more complex because it is dependent upon the particular system being modeled.

The following structure models the way the author takes his baths. The bath begins when the faucet control is turned on in order to begin filling the tub. As the bathtub fills, its water level is constantly being compared against some desired level of water necessary for the bath. Once the tub is filled to 100 percent of the desired level, the faucet control is turned off and the inflow rate becomes zero. This structure is represented in Figure 4c.

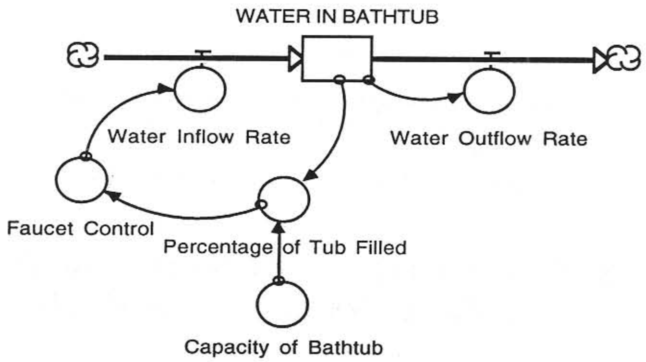

Figure 4c: STELLA Diagram of Inflow Control of Water in a Bathtub

After soaking in the bathtub, it is time to drain the water. Again, the amount of time spent in the bathtub is compared to the desired amount of bath time. Once the time spent in the tub is 100 percent of the desired time, the drain control is turned on so the water outflow is activated. Once the tub is empty, no more water can flow down the drain so the outflow rate goes to zero despite the fact that the drain is open. This structure is represented in Figure 4d.

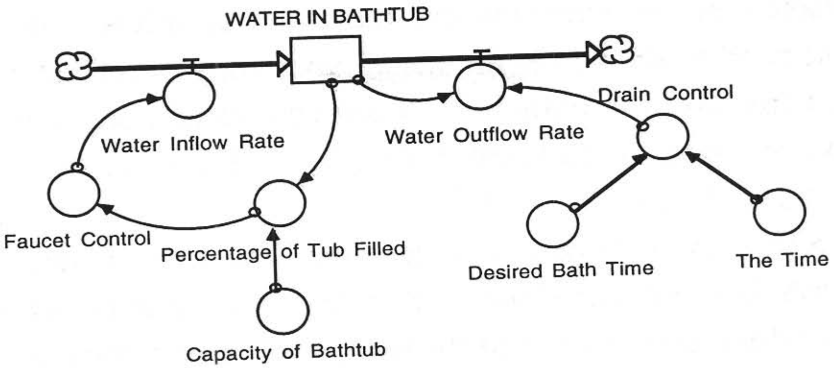

Figure 4d: STELLA Diagram of Water in a Bathtub

Macintosh Basics

We will now begin with a short tutorial on some of the basic features of the Macintosh computer. After being introduced to the Macintosh, the system dynamics portion of the tutorial will lead you through an exploration of aspects of Newtonian mechanics. Do not worry if you have no prior understanding of Newtonian mechanics. The purpose of this tutorial is to familiarize you with the STELLA program and the basic structures used in system dynamics, so all necessary principles will be explained along the way.

At all steps we will try to explain the physical phenomena being modeled; however, if there is something you do not understand about the physics model don't worry about it. If there is something you do not understand about the STELLA program or system dynamics you should still continue. Future readings should help to clarify any confusion.

This process will occur in stages, beginning with a very simple structure and gradually expanding that structure. For readers already familiar with the workings of a Macintosh computer, you may skip ahead to the section entitled "The Motion Model."

For readers unfamiliar with the Macintosh computer, or computers in general, do not be discouraged. The Macintosh is powerful because it is simple. With the Macintosh, one learns through exploration and experimentation. By simply learning to point and click, anyone can use a Macintosh.

The first thing to do is to turn the power switch of the computer on.

In most Macintosh computers (Macs), the power switch is in the rear left of the computer. With the power on, install your copy of STELLA onto the Macintosh hard drive by following the instructions that begin on page two of the packet entitled "STELLA® II Version 2.2 Release Notes" which come with the software.

Once STELLA is on your Mac, take the First Three Hours disk included with these materials and insert it face up, metal facing inward, into the disk drive on the front of the computer. The picture shown in Figure 5, called an **icon**, should appear in the top right portion of the computer monitor.

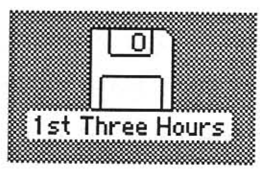

Figure 5: Macintosh Disk Icon

The Macintosh uses picture icons to represent the programs or files which are available on the computer. Typed commands are often unnecessary because manipulation of the programs can be accomplished through the use of the mouse and picture icons. The **mouse** is the small white device connected to the keyboard of the computer. The mouse allows the user to manipulate or control an arrow on the monitor of the Macintosh. To see the contents of the First Three Hours disk, use the mouse to position the arrow on top of the First Three Hours disk icon.

- **With the arrow on top of the icon, click the button on top of the mouse <u>twice</u> <u>rapidly.</u>**

This action is called **double-clicking**, and it is used to open an icon so that the contents represented by the icon may be viewed. Once you have double-clicked on the disk icon, the window shown in Figure 6 should appear.

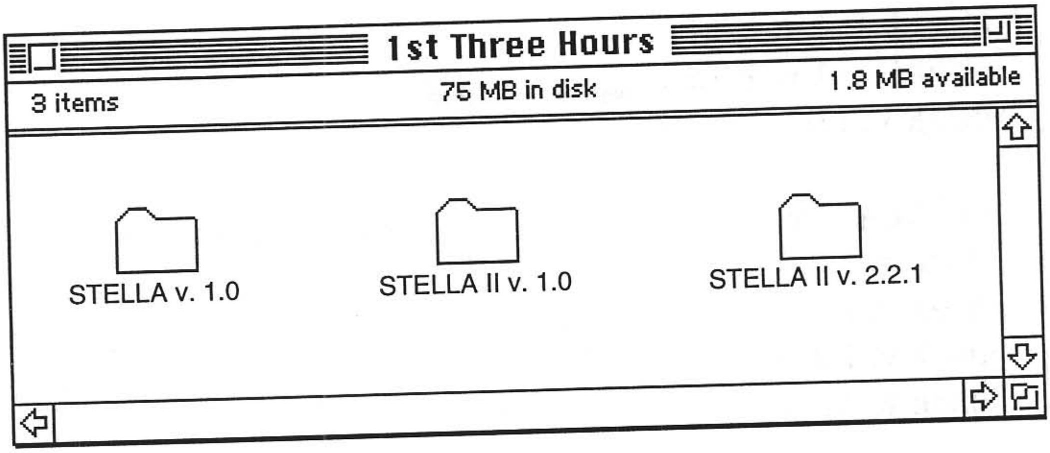

Figure 7: Window Showing Contents of First Three Hours Disk

The icons which look like file folders are true to their image and simply contain files. File folders allow Macintosh users to personalize their files and store them in the file folders of their liking. To see the contents of a file folder, simply use the mouse to position the arrow over the folder, and double-click.

There are several versions of STELLA and ithink that are not completely compatible with each other. This guide is written for STELLA II v2.2.1 and ithink v2.2.1. If you have an older version of STELLA or ithink, the commands in this guide will be slightly different from the commands necessary for your version, but it is assumed that if you have an older version you already know how to use it and will be able to follow along.

There are three folders on the First Three Hours disk with the appropriate models for the different versions of STELLA and ithink. The table in Figure 8 tells you which folder to open for your version of STELLA or ithink.

Your Software Version	Folder to open
STELLA v. 1.0	STELLA v. 1.0
STELLA for Business	"
STELLA for Education	"
STELLA II v. 1.0	STELLA II v. 1.0

STELLA II v. 1.0.1	"
STELLA II v. 1.0.2	"
ithink v. 1.0	"
STELLA II v. 2.2.1	STELLA II v. 2.2.1
ithink v. 2.0	"
ithink v. 2.1	"
ithink v. 2.2	"
ithink v. 2.2.1	"

Figure 8: Software Versions

- **Double-click on the appropriate folder for your version of ithink or STELLA.**

The contents of the folder should be displayed in the new window shown in Figure 9.

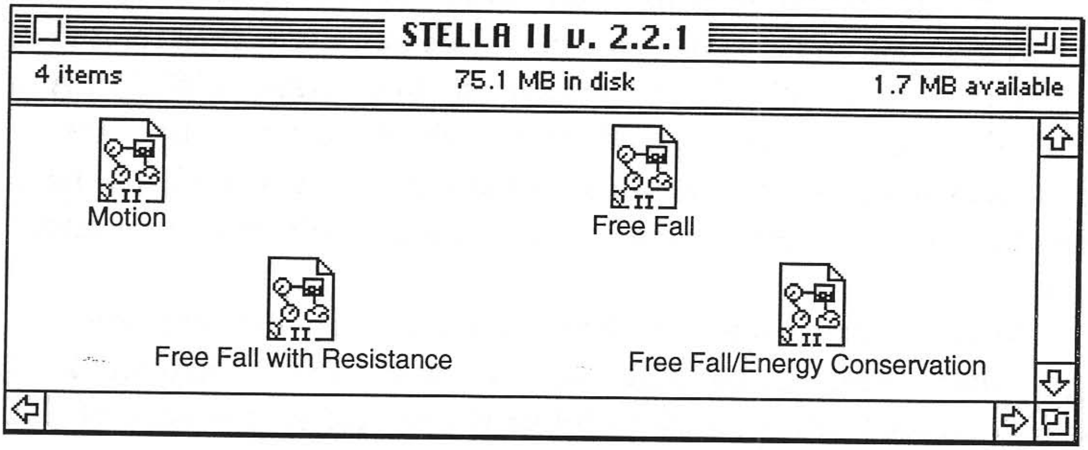

Figure 9: Macintosh Window Showing "STELLA II v. 2.2.1" Folder

The icons in the above window are STELLA model icons. Double-clicking on a STELLA model icon will activate that particular STELLA model.

- **Double-click on the "Motion" icon to begin the tutorial.**

The Motion Model

For those familiar with the Macintosh who have skipped ahead:

- **Double-click on the "First Three Hours" disk icon**
- **Refer to the table in Figure 8** and find the folder to use for your software version.
- **Open the appropriate file folder for your version of STELLA**
- **Double-click on the "Motion" model icon**

Once the motion model is open, the window shown in Figure 10 should appear.

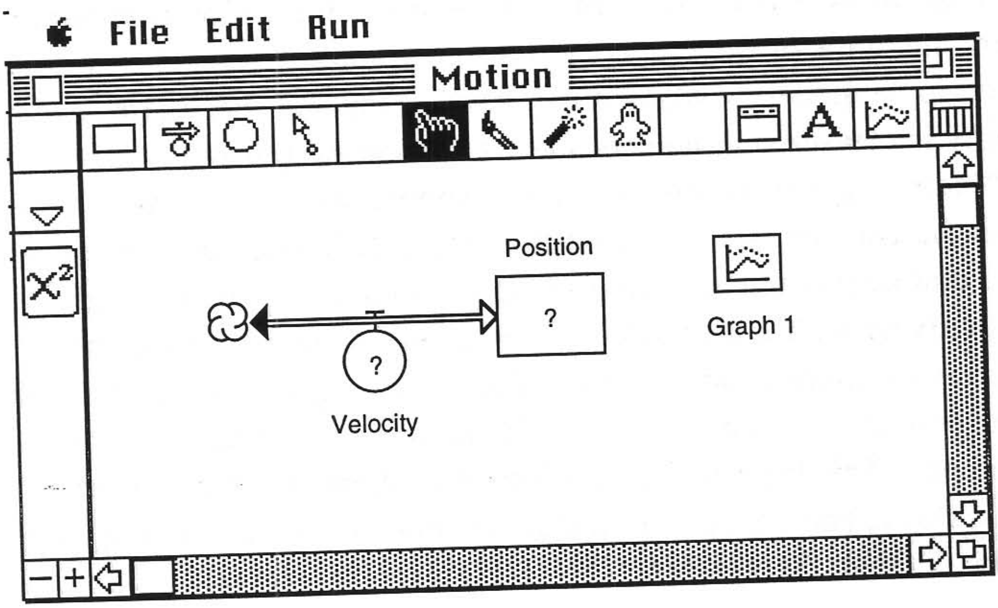

Figure 10: STELLA Diagram Window with Motion Model

Figure 10 depicts the diagram window of STELLA. The diagram window is where the building blocks of STELLA (stocks, flows, connectors, and converters) are assembled to define the structure of a system.

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The model shown above represents the relationship between velocity and position. Position is the stock which accumulates over time, and velocity is the flow which fills up the stock. Velocity is a measure of how quickly an object is moving. It is the rate of change of position over time. The clear arrowhead on the flow pointing into the stock indicates that velocity is an inflow which will add to the stock so long as velocity remains a positive number. The darkened arrowhead on the left side of the flow indicates that the velocity will deplete the stock if the velocity becomes negative. Thus, if the velocity is equal to 10 meters per second, the position stock increases an additional 10 meters with each passing second. This means that after one second, the object will have moved forward 10 meters, after two seconds, 20 meters and so on. However, if the velocity is equal to -10 meters per second, the position stock decreases by 10 meters each second and the object moves backward.

A flow shares a special relationship with a stock because a flow is the only thing which can change a stock over time. The flow is always the rate of change of the stock. Therefore, if the stock of position is measured in meters, the units of flow must be meters per unit of time. For the sake of this example model, position is measured in units of meters (m) and velocity is measured in units of meters per second (m/sec).

Examining the motion model, one should see question marks contained within the velocity (flow) and position (stock). These question marks are a signal that neither the velocity nor the position have been defined quantitatively within the model. If the mouse is moved within the STELLA Diagram window on the Macintosh, a graphical representation of a hand should move on the window in the same direction as the mouse movement. This hand acts as a pointer and allows the model user to "open" stocks, flows, and converters so that the contents of the building blocks may be defined. To see this:

- **Place the hand over the flow labeled *velocity* as shown below**
- **Double-click on the flow labeled *velocity***

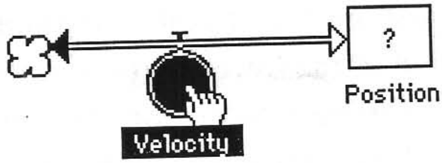

Figure 11: STELLA Diagram Showing How to Open Velocity Dialog Box

A window called a **dialog box** should appear as shown in Figure 12.

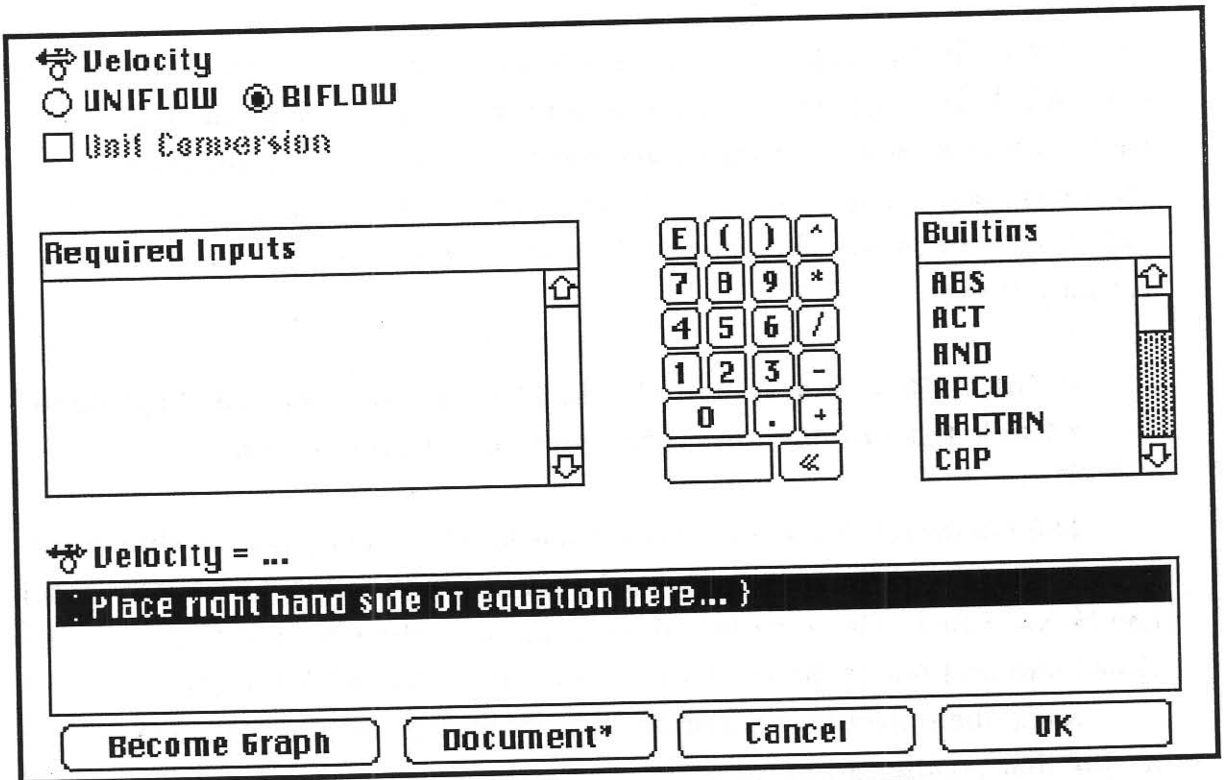

Figure 12: STELLA Dialog Box of Flow

A dialog box is where the variable values and relationships within the structure of a model are quantified. The dialog box is equipped with a built-in calculator and built-in functions to enter both numbers and arithmetic functions by clicking on them rather than typing them in by hand. On the left side of the dialog box is a list of required inputs. This list contains the names of variables which have information connectors pointing into the velocity flow. Since there are no connectors sending information to the velocity, there are no variables which are required inputs in the velocity equation. The equation defining velocity is contained within the rectangle found in the lower portion of the dialog box. You may wish to include some more information about the model element than is allowed in this dialog box. To do this, **click on the Document button** at the bottom of the dialog box. The document box should open up. A brief explanation has already been entered, but you can enter your own comments either here or when you build your own models. Try looking at the document comments for other model elements throughout this tutorial. When you are done, **click on the Hide Document button.**

Before it is possible to define the velocity, it is necessary to know what system is being modeled. For the sake of this example, assume that a frictionless ball begins at the origin and moves with a constant velocity of 10 meters per second. Because the ball is frictionless, the velocity of the ball does not change. There is no friction to slow it down. To define the velocity flow:

- **Enter 10 using either the built-in keypad or the keyboard**
- **Click the OK button.** The dialog box should close.

The position stock has a very similar looking dialog box as shown in Figure 13. The difference is that only the initial value of the position stock can be specified. Once the initial condition of a stock is specified, only the flows into and out of the stock can change the value of that stock.

Since the object being modeled has its initial position at the origin, define that position to be zero:

- **Double-click on the stock labeled *Position***
- **Enter 0 using the built-in keypad and your mouse or using the keyboard**
- **Click on OK when finished.**

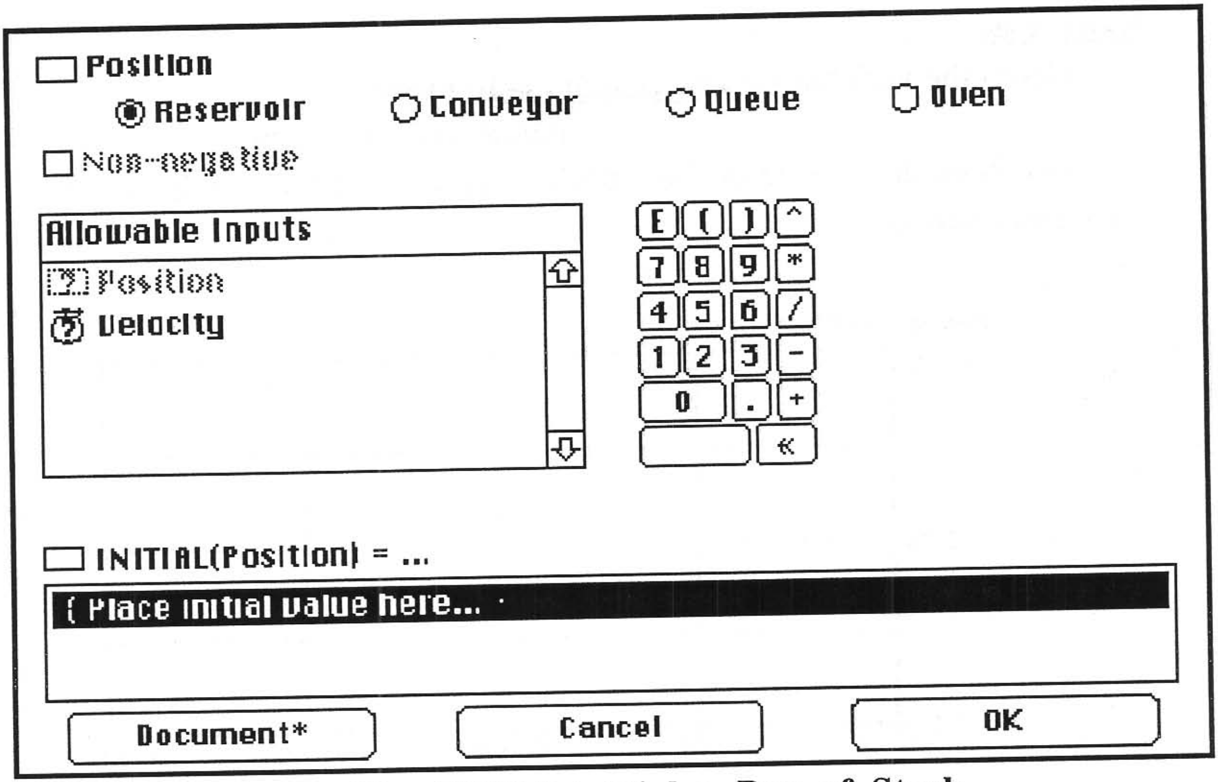

Figure 13: STELLA Dialog Box of Stock

At this point, the position and velocity should be defined. However, before students can really understand a system, they must be able to relate the structure of the system to its behavior. **Mental simulation** is the process of predicting system behavior from system structure. The ability to mentally simulate a system and gain insight into its behavior from its structural representation is one goal of system dynamics teaching. The mental link between structure and behavior is a key to understanding a system. Mental simulation should be employed by every model user before a computer simulation is performed. It is far too easy for a student to convince himself that he would have predicted a system's behavior if the computer does all the work. Mental simulation forces a student to work through a system and commit himself to a prediction of system behavior before the computer generates the model behavior.

Exercise:

Given the variable values: velocity = 10 m/sec

initial position = 0 m

Graph on the axis below how position and velocity will behave over a 20-second period:

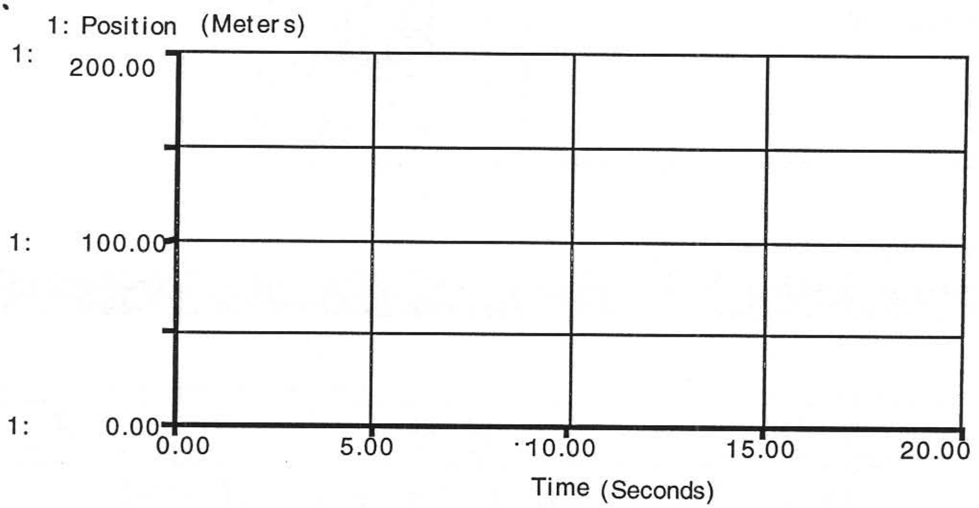

Figure 14: Mentally Simulated Behavior of Position over Time

Once a guess is drawn on Figure 14, the user can create this graph using STELLA. STELLA graphs allow model users to graph each variable's behavior either over time or relative to another variable. For the motion model, STELLA will simulate how the position and velocity vary with time. In this case, the graph has already been created for you.

There should be a picture of a small graph labeled *Graph 1* in your STELLA window next to the model. This icon indicates that there is a graph which accompanies the model.

- **Double-click on the "Graph 1" graph icon in your model**

A blank graph should appear on your screen. To fill in the graph:

- **Select Run from the Run menu**

Two variables should be seen plotted over time: linearly growing position and constant velocity. Your graph should appear as the graph shown in Figure 15.[5]

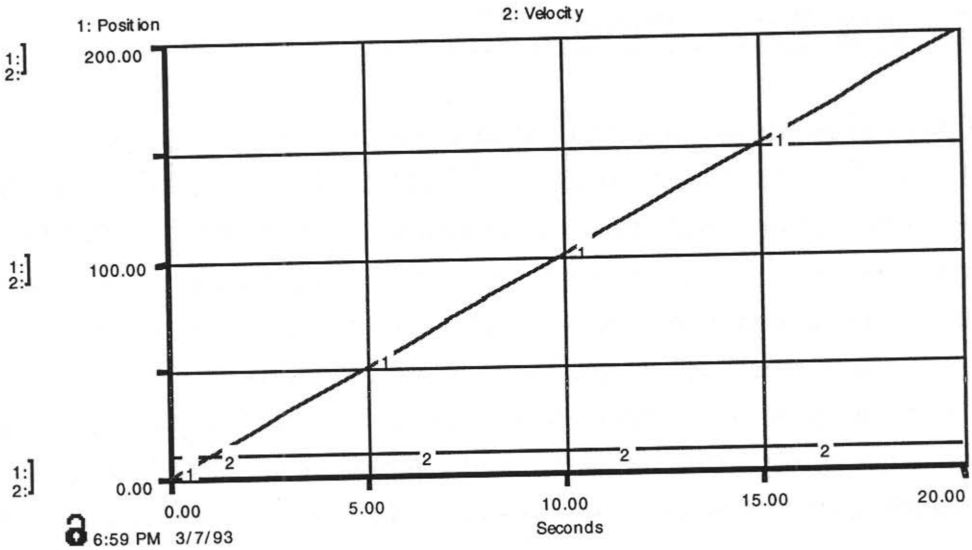

Figure 15: Graph of Position and Velocity over Time

At first glance, this graph is slightly confusing. There are two separate variables graphed on the same axis. The variable labeled 1 is the position and the variable labeled 2 is the velocity. Position is increasing due to the constant flow of velocity into the stock. The position linearly increases with time. Velocity is a constant 10 meters per second so it remains the same, independent of time. A graph similar to this can be generated for many other situations. One example is hunger which increases at a constant rate while you are not eating.

For those who have taken calculus, you might recognize that the motion model is nothing more than an integration of position over time. It turns out that integration, as opposed to differentiation, is a much more logical approach to mathematics in general. Nowhere does nature differentiate. Nature only integrates. Things in nature accumulate over time. People living in the natural world develop an intuitive sense of integration. Every junior-high-school student has an intuitive feel for the

[5] Please note that this graph has been defined and preset in order to simplify the introductory packet. In the future, you will define your own graphs using STELLA.

way things accumulate, whether it be water in a bathtub or money in a bank account. This intuition is all that a student needs to understand the fundamental concepts of system dynamics modeling.

Modeling With a Purpose

The motion model is a first cut at modeling some principles of mechanics. The model's usefulness will shortly be enhanced by adding more concepts from mechanics to the structure of the model. However, before adding to the structure of the model, it is essential to ask: What is the purpose of this model? How is the model useful in achieving the purpose? These questions should be asked before any model is developed. Every system dynamics model must be developed with a purpose in mind. It does no good to simply begin to model a system without having a clear understanding of the problem the system is to address and the concepts which the system is meant to communicate. In designing a model, one must tailor its complexity to an audience and build it around a set of principles, exercises, or problems.

Even in its simple state, the motion model can be used to communicate powerful concepts. The motion model describes the position of an object being changed by the object's velocity. Position and velocity can be either positive or negative quantities. Velocity's ability to act as an inflow or outflow to the position stock makes it a one-dimensional vector quantity where the magnitude of the velocity is its absolute value and the direction is its sign. Likewise, position can be mapped to a coordinate system with a defined initial value. By understanding the directional qualities of the stock-and-flow relationship, students are learning the principle of vectors.

The motion model can also be used to teach generic integration principles and problem solving techniques to students which are common to all stock-and-flow systems. Once the relationship between a stock and a flow is learned, this can be applied to all dynamic systems. Past experience shows that using stocks and flows, junior-high students could describe behavior in complex systems which many calculus students could not solve mathematically.

Free Fall

A model of motion which simply takes account of velocity and position is a useful starting place when discussing mechanics, but the model leaves out many important concepts by having such narrowly defined model boundaries. An obvious point of expansion is to bring acceleration into the model. Acceleration provides a credible way to change velocity over time. The following example will introduce acceleration in the context of a falling body.

People in general have an intuitive sense for the relationship between speed and distance. Most people would be able to compute the distance traveled by a car going 55 miles per hour in one hours time. However, when students are faced with acceleration problems, their intuition clouds. They have a difficult time conceptualizing something which is measured in units of miles per hour per hour or meters per second per second.

From the system dynamics perspective, an obvious way to help students develop intuition into acceleration problems is to relate an acceleration system to a system with which students are thoroughly familiar. Because system dynamics is a building process, by the time students are ready to move forward to a model employing acceleration, they will have already mastered the velocity system, which employs the exact same structure as acceleration. A STELLA model of acceleration is shown in Figure 16.

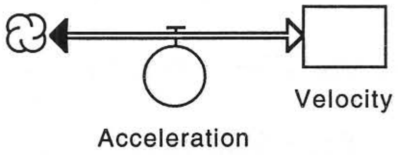

Figure 16: STELLA Diagram of Acceleration and Velocity

Acceleration and velocity share the identical structural relationship that is shared between velocity and position. Acceleration is the rate of change of velocity over time. Because of this, students can instantly transfer everything they have learned about the relationship between the position-velocity stock-and-flow structure to the velocity-acceleration stock-and-flow structure. In fact, by studying one stock-and-flow structure, students can apply what they have learned to many other examples of stocks and flows.

The only difference between the two structures lies in the units of measure. The motion model had a stock of position measured in meters (m) and a flow of velocity measured in meters per second (m/sec). The acceleration model has a stock of velocity measured in meters per second (m/sec) and a flow measured in meters per second per second (m/sec/sec). The exact same relationship between the stock and flow holds. *The flow is always measured in the same units as the stock divided by a measure of time.*

Stock	Stock units	Flow	Flow units
Position	m	Velocity	m/sec
Velocity	(m/sec)	Acceleration	(m/sec)/sec

Figure 17: Relationships between Stocks and Flows

Combined acceleration, velocity, and position in a free-fall model without any resistance can be represented as in Figure 18. This structure is generic and can be used to represent the linear motion of any particle or body. To call this model up on your computer, you must first exit from the motion model.

- **Select Close Model from the File menu.**
- **Click the Don't Save button** so you won't make your changes permanent.
- **Select Open from the File menu** to load a new model into STELLA.
- **Click once on the Free Fall model.** It should become highlighted.
- **Click on the Open button**

You have just told STELLA to quit from the *Motion* model and load a new model called *Free Fall.* A model identical to the one appearing in Figure 18 should appear on your screen.

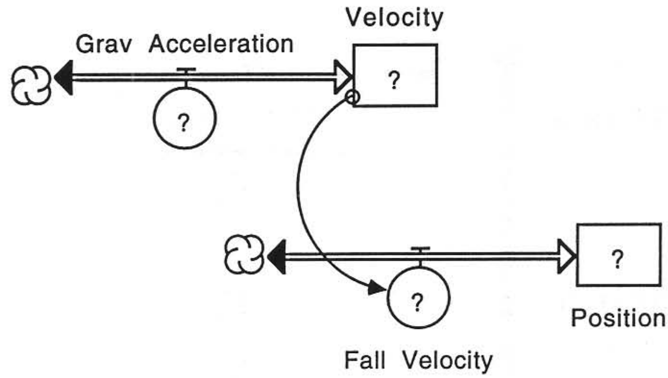

Figure 18: STELLA Diagram of Free Fall Model

The diagram in Figure 18 shows a constant gravitational acceleration flowing into a stock of velocity. The velocity stock is then shown passing information to a flow labeled fall velocity. The fall velocity is numerically equivalent to the velocity stock, but the fall velocity is used as a flow into the stock of position. The two models previously shown are simply combined to include the effect of acceleration on position through changing velocity (see Figures 11 and 16).

The model structure is present, but it still must be quantified based on values from the particular system being modeled. Assume a scenario where an object is dropped from a helicopter hovering 2000 meters above the ground. In such a scenario, the initial vertical velocity of the object is 0 since the helicopter is hovering in a stationary position. The gravitational acceleration is -9.8 meters per second per second. The initial position of the object is simply the height of the helicopter above ground assuming a coordinate system with position zero equal to ground level (see Figure 19).

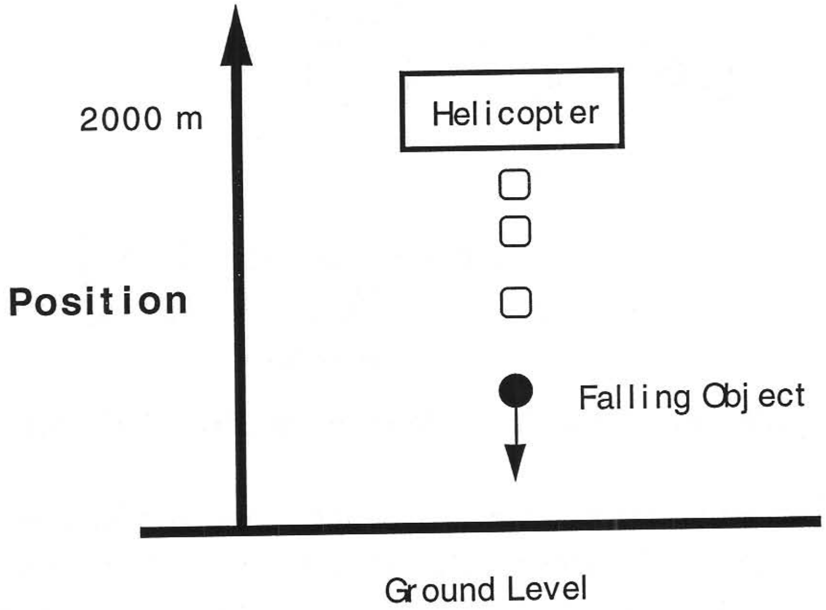

Figure 19: An object falling from a helicopter

The reason that the acceleration was chosen to be negative is because a typical coordinate system assigns the upward direction positive values and the downward direction negative values. The object is falling toward the ground, so at all times its velocity is negative. As the object falls more rapidly, its velocity becomes more negative. When a flow causes a stock to decrease (become more negative) the flow is given a negative value. Since the acceleration (flow) causes velocity (stock) to decrease, it must be negative. This means that as the object falls, the acceleration causes the velocity to become more and more negative so the object moves faster and faster toward the ground. The same relationship holds for the velocity (flow) and the position (stock).

Let's begin to quantify the model structure with the initial value of position.

- **Double-click on the stock labeled *Position***
- **Type 2000 using either the built-in keypad or the keyboard**
- **Click on OK**
- **Repeat this process for:**
  ***Velocity* (initial value) = 0 (m/sec)**
  ***Gravitational Acceleration* = -9.8 (m/sec^2)**

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To define the fall velocity:

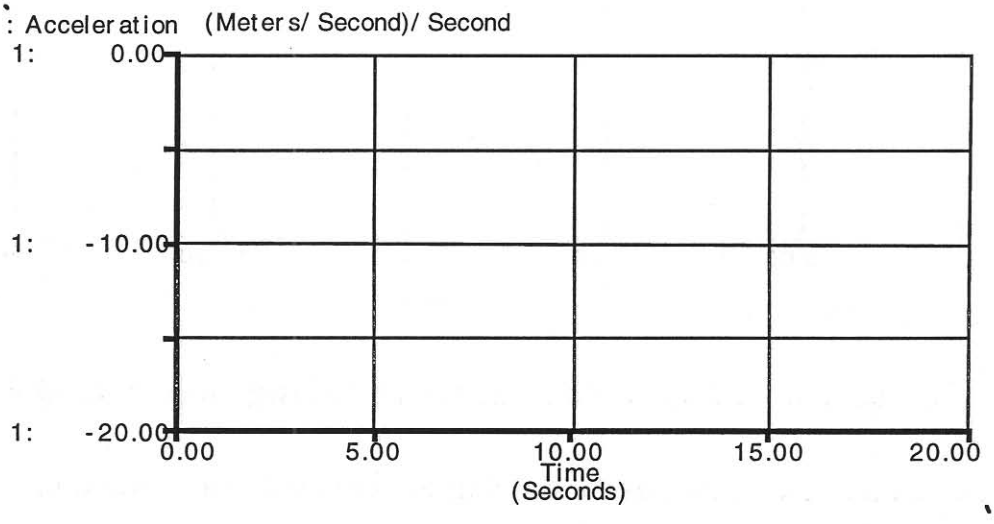
- **Double-click on the flow labeled *Fall Velocity***
- **Click on Velocity (under the required inputs list)**
- **Click on OK**

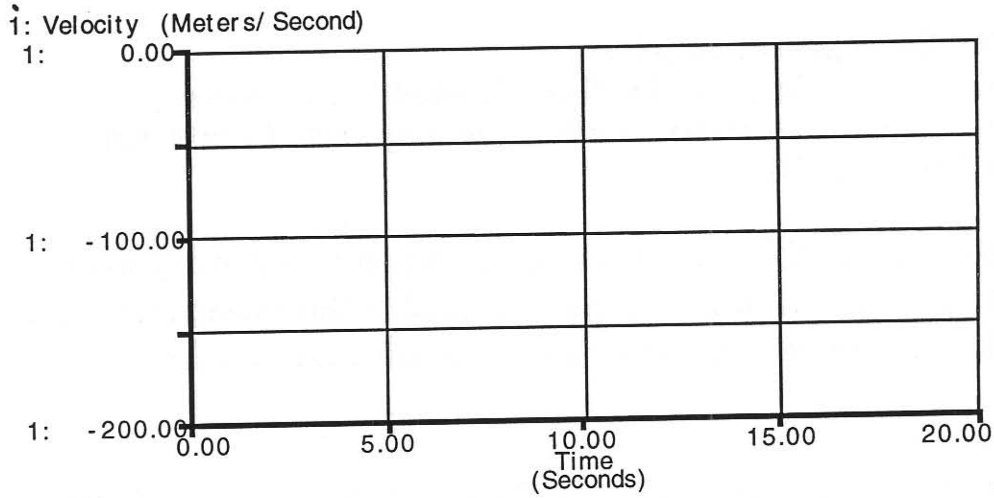
Having quantified the structure, the model is now ready to run. However, before having the computer simulate this system, test your intuition and mental simulation skills with this next exercise.

Exercise:

Graph the acceleration, velocity, and position as a function of time.

Remember that: acceleration = -9.8 (m/sec)/sec
initial velocity = 0 m/sec
initial position = 2000 m





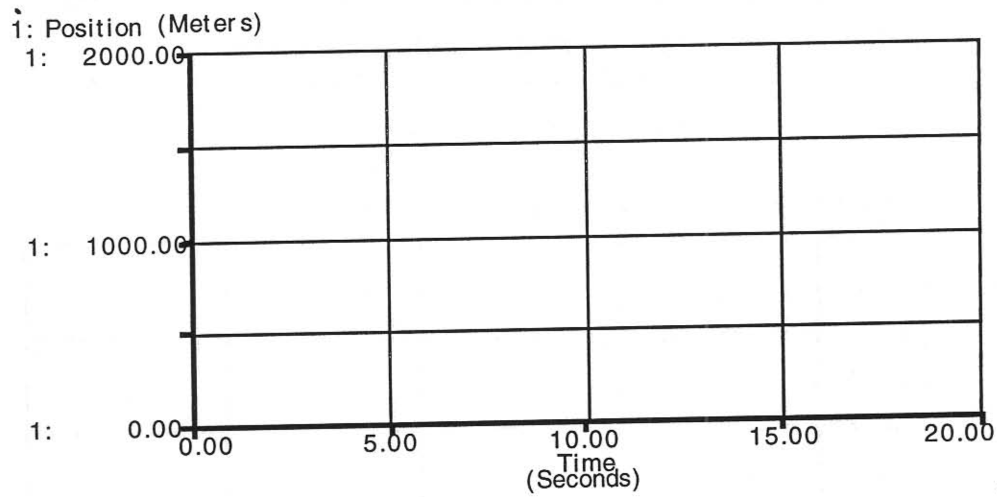


Figure 20: Mental Simulation of falling object model

Let's compare your mental simulation skills with the computer simulation. To simulate this system:

- **Double-click on the *Graph 1* icon** to open the graph.
- **Select Run from the Run Menu**

A graph showing the position of the object over time should appear as in Figure 21. Is this what you had for your mental simulation? Check your mentally simulated graph of velocity against the computer simulation. (You can change between pages of the graph by clicking on the folded up corner in the lower right hand corner of the graph window)

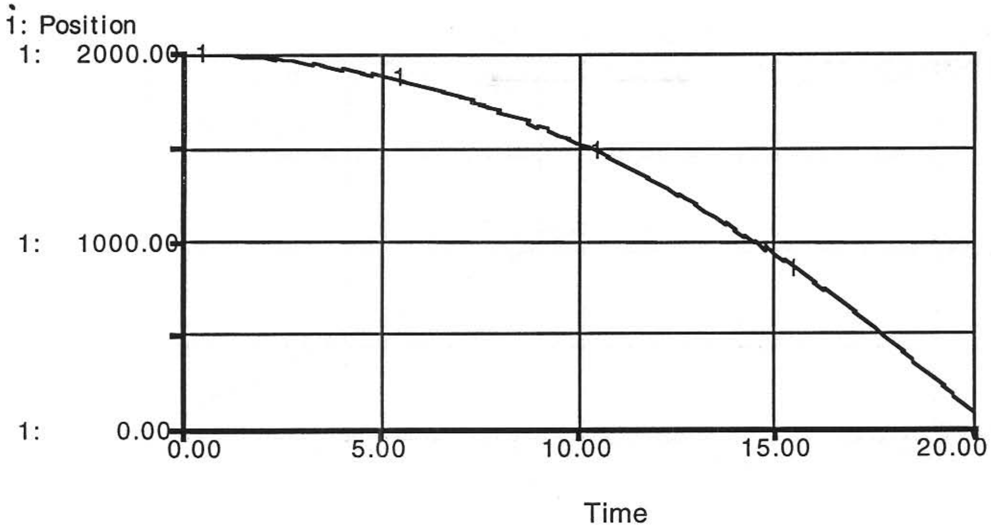


Figure 21: STELLA Graph of Position over Time

The graph in Figure 21 shows that the object starts off 2000 m above the ground and falls down to ground level, speeding up as it goes.

One key aspect of system dynamics is that it allows one to make the connection between structure and behavior. The structure of the free fall system is two stock-and-flow substructures. These structures combine to produce the behavior in position as shown in Figure 21. We can analyze these stock-and-flow structures one at a time to see how they combine to produce the overall behavior of the system.

Consider the constant flow of acceleration into the stock of velocity. Because the flow is a negative value, each second the acceleration decreases the velocity by 9.8 meters per second. (See Figure 22) One thing always true about stock-and-flow relationships is that the magnitude of the flow will determine the steepness of the slope of the stock over time. Because the acceleration is constant (the magnitude of the flow is constant), the velocity decreases with the same steepness through time; it decreases linearly. After 1 second, the velocity is -9.8 m/sec, and after 10 seconds it is -98 m/sec.

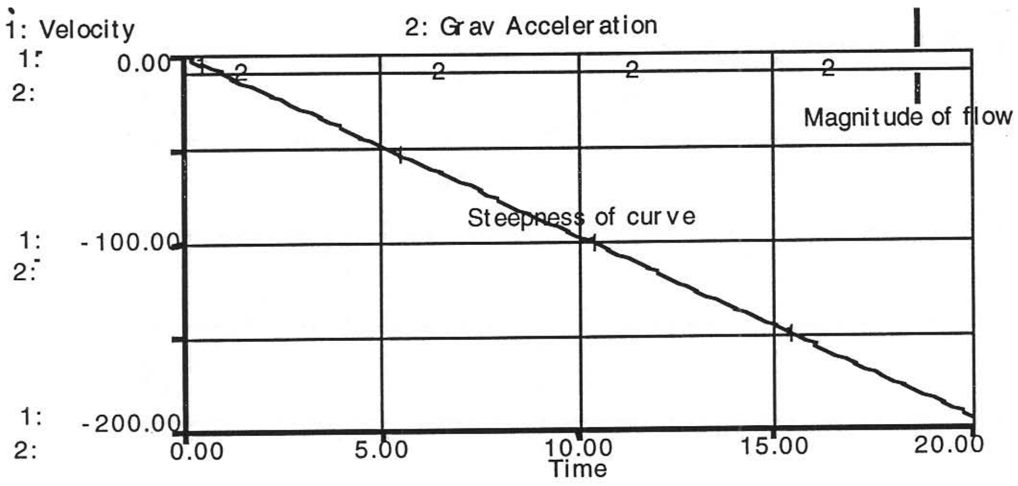


Figure 22: Computer-Simulated Graph of Acceleration and Velocity

Having determined the behavior of the stock of velocity due to the flow of acceleration, we can use the same procedure to determine the behavior of the stock of position with the flow of velocity. Relating the magnitude of the flow to the steepness of the change in the stock over time will always yield a qualitative understanding of the dynamics of the system. The exact numbers may be a little harder to compute, but the relationship between variables can always be captured in this manner.

The vertical velocity is 0 m/sec at the beginning of the simulation and decreases linearly after 0 seconds. Examining the graph in Figure 23, we can see that the magnitude (absolute value) of the flow, velocity is increasing with time. You learned before that the steepness of the curve depicting a stock depends on the magnitude of the flow affecting that stock. So, as the magnitude of the velocity flow increases over time, so must the steepness of the curve depicting the position stock. The increasing magnitude of the velocity causes the object to fall faster and faster.

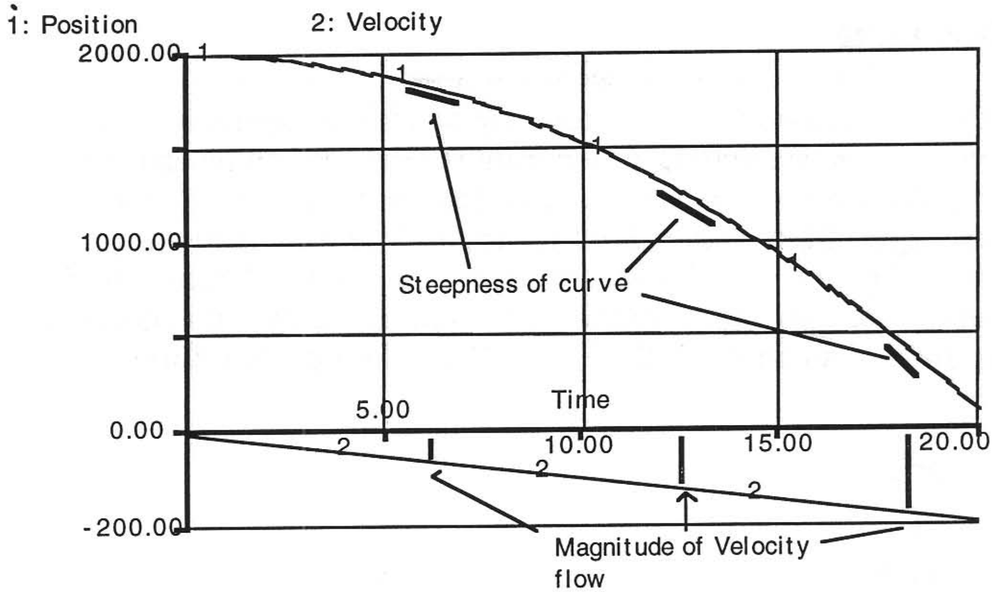


Figure 23: Velocity and Position Depicting Relationship between Stock and Flow

Catch a Train

The two-stock generic structure created in the free fall model can be applied to a host of different physical situations. The following few pages contain an exercise and modeling description which might be assigned to a first-year physics student with basic knowledge of system dynamics. An exercise such as this tests a student's ability to translate a written problem into a precise quantitative form. This exercise requires a student to define the structure of the model, anticipate the system behavior before simulation, observe the system behavior through simulation, and explain how the structure of the system relates to the behavior.

- **Read the description of the following exercise and model the described systems using STELLA.**

Catch a Train

Jay is scheduled to take a train trip to visit his grandmother. However, Jay is late getting to the train station. When he arrives, the train is pulling out of the station. Jay decides to run for the train.

Jay begins 20 meters behind the train. The train is moving away from Jay at a velocity of 2 meter/sec and is accelerating at .5 meters/sec/sec. Jay begins running at 7 meters/sec with no additional acceleration. Can he catch the train? If so, during what time interval?

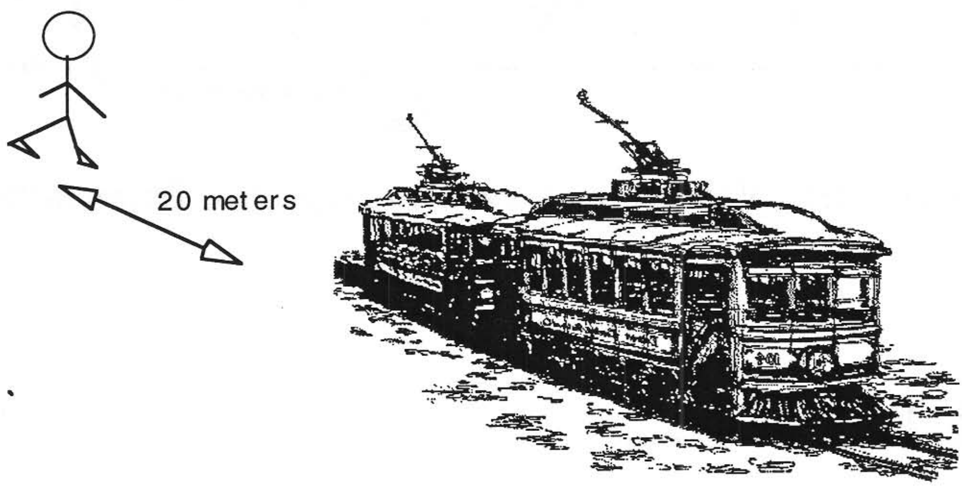


Figure 24: Illustration of "Catch a Train" Problem [6]

The first thing to recognize about this problem is that the structure of the "catch a train" system is exactly the same as the structure we have been working with in the free fall model. The only difference between modeling this problem and modeling free fall is that there are two bodies that have to be modeled in "catch a train," namely Jay and the train.

The written description of the "catch a train" system establishes the acceleration, initial velocity, and initial position of both Jay and the train. We need to simply change the variable names of the free fall model slightly to build the structure of the "catch a train" system. Let us begin the process by modeling Jay. We must first change the variable names of the free fall model so that they correspond to Jay in the "catch a train" system. To do this, let's return to the diagram window.

[6] Tom Rubarth is the train's artist. Matt Halbower takes credit for the portrayal of Jay.

• **Click on the close box in the upper-left-hand corner** to close the graph window
• **Click <u>once</u> on the *Gravitational Acceleration* variable** so that the variable name becomes highlighted
• **Type *Jays Acceleration***
Repeat this process for all of the variables:
• **Click once on the variable and type in the new variable name.**
• **Continue until the free fall model appears as shown in Figure 25.**

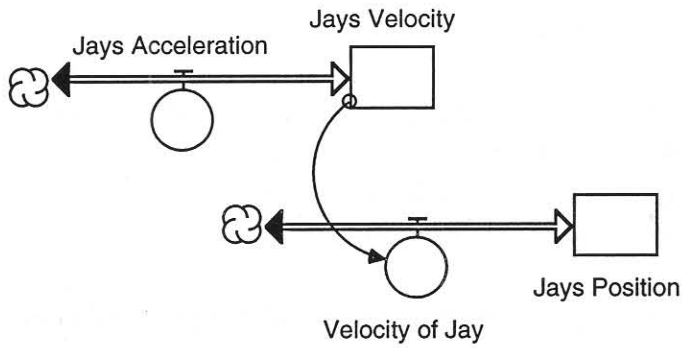


Figure 25: STELLA Diagram Depicting Structure of Jay in "Catch a Train"

The model structure of Jay appears to be complete, but before the "catch a train" system can be modeled, a second structure is necessary to represent the train. Although it is possible to build the train's structure from STELLA building blocks, a simpler method to derive the structure exists. Since the structure modeling Jay's behavior is generic, and therefore transferable, it is possible to copy the structure and use the copy to model the train. To copy a structure:

• **Choose Select All from the Edit menu** to select the entire model.
• **Select Copy from the Edit menu** to indicate that you wish to make a copy of the entire model
• **Select Paste from the Edit menu** to place a copy of the model in the STELLA window.

The new structure should appear highlighted on your screen. This new structure might be laid on top of the old structure. If this is the case:

• Move the STELLA hand over part of the highlighted structure.
• Click once and hold the mouse button down.
• Move the hand to an empty section of the screen.

An outline of the structure should follow with the hand. When the structure is in an empty part of the screen, **release the mouse button** to deposit the structure. You may not have enough room in your STELLA window to place the second model. If this is the case, you should expand the size of your window.

• Click and hold the mouse on the resize icon ⊡ at the bottom right corner of the window.
• Drag the mouse to resize the window.
• Release the mouse button.

The new structure is identical to the old with the exception that the variable names have numbers after them to differentiate from the original structure. Since we do not want structures representing two people, let's rename the new structure so that it represents the train.

• Click once on the flow labeled *Jays Acceleration 2* so that it becomes highlighted.
• Type *Train Acceleration* on the keyboard.
Repeat this process for all of the variables:
• Click once on the variable and type in the new variable name.
• Continue until the model appears as shown in Figure 26.

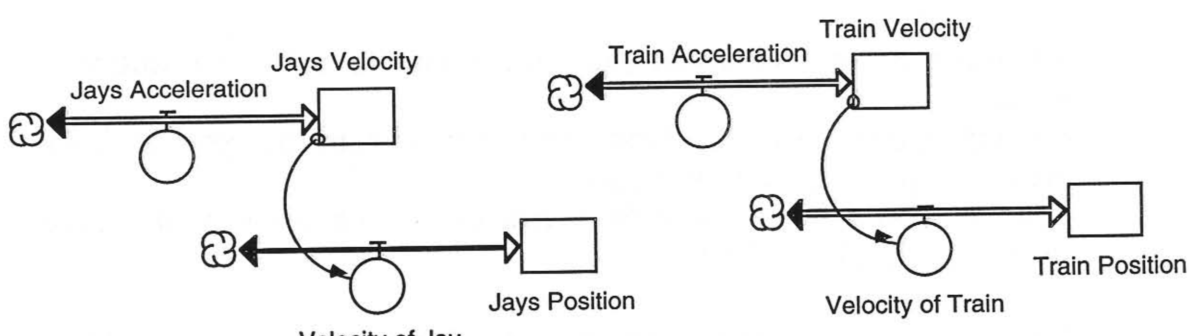


Figure 26: "Catch a Train" Diagram

Now that it looks like we have modeled the "catch a train" scenario, we have to quantitatively define the stocks and flows so that they match the story description. Let's begin with the train's position. From the story description, Jay starts out 20 meters behind the train. Therefore, if we define Jay to begin at a position equal to the origin (initial position = 0), the initial position of the train is at 20 meters.

- **Double-click on the stock labeled Train Position.**
- **Enter "20" on either the built-in calculator or keyboard.**
- **Click on OK.**
- **Repeat this process for the remaining variables:**

Train Acceleration **= 0.5 (m/sec^2)**
Train Velocity **(initial) = 2 (m/sec)**
Jay's Acceleration **= 0 (m/sec^2)**
Jay's Velocity **(initial) = 7 (m/sec)**
Jay's Position **(initial) = 0 (m)**

Make sure that the input values correspond to the written description of the system. You should not have to modify the flows labeled "velocity of train" and "velocity of Jay" because they will continue to be equal to the velocity stocks.

Before computer simulation of the system, a student should mentally simulate the system to analyze how the structure relates to the behavior. Do you think Jay will catch the train? Since we have already mentally simulated this structure once with respect to free fall, let's charge ahead with the computer simulation.

Before we can usefully simulate this system to see whether or not Jay will catch the train, we must place Jay's position and the train position on the same axis to see if the positions ever cross. To do this we need to define a new graph containing both positions on identical scales.

- **Double-click on the "Graph 1" icon.**
- **Double-click anywhere on the graph which appears.**

The window shown in Figure 27 should appear.

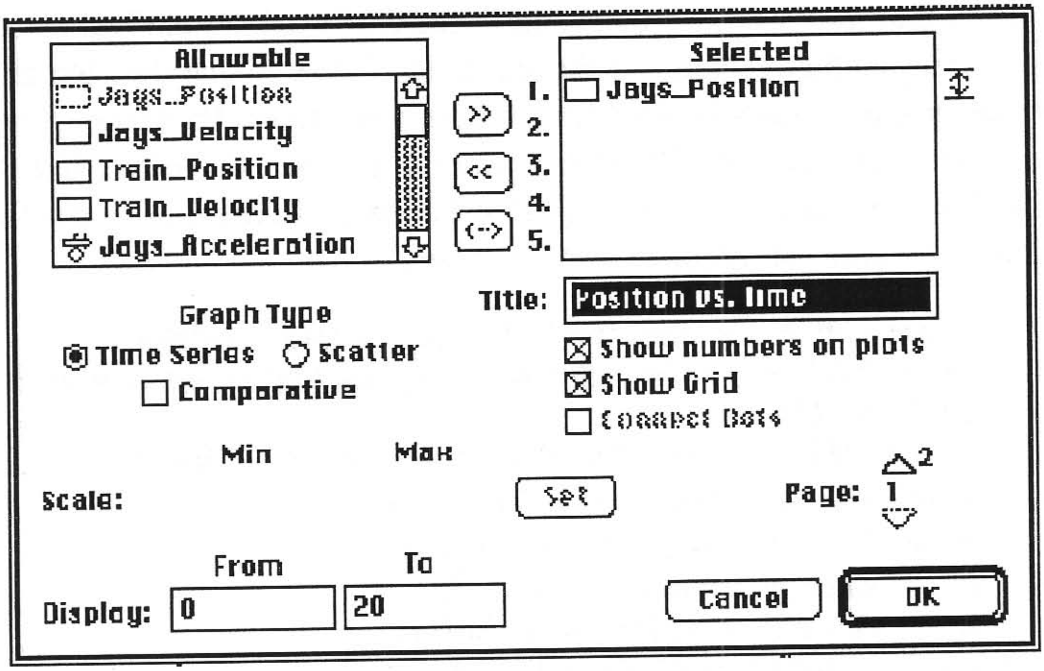


Figure 27: Graph Pad Dialog Box

To graph both the train position and Jay's position on the same axis, we must place both position variables under the selected heading on the right. To add the Train Position to the graph:

- **From the allowable list, double-click on the stock *Train Position*.**

Jay's Position and the Train Position should both appear on the list of selected variables. If one of them is not on the list, click on that variable from the list of allowable inputs and click the enter button. Once both variables appear under the selected heading, we must give the positions identical scales. To scale:

- **Click on *Jays Position*** in the allowable list
- **Drag the cursor to *Train Position*** so that they are both highlighted.
- **Click on the arrows to the right of the selected list until there are flat bars at each end of both arrows.**
- **Type "0" into minimum (Min) Scale.**
- **Hit the tab key and type "200" into the Max Scale.**
- **Click the Set button.**

- **Click on OK.**

The graph is now defined, and your model is ready to be simulated.

- **Select Run from the Run Menu.**

The behavior of the system should appear as in Figure 28.

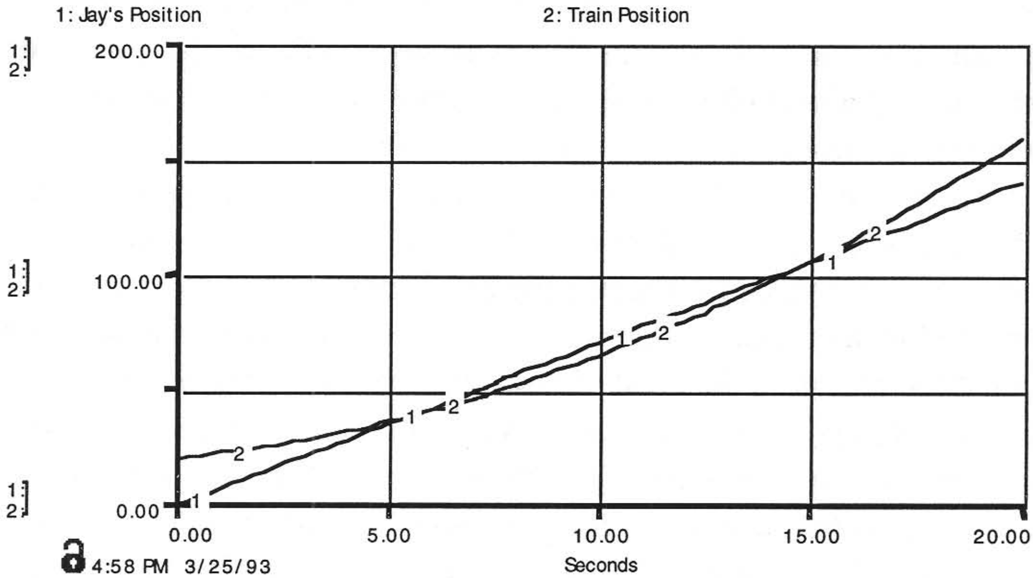


Figure 28: Simulated Graphs of Jay's and the Train's Position

As you can tell from the graph, Jay is at the same position as the train at two times: after 5.5 seconds and after 15.7 seconds. Was your prediction of whether or not Jay would make the train correct?

If you would like to save your Catch a Train model for future reference:

- **Select Save As... from the File menu.**
- **Type "Catch a Train model."**
- **Click once on the save button.**

Once you have saved the model:

- **Select Close Model from the File menu.**

Terminal Velocity

The modeling examples so far are good representations of types of problems which students might see in an introductory physics course. All the modeled bodies moved with uniform velocity or uniform acceleration. Under these assumptions, the equations of motion are relatively simple. Unfortunately, many classrooms do not go beyond the simple problems to discuss more realistic physical systems because of the mathematical complexity associated with solving such problems.

In the context of these idealized mechanics problems, system dynamics and STELLA can aid in both communication and understanding by introducing a language to describe the link between the structure of a system and its behavior. However, unlike typical mechanics instruction, system dynamics does not need to limit students to solving idealized problems because of mathematical complexity. Typical high school physics classrooms cannot look at realistic situations such as modeling the motion of a parachutist because of the complexity of the mathematics. System dynamics and STELLA can be used to model such situations without any knowledge of complex mathematics or differential equations. These models can give students an exact analytical solution to problems of complex motion, and, more importantly, help them develop an intuitive sense for how more complex systems behave qualitatively. To prove this point, let's see exactly how difficult it is to both understand and model the mechanics associated with parachuting.

If you will think back to the original model of free fall, notice that the only missing component which is necessary to model a parachutist is a frictional force resulting from air resistance. We can expand our free fall model by adding the effects of the frictional resistance of air on bodies falling with high speeds.

Before adding a force resulting from air resistance, it is important to understand the structure necessary to define such a force. The structural relationship can be derived qualitatively from a few simple experiments. By holding an open hand out of the window of a speeding automobile, you can readily feel that air offers a substantial frictional resistance to motion. However, when the hand is tightened into a fist, the amount of resistance seems to decrease. The only thing that changes when a hand is made into a fist is the surface area exposed to the air. This suggests that a greater surface area will result in a greater air resistance force than a smaller surface area. The causal relationship between surface area and frictional force is important when modeling a parachutist since an open parachute has a much greater exposed surface area than a closed parachute.

A second experiment which can be performed to determine the structure necessary to define air resistance is to simply wave a hand through the air. The frictional resistance seems much less when a hand is simply waving through the air as compared to a hand held outside the window of a speeding car. This suggests that a hand moving relatively fast through the air has a higher frictional force than a hand moving slowly through the air. The resistive force is therefore a function of the velocity of an object.

It turns out that air resistance increases roughly in proportion to the square of the velocity. Hence a free falling body will experience larger and larger frictional resistance as its velocity increases. As the velocity increases, the air resistance exerts a greater retarding force thereby decreasing the rate of increase in velocity (acceleration). A diagram illustrating these connections between variables is illustrated in Figure 29.

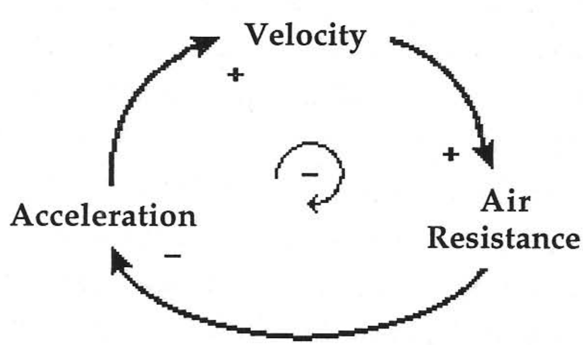


Figure 29: Causal Loop Diagram Illustrating Free Fall with Resistance

The feedback diagram shown above is referred to as a **causal loop diagram.** Arrows in causal loop diagrams indicate a causal influence while the plus or minus signs at the ends of the arrows indicate the direction of the relationship. In the above diagram, the arrow between acceleration and velocity indicates that acceleration has a positive effect on velocity so that increasing acceleration increases velocity. Likewise the positive relationship between velocity and air resistance says that increases in velocity will increase the air resistance. The relationship between air resistance and acceleration is negative indicating that an increase in air resistance will decrease the acceleration. This is a negative relationship because an increase in one variable leads to a decrease in the other. Linking these three causal relationships together, it can be shown that the resulting **feedback loop** tends to stabilize the system by bringing it into equilibrium.

To illustrate this, grab a pen and draw an upward pointing arrow next to the word velocity on the diagram shown in Figure 29. This upward pointing arrow indicates an increase in the velocity of the falling object. If the velocity increases, the causal relationship between velocity and air resistance suggests that the air resistance also increases. Symbolize this with an upward arrow next to air resistance. An increase in the air resistance suggests a decrease in the acceleration which you can represent using a downward pointing arrow next to acceleration. Finally, note that a decrease in the acceleration lowers the rate of increase in velocity, represented by a downward pointing arrow next to velocity. When you are done, you should have a diagram similar to the one shown in Figure 30.

Notice that you now have both an upward and downward pointing arrow next to velocity. This is because every change that occurs in a variable within the feedback loop is counteracted by the loop itself. A loop which displays this property is known as a **negative or stabilizing feedback loop**, and it always approaches some equilibrium value. A negative feedback loop is depicted graphically as a three quarters circle with a negative sign inside as shown inside the feedback loop in Figure 30.

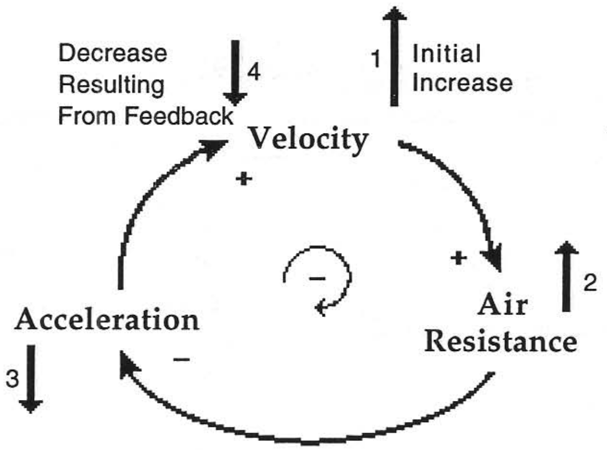


Figure 30: Causal Loop Diagram Illustrating Negative Feedback

This feedback loop tells us that the resisting force ultimately becomes so large that it counterbalances the pull of gravity. This results in a constant falling velocity. This ultimate velocity is called the **terminal velocity**. The precise value of the terminal velocity depends on the mass of the body, the surface area, and the shape.

A STELLA model of free fall with resistance is included on your First Three Hours disk. It is identical to the free fall model with the exception of the additional structure which models air resistance.

To open the free fall with resistance model:

- **Select Open from the File menu.**
- **Click on the model labeled "Free Fall with Resistance."**
- **Click the Open button.**

The diagram shown in Figure 31 should appear.

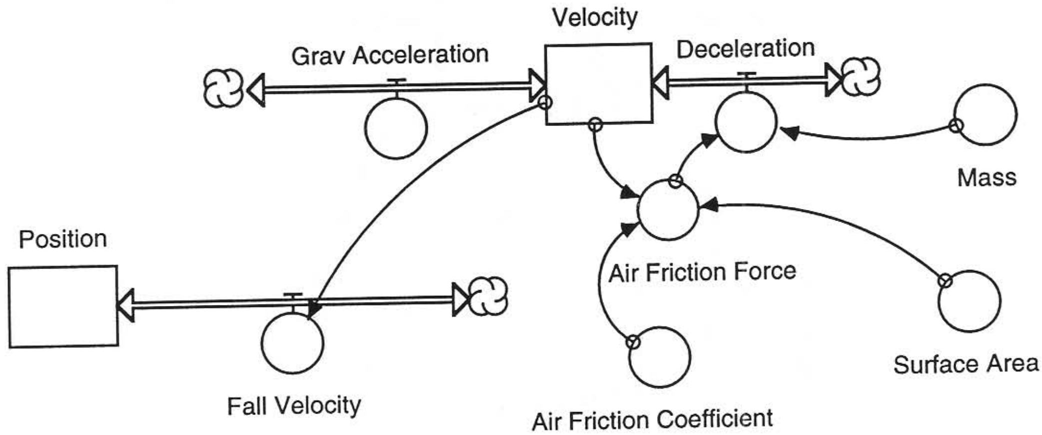


Figure 31: STELLA Diagram of Model Illustrating Free Fall with Air Resistance

As before, there is a flow of gravitational acceleration filling a stock of velocity. Also, as before, the fall velocity acts as a flow to fill a stock of position. The new structure is the outflow from the velocity stock. This outflow of deceleration is a function of the air friction force and the mass of the falling object. The air friction force is a function of the surface area and velocity of the falling object. The air friction force, deceleration, and velocity form the causal loop explained previously. As velocity increases, the force of friction on the falling body increases. Increasing the force of friction increases deceleration which decreases the velocity.

The air friction force is modeled as the surface area of the falling body times a constant times the velocity squared. The force is then converted to deceleration by dividing by the mass of the body.

Air_Friction_Force=
Velocity*Velocity*Surface_Area*Air_Friction_Coefficient
Deceleration = -Air_Friction_Force/Mass
Air_Friction_Coefficient = 0.227 kg/m^3

The Air Friction Coefficient is a measure of how "resistive" air is. If an object were falling through water, the friction coefficient would be much higher. In a vacuum, the friction coefficient is zero.

There is an additional piece of this model which is not depicted in Figure 31. If you look to the right of the STELLA diagram window, you should see a scrollbar with arrows at the top and bottom. Place the mouse pointer over the bottom arrow and hold the mouse button down. After a few seconds, you should see the following structure.

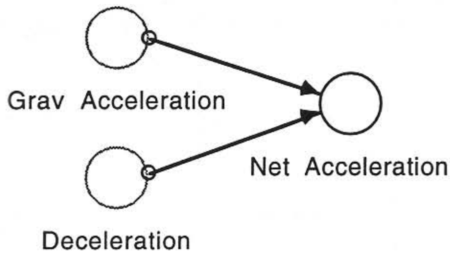


Figure 32: STELLA Diagram of Net Acceleration

The structure in Figure 32 computes the net flow (net acceleration) into the stock which is equal to the inflow (gravitational acceleration) minus the outflow (deceleration). The net flow is the rate of change of the stock. When the net flow is 0 (the inflow equals the outflow), the stock remains constant through time.

The system is currently set up to model the same scenario as the free fall example. A helicopter hovering 2000 meters above the ground drops a large object (the size of a person).

You may wish to **double-click on each model element** and **read the document comments** to get a better idea of what each element contributes to the model. How do you think this system will behave over time? Grab a sheet of paper and sketch the net acceleration (gravitational acceleration - deceleration), the velocity, and the position.

When you are convinced that you have the correct behavior, simulate the model.

- **Double-click on the "Graph 1" icon.**
- **Select Run from the Run Menu.**

The graph of position found in Figure 33 should appear.

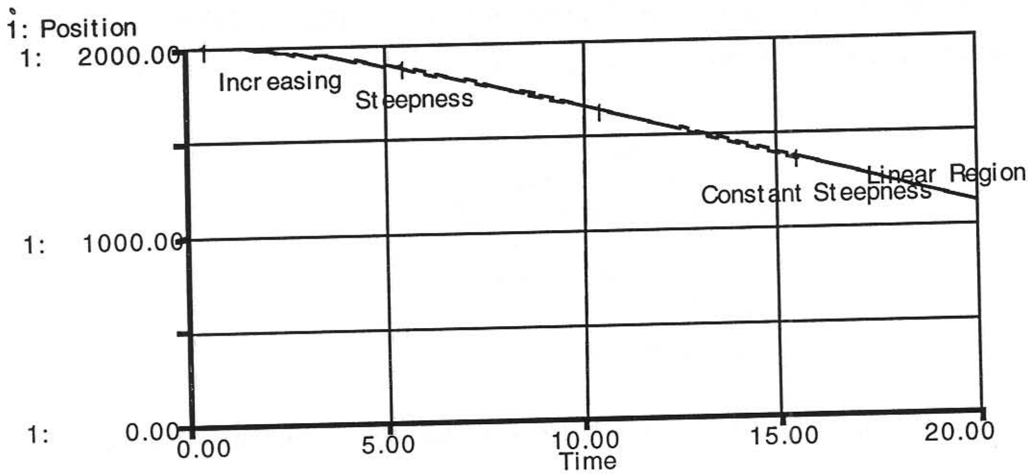


Figure 33: Graph of Position over Time

The graph of position over time in Figure 33 is not the same as that for a falling object without air friction. What happens in this case is that, as the object moves faster and faster, the resistive force from the air increases. Eventually, when the object is moving fast enough, the acceleration due to air friction exactly balances the acceleration due to gravity. When this happens, the acceleration is equal to zero, so the velocity stops decreasing. Remember, acceleration is a flow that affects velocity. In this case, acceleration causes the velocity to become more negative, to decrease. When the acceleration becomes zero, it is no longer causing velocity to decrease. Since velocity is no longer changing, the steepness of the position curve also stops changing. The velocity at which this occurs is called *terminal velocity*.

If you click on the folded corner in the lower left hand corner of the graph window, the graphs of net acceleration and velocity shown in Figure 34 should appear.

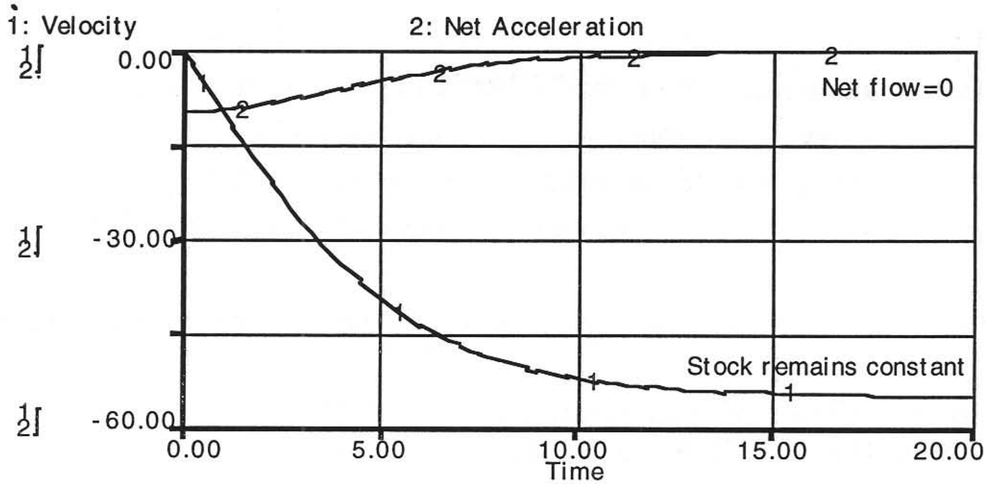


Figure 34: Graph of Net Acceleration and Velocity over Time

Was your mental simulation correct? Did you predict that the net acceleration would approach 0 making the velocity a constant? Did you show on your graphs that once velocity was constant, the position decreased linearly? One item that is interesting to note is that the body fell a much shorter distance than the free fall model after 20 seconds. The reason for this is the air friction which slows down the object. It would be like you and your friend having a running race, except you have to run in a pool. He will go further than you over any time period.

Try modifying the model to simulate someone jumping out of a plane with a parachute. To model a parachutist, change the surface area of the falling person to 80 square meters.

- **Select Close Window from the File menu** to close the graph.
- **Double-click on the converter labeled *Surface Area.***
- **Type "80" into the keyboard.**
- **Click on OK.**

Double-click on the Graph 1 icon and **run** the model to see what effect an increased surface area has. What is the new terminal velocity? How quickly does the parachutist reach terminal velocity?

If you want to keep exploring, it might be fun to research the following set of questions:

What if you found yourself in free fall on the planet Jupiter? What is the gravitational acceleration there and what is the atmosphere like? What changes would have to be made to the model to simulate free fall on Jupiter? How much would an ordinary person weigh on Jupiter? How does the terminal velocity on Jupiter compare with terminal velocity on earth?

When you have completed your work on the terminal velocity model:

- **Select Close Model from the File menu.**
- **Click the Don't Save button.**

Free Fall and Energy Conservation

One powerful feature of system dynamics is that one can model a system in differing degrees of complexity. We began by modeling a free falling body while ignoring the effects of resistance on the motion of that body. We then added to the structure of the model to take resistive forces into account. A further addition might be to analyze the energy associated with free fall. A free falling body provides an excellent example of the process of transforming potential energy to kinetic energy.

By adding converters to keep track of the energy in the system, we are not adding anything that will modify the existing structure. We are just keeping track of values already contained in the model in a different form.

Let's begin with potential energy. Potential energy is the energy stored in an object due to its position. Potential energy is defined as the weight of the falling body times the height above ground. The weight is the mass of the body times the gravitational constant. The "free fall with resistance" model already contains the mass, gravitational acceleration constant, and position above ground. All that has to be done to keep track of the Potential energy in the system is to define two new parameters (see Figure 35) . One parameter can be labeled as the "Weight", and it can be defined as the gravitational acceleration times the mass. The other new parameter can be labeled as the "Potential Energy", and it can be defined as the weight times the position.

The kinetic energy is defined as one-half the mass times the velocity squared. It is the energy in and object due to being in motion. By creating a new converter labeled "Kinetic Energy" and defining its equation to be the mass times the velocity times the velocity, we can keep track of kinetic energy in the system.

To see how this works, call up the model named Free Fall and Energy Conservation.

- **Select Open from the File Menu**
- **Click once on the file labeled "Free Fall/Energy Conservation"**
- **Click the Open button**

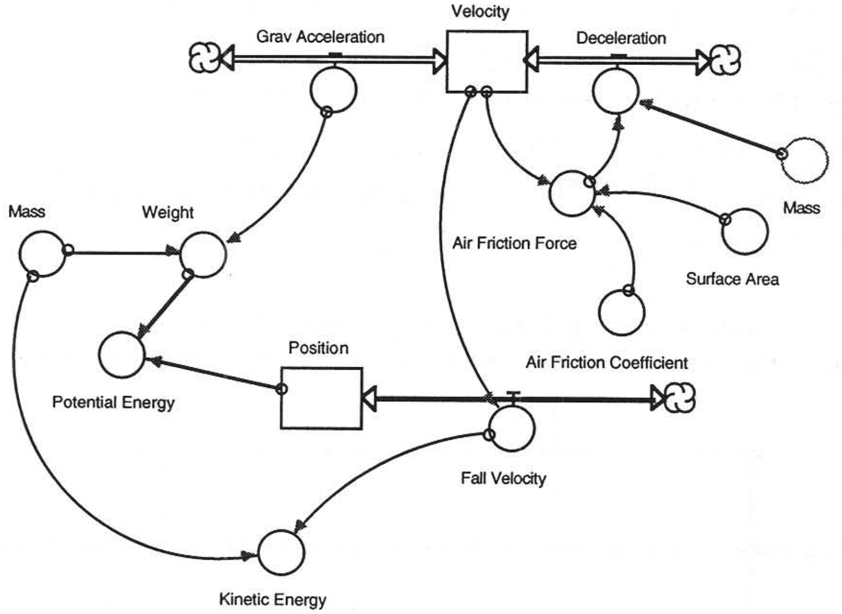


Figure 35: STELLA Diagram of Free Fall and Energy Conservation Model

This STELLA structure is identical to the structure in the terminal velocity model. The only additions are potential energy, kinetic energy, weight, and total energy. Do not worry if you do not see a total energy variable in Figure 35. Once again, the structure in Figure 35 does not show the entire STELLA diagram. Move down the scrollbar on the right of the diagram window until you see the structure shown in Figure 36. The converter labeled Total Energy is defined as the sum of the kinetic energy and the potential energy of the falling body. The total energy is important so that we can compare the total energy, kinetic energy, and potential energy of the system over time.

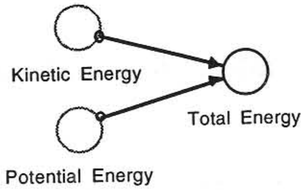


Figure 36: Total Energy Diagram

<u>**Exercise:**</u>

On the axis in Figure 37, sketch how you believe the total energy, kinetic energy, and potential energy of the system will behave over time. <u>A few hints</u>: The kinetic energy begins at 0 because the object starts at rest, and the initial total energy in the system is 1,372,000 joules (mass*g*position= 70*9.8*2000=1,372,000, where g is the gravitational acceleration constant).

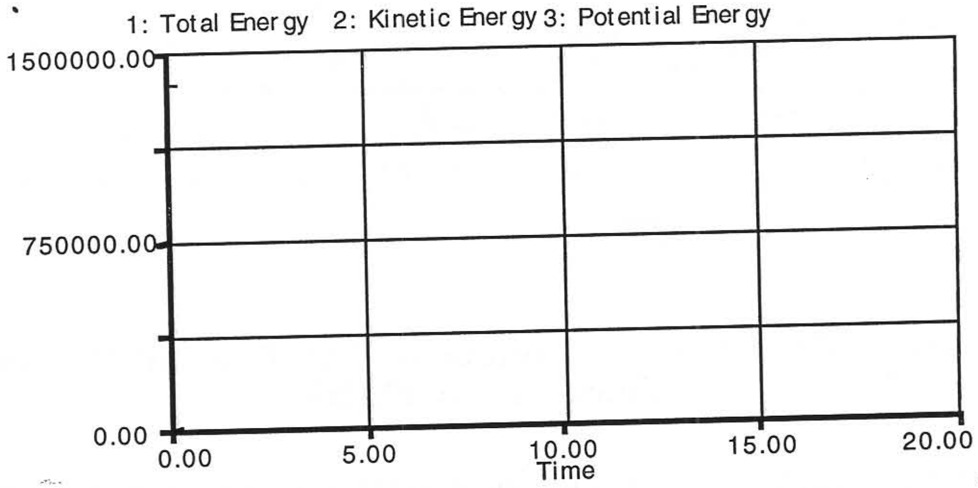


Figure 37: Mental Simulation of Total Energy, Kinetic Energy, and Potential Energy

Once you are satisfied with your graphs:

- **Double-click on the Graph 1 icon**
- **Select Run from the Run menu**

The energy graph should appear as in Figure 38.

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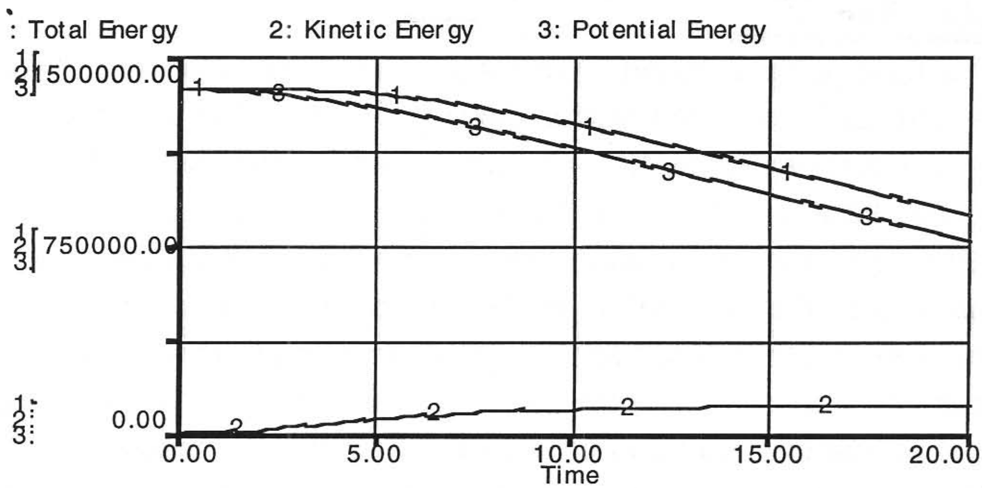

Figure 38: Graphs of Total Energy, Kinetic Energy, and Potential Energy

Was your mental simulation correct? Did you predict that the total energy of the falling body would decrease? How can this can be possible if there is conservation of energy? How is the energy escaping from the system? What is the energy being transformed into? What is the effect of the frictional force of air resistance on energy? Did you predict that the kinetic energy would rise to a certain level and remain constant because the object reached terminal velocity?

Debriefing

You have just completed a great deal of material. In essence, you constructed, analyzed, and tested a Velocity, Acceleration, Position, Energy, and Resistance model. The initial model simply showed the relationship between velocity and position. From there, the relationship between acceleration and velocity was explained using the identical structure explored in the motion model. Velocity, acceleration, and position were then combined and analyzed in terms of the system's overall behavior. Air resistance was then added to show the feedback structure involved in free fall and terminal velocity. Finally, converters were added as bookkeepers for kinetic and potential energy. Conservation of energy was explored as we modeled how the potential energy of a falling object is turned into kinetic energy with losses of energy due to air resistance forces.

Hopefully at this point you see some potential in system dynamics modeling applied to the classroom. However, most educators ask how they are to incorporate system dynamics and learner-centered learning projects into an already overloaded curriculum. Consider what this science teacher has to say about his experience with introducing system dynamics. "Our classrooms have undergone an amazing transformation. Not only are we covering more material than just the required curriculum, but we are covering it faster (we will be through with the year's curriculum this week and will have to add more material to our curriculum for the remaining 5 weeks) and the students are learning more useful material than ever before."[7]

By integrating system dynamics and learner-centered learning into current curricula, educators create a learning environment which will serve to anchor facts and details through structural and behavioral relationships. Your student might even have a great deal of fun using system dynamics to explore the world through computer simulation.

Included on the next few pages are a list of ideas for other models not included in your introductory packet. Please peruse the applications list to see if there are examples relevant to your classroom.

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[7] Draper, Frank. Orange Grove Middle School. Letter to Jay Forrester, May 2, 1989, p.2.

Pre-College System Dynamics Curricula

Ozone Depletion Model - A model illustrating the chemical reactions involved between CFCs and ozone in the upper atmosphere.

$$Cl + O_3 \rightarrow ClO + O_2$$
$$ClO + O \rightarrow Cl + O_2$$

This model could then be coupled to models of CFC production and ultraviolet radiation. Further expansion could explore increased radiation effects on earth in terms of increased melanoma and crop loss.

Convection Model - A model of solar energy's effect on the temperature of air and the convection currents which arise from these temperature imbalances.

Boiling Water Model - A model illustrating the heat of vaporization as well as the difference between temperature and heat can be produced and studied.

Heat Diffusion - A model of heat diffusion between two regions of different temperatures could be applied to the example of a home during a New England winter. With the addition of a furnace control mechanism, the model could be expanded to illustrate feedback between the desired temperature on the thermostat and the actual temperature. A cost accounting system could then be added for the purpose of allowing students to design their own furnace control mechanism (feedback mechanism) which would operate with minimal costs and maximum convenience.

Nuclear Chain Reaction - A nuclear chain reaction model could show the behavior and structure of a chain reaction as well as keep track of energy released. Additionally, the structure associated with a chain reaction is very generic. This type of generic structure means that a model of a chain reaction could be changed to a model of a disease epidemic by simply changing variable names.

Radioactive Decay - Model of Radioactive half-life with a linkage to energy of radiation given off.

Greenhouse Effect - Like many of the other models, a greenhouse effect model can be as simple or complex as you desire. Students might start off with the chemistry and physics behind the greenhouse effect. With this mastered, structure might be added so that students could become the policy makers in a greenhouse effect simulation. They would have to learn the science behind the greenhouse effect as well as balance the competing interests of industry and the environment. There might be subsystems representing alternative fuels, the automobile industry, or any other party involved in the system.

Kaibab Plateau Ecosystem - The Kaibab Plateau ecosystem is a region of approximately 730,000 thousand acres north of the Grand Canyon. In the early 1900s a bounty was awarded to hunters who killed the predators in the region. Once the predator population disappeared, the deer population began to multiply to such a large extent (4,000 to 100,000) that the deer destroyed their own food supply which ended up nearly destroying the herd. An excellent model of these ecosystem dynamics already exists. Further, rather than simply studying the dynamics, students can act as the managers of the Kaibab Plateau Wildlife Preserve. This allows them to experiment with policies which will bring the ecosystem into balance.

Electrical, Physical Generic Structure - The idea here would be to show the similarity in structure (generic structure) which is shared by an electrical and physical system.

Insulin Production and Blood Sugar Levels - A quantitative model examining the feedback processes between blood sugar level and insulin production is being produced. Emphasis will be placed on examining the system changes which occur for victims of diabetes. This model can be further coupled to a model of digestion. It could then be expanded to other bodily systems until a model of the human body is produced.

Chemical Reactions - Any chemical reaction can be simulated on STELLA.

Regulation of Body Temperature
Temperature and Rainfall Regulation
Projectile Motion Model
Motion Down an Inclined Plane
Pressure, Temperature, Volume Interactions
Model of Lightning and Potential Difference
Lynx and Hares Ecosystem
Energy Efficiency in the food chain
Stomate in a Leaf
Photosynthesis

Social Science:

Urban Growth Model - One of the original applications of system dynamics was an analysis of the causes of urban growth and decay which examined the effects of a number of urban renewal programs, including low-income housing, job training, and new enterprise production.[8] Since that time, system dynamics has been applied to the relationships between population, pollution, natural resources, and economic growth.

Pollution causes and Environmental awareness
Case study of Tragedy of Sahel in Sahara Desert
Traffic Jams
AIDS Epidemic
Finite Natural Resources
Population Dynamics
Causes of the American Revolution

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[8] Forrester, Jay. Urban Dynamics. Productivity Press, 1969.
Alfeld, Louis and Graham, Alan. Introduction to Urban Dynamics, Productivity Press.
Mass, Nathaniel. Readings in Urban Dynamics Volume 1, Productivity Press.
Schroeder, Walter; Sweeney, Robert and Alfeld, Louis. Readings in Urban Dynamics Volume 2, Productivity Press.

Sources of Further Information

For additional information on the models from the Pre-College System Dynamics Curricula:

Lees Stuntz
Creative Learning Exchange
1 Keefe Road
Acton, MA 01720
Phone: (508) 287-0070
Fax: (508) 287-0080
Email: stuntzln@world.std.com

For information on the System Dynamics in Education Project, please contact:

Nan Lux
System Dynamics in Education Project
System Dynamics Group
E60-383
30 Memorial Dr.
Cambridge, MA 02139
Phone: (617) 253-1574
Fax: (617) 252-1998
Email: nlux@mit.edu

To inquire about educational prices for STELLA II software, please contact:

High Performance Systems
45 Lyme Road
Hanover, NH 03577
Phone: 1-800-332-1202, (603)-643-9636

If you have any questions about obtaining books from Productivity Press, contact:

Productivity Press
P.O. Box 13390
Portland, OR 97213
Phone: 1-800-394-6868, (503)-235-0600
Fax: 1-800-394-6286

To join the K-12 Discussion Group for educators interested in using System Dynamics to teach, email Nan Lux, discussion group administrator, at **nlux@mit.edu**

The address for our System Dynamics home page on World Wide Web (Mosaic) is: **http://sysdyn.mit.edu**

Appendix 9: Article: Modeling Dynamic Systems

Summary:
Another introduction to System Dynamics

1

Modeling Dynamic Systems

> Indeed, from Pythagoras through pyramidology, extreme irrationalities have often been presented in numerical form. Astrology for centuries used the most sophisticated mathematical treatments available—and is now worked out on computers: though there is, or used to be, an English law which provided that "every person pretending or professing to tell Fortunes, or using any subtle Craft, Means or Device . . . shall be deemed a Rogue and Vagabond."[1]

1.1 Model Components

Model building is central to our understanding of real-world phenomena. We all create mental models of the world around us, dissecting our observations into cause and effect. Such mental models enable us, for example, to successfully cross a busy street. Engineers, biologists, and social scientists simply mimic their observations in a formal way. With the advent of personal computers and graphical programming, we can all create more complex models of the phenomena in the world around us. As Heinz Pagels has noted,[2] the computer modeling process is to the mind what the telescope and the microscope are to the eye. We can model the macroscopic results of microphenoma, and vice versa. We can simulate the various possible futures of a dynamic process. We can begin to explain and perhaps even to predict.

Frequently, the phenomena occurring in the real world are multifaceted, interrelated and difficult to understand. In order to deal with these phenomena, we abstract from details and attempt to concentrate on the larger picture—a particular set of features of the real world or the structure that underlies the processes that lead to the observed outcomes. Models are such abstractions of reality. Models force us to face the results of the structural and dynamic assumptions we have made in our abstractions.

The process of model construction can be rather involved. However, it is possible to identify a set of general procedures that are followed frequently. These general procedures are shown in simplified form Figure 1.1. Real events stimulate our curiosity about a particular phenomenon. This curiosity can be translated into a question or set of questions about observed

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[1]Conquest, R. 1993. *History, Humanity and Truth*, 22nd Jefferson Lecturer in the Humanities, Washington, DC, May 5, 1993.
[2]Pagels, H. 1988. *Dreams of Reason*, Simon and Schuster, New York.

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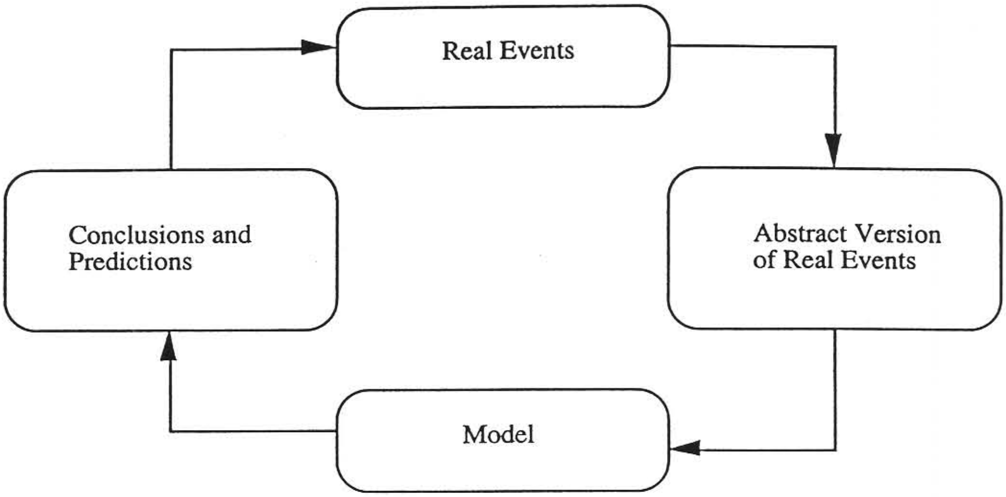

FIGURE 1.1

events and the processes that brought these events about. Key elements of processes and observations can be identified to form an abstract version of real events. Particularly, we may want to identify variables that describe these events, and outline the relationship among variables, thereby establishing the structure of the model. Based on the performance and the results of operating or "running" the model, we can draw conclusions and provide predictions about events yet to be experienced or observed. These conclusions and predictions, in turn, can be compared with real events and may lead to the falsification of a model, its acceptance, or more likely, its revision. When crossing the busy street, we make an estimate of the width of the street, the number and speed of the approaching cars, and our own speed. We may abstract away from extraneous details such as the color of the cars or the species of birds in the trees on the other side of the street. Once we made our observations or estimates, and our abstractions, we relate the various pieces of information to each other—we develop a model. Before we cross the street we "execute" our model in our mind, consider the outcome, and then decide whether we have a fair chance of arriving unharmed on the other side. If we do, we likely use this model again. If we don't, but are lucky enough, we revise the model and use that revised version for our next decision. Perhaps the birds in the trees on the other side of the street are vultures and we should have used that information as a sign that this is a particularly dangerous spot to cross. We should have been more precise in the estimate of the speed of the cars or the width of the street.

Modeling is a never-ending process—we build, revise, compare, and change models. With each cycle, our understanding of the reality improves.

Two general types of models can be distinguished. The first type is models that represent a particular phenomenon at a point of time. For example,

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a map of the United States depicts the location and size of a city or the rate of infection with a particular disease, each in a given year. Other models describe and analyze the very processes by which a particular phenomenon is created. We may develop a mathematical model describing the change in the rate of migration to or from a city, or the change in the rate of the spreading of a disease. Similarly, we may develop a model that captures the change of these rates *over time*. The latter type of models are dynamic models that attempt to capture and represent the change in real or simulated time.

An understanding of the dynamics and changing interrelationships of systems, such as social, biological, and physical systems, is of particular importance in a world in which we face increasing complexity. In a variety of disciplines, scientists ask questions that involve complex and changing interrelationships among systems. What are the impacts of a vaccination program on the rate of infection in a population? How does the profit-maximizing rate of oil exploration in the lower 48 United States change with a change in the interest rate? What are the time paths of toxins carried in a river and how do these toxins affect the local wildlife? All good modeling processes begin (and end) with a good set of questions. These questions keep the modeler focused and away from the miasma of random exploration.

Models help us understand the dynamics of real-world processes by mimicking with the computer the actual but simplified forces that are assumed to result in a system's behavior. For example, it may be assumed that the number of people migrating from one country to another is directly proportional to the population living in each country and decreases the farther these countries are apart. In a simple version of this migration model, we may abstract away from a variety of factors that impede or stimulate migration, besides those directly related to the different population sizes and distance. Such an abstraction may leave us with a sufficiently good predictor of the known migration rates, or it may not. If it does not, we reexamine the abstractions, reduce the assumptions, and retest the model for its new predictions.

It is an elementary preprinciple in modeling that one should keep the simulation simple, even simpler than one knows the cause and effect relationship to be, and only grudgingly complexify the model when it does not produce the real effects. After all, it is not the goal to develop models that capture all facets of real-life systems. Such models are useless because they are as complicated as the systems we wanted to understand in the first place.

Computer models are causal in the sense that they are built by using general rules that describe how each element in a system will respond to the changes of other elements. In the migration example above, the number of migrants was assumed to be proportional to the size of the population in each country. With migration, these population sizes change over time, thereby leading to new levels of migration over time.

When a model is simulated with a computer, each element of the model is specified by initial conditions and the computer works out the system's responses according to the specified relations among elements. These initial conditions may be based on actual measurement, such as the size of a population in a city or the number of people affected with a disease, or estimates, such as estimates for the contact rate of infected people with uninfected ones. The estimates, in turn, may be based on empirical information or are just reasonable guesses by the modeler and are used to illustrate the particular processes, rather than provide exact empirical information.

Models help us in the organization of our thoughts, data gathering, and evaluation of our knowledge about the mechanisms that lead to the system's change. For example:

> One can create a computer model of a forest ecosystem, consisting of a group of assumptions and information in the form of computer language commands and numbers. By operating the model the computer faithfully and faultlessly demonstrates the implications of our assumptions and information. It forces us to see the implications, true or false, wise or foolish, of the assumptions we have made. It is not so much that we want to believe everything that the computer tells us, but that we want a tool to confront us with the implications of what we think we know.[3]

Some of the elements that make up the system for which a model is being developed are referred to as state variables. State variables may or may not be conserved. Each conserved state variable represents an accumulation or stock of materials or information. Typical conserved state variables are population, resource endowments, inventories, and heat energy. Nonconserved state variables are pure indicators of some aspects of the system's condition. Typical nonconserved state variables are price and temperature. System elements that represent the action or change in a state variable are called flows or control variables. As a model is run over time, control variables update the state variables at the end of each time step. Examples for control variables are the number of births per period, a variable that changes the state variable "population," or the number of barrels of crude oil extracted changing the state variable "reserves."

Typically, components of the system that is being modeled interact with each other. Such interactions of system components are present in the form of feedback processes. Feedback processes are said to occur if changes in a system component initiate changes in other components that, in turn, affect the component that originally stimulated the change. Negative feedback exists if the change in a component leads to a response in other components that counteracts the original change. For example, the increase in the density of a prey species leads to an increase in predator density that, in turn, reduces prey density. Analogously, positive feedback is present if

[3]Botkin, D. 1977. Life and Death in a Forest: The Computer as an Aid to Understanding, in: C. Hall and J. Day (eds.) *Ecosystem Modeling in Theory and Practice: An Introduction with Case Studies*, John Wiley and Sons, New York, p. 217.

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the change in a system component leads to changes in other components that then strengthen the original process. For example, if the valve of a boiler is defective it may not open properly when the pressure of steam inside the boiler increases. If with increasing pressure the valve gets stuck more tightly, pressure will increase even further, thereby restricting further the opening of the valve. The result may be that the boiler ultimately explodes. Positive feedback, when uncontrolled, results in "explosive" dynamics. The defunct boiler is an apt example, and so is the case of population "explosion."

Negative feedback processes tend to counteract any disturbance and lead systems toward steady state. One possible steady state for interacting predator and prey populations would be that the size of each population stabilizes in the long run. Such stabilizing dynamics are in contrast to the positive feedback processes that tend to amplify any disturbance, leading systems away from equilibria.

Typically, systems exhibit both positive and negative feedback processes that have different and varying strengths. Variation in feedback processes can be brought about by nonlinear relationships. Such nonlinear relationships are present if a control variable does not depend on other variables in a linear fashion but changes, for example, with the square root of some other variable. As a result of nonlinear feedback processes, systems may exhibit complex dynamic behavior.

Once a stimulus on a system occurs, the response of the system may not be instantaneous. Rather, there may be a time lag between the stimulus and the response. In some cases, the length of the time lag is rather well known. For example, a power outage during winter in the American Northeast is typically followed by an increase in the number of births 9 months later. How the power outage translates into demand for classrooms or school buildings 6 years later when the children are of school age, is less obvious and depends on a large number of other factors, such as migration behavior of families, availability of teachers, and availability of public funds.

People often lack an understanding of time-lagged system behavior and they have a chronic inability to control such behavior both with regard to the systems that humans create and with regard to natural systems. The less well entrenched these systems are and the shorter they have been operating, the easier and less expensive it is to change them. Changing the power supply for a new residential development can be relatively straightforward, but changing a country's dependency on petroleum resources is extremely difficult—it involves changes to the entire infrastructure that supports our current lifestyles, ranging from petroleum refineries and power generation to automobile manufacturing and public transportation. Phasing out chlorofluorocarbons required an understanding of their effect on stratospheric ozone depletion as well as the time lags associated with their release and their damage on the environment. Understanding and managing carbon flows through the fossil-fuel-based economy and the global ecosystem requires an understanding of multiple, interdependent, time-lagged systems. Yet, by the time ignorance of environmental impacts has been reduced, it is often too expensive and too difficult to influence system behavior.

Systems modelers pay special attention to nonlinearities and time lags in their models. Throughout their lifetime they try to sharpen their perception of nonlinearities and other systems features, and they improve their skills in modeling them. The eloquence of their models inspires other modelers and opens their eyes to see the world in a new way.

1.2 Dynamic Modeling as a Skill and Art

The intricacies of many real-world systems overwhelm the ability of humans to adequately understand these systems. Our mental models are often inadequate to provide a comprehensive perspective on the many interrelated aspects of systems and to anticipate their behavior. This is why we need to develop formal models, and why we need to develop skills to play out the assumptions of our formal models—we need help in handling uncertainty, feedbacks, and lags.

Many of the decisions that society faces also require that its members are effective in sharing their information and knowledge with each other—that they communicate their assumptions about system behavior and that they identify the likely system responses under alternative assumptions. One approach to societal decision making would be to identify a group of experts and ask them for advise. This is typically done in management decision making where consultants are brought in to find solutions for problems, and in policy decision making where studies are commissioned to chart the likely behavior of a social, economic, technological, or environmental system. In either case, it is the experts who define the problem such that it can be addressed with their problem-solving expertise. Once they have nailed the problem down, they provide advice on how to address it.

If you ask different groups of experts, they may look at the problem differently and they may come up with different solutions. After all, disagreement among narrowly chosen perspectives on a complex system is a likely result of complexity itself. But once the experts disagree, the question *What should I do?* changes into the question *Which advisor should I believe?* and this new question is often as difficult to answer as the first one.

Of course, one could always add layers to this process—such as have an advisory staff help with decision making or with the selection of advisors. Obviously that would not resolve your problem, but rather move it to a different level in the decision-making hierarchy.

The advice on which experts base their judgment is typically derived from models of the respective system. Consultants develop databases and simulation tools to help managers make decisions. In some cases, these models have not been developed from scratch by the people who use them, but simply modified or combined to provide an answer to a specific question. Noticing their reliance on models, you may therefore be tempted not to ask experts for the answers that they generate with their models, but instead to ask them to give you their models so you can form your own opinions.

Expert systems, simulation games, and learning laboratories are three examples of model environments produced by consultants and scientists to provide decision makers with an ability to play out the consequences of alternative actions in what-if scenarios. Although these decision support tools are a step forward in empowering decision makers, they still are based on the understanding that an outside expert brings to the problem, rather than on the knowledge of the people directly involved. The question *What should I do?* now changes to *What does the model do?* The problem is then not whether to believe the experts' answers, but whether to believe the assumptions they put into their models. And obviously, we all can find fault with some assumption, and therefore disregard a model's validity.

Another strategy is to go all the way and develop computer models yourself to address the specific problems that you face. The usual response by decision makers is that problem-specific model development in-house would be too costly and time consuming, and that there is no guarantee that at the end the model would be a better decision support tool than one developed by outside experts. But that does not need to be so. Today there are powerful methods and tools of computer modeling available that enable virtually anyone to develop dynamic models of complex systems, to effectively communicate different assumptions among the various stakeholders—such as the decision makers, the scientists and other experts, and the public. You will learn these methods and tools as you work through this book. And you should use them to develop models *with* those who have a problem to resolve. Work with them, help them identify the questions to be answered by the modeling process, help them arrive at an agreeable solution and finally, help them formulate new questions about their system. In this way you will learn a lot from others, and you will help people become modelers, rather than skeptical users of models developed for them—models whose construction is a mystery to them and models they do not fully understand or believe in. The very nature of this book and the books of the Dynamic Modeling Series is to help you in learning how to translate your mental models into rigorously based computer ones and how to engage yourself and others in a continuous learning process.

Besides helping people to handle uncertainty, feedbacks, lags, and group decision making, the development of formal and computer models provides authentic tasks that are intellectually challenging and rewarding. Through exchange of models among modelers, the learning process turns into a cognitive apprenticeship in which all members of the modeling group can learn from each other.

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Computer modeling becomes "dynamic" not only when feedback processes among system components are captured through time, but when model development is based on the dynamic exchange of data and information among a group of model developers and users. It is the pluralism in perspectives that helps identify key features and behaviors of complex systems. That pluralism is also an important ingredient for the usefulness of models in generating new knowledge and in providing decision support. Pluralism in perspectives is typically not promoted or maintained to derive the solutions that outside experts bring to a problem.

The process and product of dynamic modeling can help highlight gaps in an organization's or a society's understanding of its processes, and it helps identify the most important parameters in a system. As models are developed, they provide a record of the existing understanding. When the models are run, they reveal "normal" system behavior if no interference into the system takes place, and they may reveal emergent properties of the system. We may see smooth dynamics, or perhaps erratic transitions from one type of dynamics to another. Such knowledge is useful in helping us make decisions. If, for example, the system exhibits dynamics such as the solid line in Figure 1.2, an interference into that system with the intent to smooth out the rapid transitions may actually exacerbate the dynamics leading to the more pronounced up-and-down turns of the dotted line. Knowing what is "normal" for a system may help you maintain your calm and may even mean that you leave the system alone—after all, you know it will soon come back from its extreme behavior. If, however, the erratic changes in a system's dynamics are deemed unacceptable, we can use the model to play out alternative what-if scenarios in order to find those controls that smooth out the peaks.

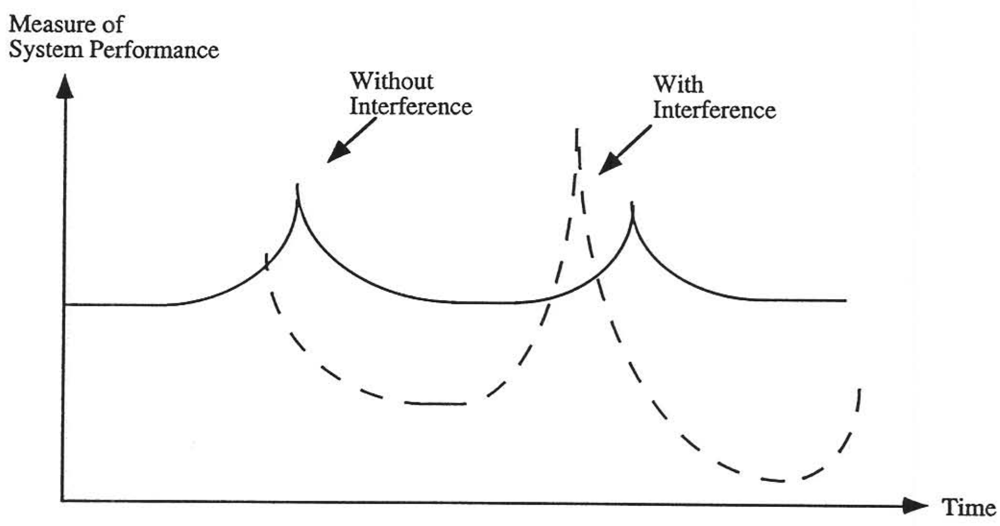

FIGURE 1.2

Perhaps there is one set of controls that makes the model behave more erratically and another set that makes it behave more smoothly. Playing with the controls in the model is easier, and the consequences of it are typically less costly, than playing with the controls in a real systems. This is why we train pilots on flight simulators. But we have not done this yet for people who make decisions about the course of ecological, social, and economic systems.

The fact that the model may be sensitive to one set of assumptions rather than another also can be exploited for data collection purposes. If there is some set of assumptions to which the dynamics are very sensitive, we may want to collect more information on that part of the model that uses the respective assumptions. If the model does not respond much if one part of it uses different assumptions, then we may not want to spend our time and effort refining that part further. Unfortunately, a lot of data get regularly collected before we know whether we actually need them. Some data are very costly to collect and ultimately get used in models, but a good guess could have sometimes done equally well.

The model facilitates not only insight into but also communication of likely system behavior by generating quantitative results. Learning and communication are also facilitated through the structure of the model itself: while the art of Dynamic Modeling requires that one is skillfully identifying system components and their interactions, the technique of Dynamic Modeling requires a master plan for the development of the model's structure—not the details, but the layout of model components. With increasing experience in building models for a wide variety of problems, similarities among systems structure may become apparent to the modelers. The more interdisciplinary the modeling approach, the more likely it is that knowledge from different disciplines is brought to bear on the development of the master plan according to which a model is designed.

For example, very successful models of the spread of a disease have been developed by using analogies from chemistry. In a chemical reaction, two reactants may react with each other to form a product. Similarly, the individuals in a population carrying a disease "react" with individuals who are susceptible to the disease and generate a "product"—sick individuals. The principles that can be used to model and understand chemical reactions can, by analogy, be used to understand the spread of a disease. Effectively using analogies can significantly reduce the effort that is necessary to develop models.

Throughout this book we encounter a variety of nonlinear, time-lagged feedback processes that give rise to complex system behavior. Such processes can be found in a large range of systems. The variety of models of this book naturally span only a small range—but the insights on which these models are based can (and should!) be used to inform the development of models for systems that we do not cover here. The models of this book provide a basis for the formation of analogies.

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Formation of analogies is one way of dealing with complexity. A great many new insights are generated by learning something from the structure or behavior of one system, which is well understood, about another system, of which we have less knowledge. The formation of analogies forces us to choose different systems perspectives. We identify the structure of one problem and compare it with the structure of another problem. We note their similarities and their differences. We lay open the assumptions that make the analogy work, and we contrast the insights we generate about one system with the findings about the processes that govern another system. The similarities between the systems generate one set of insights, while the dissimilarities prompt the adoption of a different, but complementary perspective, and help place bounds on complexity.

Analogy is different from identity in that there may be identical features but different substructures. The art of analogy is to realize what abstractions are important—which substructures may safely be disregarded—to answer particular questions. The creation of knowledge through analogy, however, is not solely based on abstraction and the subsequent recognition of similarities. Rather, true knowledge comes from the recognition of the dissimilarities, alongside the similarities.

It is the intention of this book to show you how to model, not just how to use models. In the following section we introduce to you the computer language that we'll use throughout the book, and that will be immensely helpful to foster our understanding of dynamic systems and develop our skills of analogy formation. We close this chapter with a discussion of the structure of the model-building process and an identification of a set of easy-to-follow modeling steps. These steps are not sacred; they are intended as a guide to get you started in the process.

1.3 Modeling in STELLA

STELLA® was chosen for this book as the computer language with which we model dynamic systems because it is a very powerful, yet easy-to-learn tool. The software provides also an "Authoring" feature that enables you to develop models for use by others who are uninterested in, or ignorant of, the underlying details of the model. However, since model development and understanding are the purpose of this book, we do not discuss the Authoring feature here.

The basics of the STELLA programming language are outlined briefly in the next section. In order to easily follow that introduction, install STELLA on your disk. The installation procedure is explained in the Appendix. Then open the STELLA program by double-clicking on the STELLA program icon on your disk.

STELLA is a commercially available graphical simulation program developed by High Performance Systems. Run-time versions of STELLA for Macintosh and Windows are enclosed with this book including the models

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Appendix 10: Cape Rail Link Article Student Responses

(September 20 student responses)

Summary:
These were collected on September 20 from students who took the system dynamics course.

Meaghan O'Connell

(Sop)

a) Identify and discuss the problem as you understand it:

The ride to the Cape is saturated with tourists, which means there are many traffic jams. There are old railroads which lead to the Cape but are rarely, if not never, used. If another form transportation is offered to tourists, such as railroads, will it be considered by tourists as a reasonable solution to traffic jams? Can the state afford to create new train stations, or restore old ones? What will tourists do once they get to the Hyannis train station, and they need a car to get themselves to wherever they will be staying on the Cape?

b) Identify and discuss your solution:

A minor solutions to the traffic jams would be to encourage rentals to rent on different days, other than Sat. → Sat. Although this may not seem like a big change, it does make a difference (the person we rent from rents on a Sunday → Suday basis).

As far as solving the railroad problem, I think it will just lead to more problems and more expenses for the state of Massachusetts. Railroads are not the solution for the Cape. Not everyone goes to Hyannis and if that's where the railroad stops then there needs to be some other form of transportation. The only logical solution if there were going to be a railroad service would be to have a car rental service, which would still probably lead to more problems. Railroads are not exactly convenient.

Marian Chaffe

(Sep)

a) The problem is the traffic jams going into and out of the Cape and how to solve it inexpensively. The authorities want to use a commuter railway that connects with Boston. However, Cape Cod residents are concerned that convenient access with Boston will attract unwanted development. Another complication is that the railroad is too expensive, and rebuilding the railroad tracks would be an additional hassle and expense. In addition to this, the lanscape and the fragile environment would suffer, causing even more expenses. Finally, even if a commuter rail was installed, once the passengers were chartered onto the Cape, they wouldn't have any means of getting around unless they knew someone because of the lack of public transportation and car rental services.

b.) My solution is to use the Budd cars that the Cape Cod Railroad bought. This seems to be the only possible solution - and the cheapest. High-speed commuter services are too expensive and not desired by Cape Cod residents while Amtrak doesn't have enough money to revive the Cape Codder, the Cape's previous train system. These Budd cars, however, have diesel engines, which presents a problem because they're not allowed to travel at faster speeds, making for a long ride of $2\frac{1}{2}$ hours. Nonetheless, the Budd cars are cost effective and supported by state authorities and engineers, not to mention Cape locals, whose fears about unwanted development are pacified. Other than the fact that they have diesel engines, the Budd cars present the best solution. Also, the railroads should invite a car rental service to the Cape - something that would undoubtedly profit from weekend visitors.

Joshua Carlson (Sept)

Problem: As I see it, the problem is too many people wanting to go to the cape. The area wasn't originaly planned to handle such a large volume of people ~~on~~ at condensed times. The roadways are than clogged in the summer season and even worse on summer week-ends.

Solution: As I see it, the Cape needs a form of mass transportation. This is limited by money issues, which means that what ever is ~~dun~~ done much support its ~~selfs~~ self.

An additional roadway wouldn't help due to the fact that the cities are packed also. A railway system does look good. Rather than a steady, large volume heading it to the cape, there would be shifts of high volume. It could be planned using a public ~~t~~ or private transportation system, such as buses or taxis. Plan it so that when the train arrives, the cars would be there.

The only limitation is money. As stated in the article, no one agency, such as the state, wants to support the railway. This might inevitably kill this idea. ~~from~~ ~~now~~

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Eileen Kosasih

Sep

A) The problem is that, in Hyannis, Cape Cod, there is to much traffic trying to go in and out. The Army Corps of Engineers want to restore the old Buzzards Bay Bride. John Kennedy, who is president of the Cape Cod Central Railroad, proposed a plan. He would like to have small trains to carry tourists from a Middleborough rail station to Hyannis. The Budd cars can travel slowly around the Cape, and after crossing the canal, speed up to places like Boston. However, Michael Sullivan thinks it won't profit too much. Cape Cod Transit Task Force would like to restore Amtrak's Cape Codder, but they have financial problems.

B) I believe that America's transportation system is horrible and terrible. Other places like France or Japan have organized systems like monorails, which are fast, easy, and convenient. We should build one. It would reduce traffic by a lot, not only be useful to tourists, but regular people that need to go to Boston and such for work. So, it would be more beneficial to our economy.

Mark Daniels

(Sep)

a) It is my understanding that there is a debate ~~as~~ to allow Railway service to be established in Cape Cod, leading to Hyannis

b) My solution to this would be to allow the rail service ~~to~~ to operate, but limit the number of trains that use it and the number of passangers on each trip. Passangers will make use of an extended bus service on the Cape.

In this way, I believe that roadways will become less congested and people would use the alternative transportation. By limiting this service, however, the area will not become as industrialized or developed as the opposers envision.

Mark.

Samuel Gurwitz

(SEP)

from Boston and other major cities

A, Every year, people flock to the beaches of Cape Cod. The Cape becomes too crowded and the trip takes too much time. A few propositions have been made to develop a high speed train for vacationers. However, such a this could lead to problems, like pollution or over development.

Hopefully, this would reduce traffic and make a trip to the Cape less time consuming.

implement

B, I agree with Kennedy's proposal. The cape should this new rail line with self-propelled Budder cars, Hopefully, some people would ride on them in the summer, people would be attracted to their nostalgic look and how easy they can make a trip to the Cape. However, Only a few cars should run so excessive over-development would not occur reducing traffic and pollution

We should make a model of the environmental + chemical impact of the new rail line.

Mark Sherman

(SEP)

a) ~~Problem~~: huge traffic jams to and from cape cod every weekend in summer. Trains may be the solution, but they may spark unwanted economical growth. Cape Cod is already very popular for tourists and could not handle a rapid increase in anything. The ecosystem is also very sensitive, and railways could disturb it. A slow-speed train line is possible, may not be as disturbing, but is prohibitively expensive for state subsidation.

b) low-speed "Budd Car" weekend trains:
- too slow for commuters ✓
- no major economic growth ✓
- attractive to tourists
- less cars crossing bridges ✓
- No car rentals on cape ✗
- Low profit margin ✗

$2 mil/year subsidation + $500,000 restoration

Cape-Codder (D.C. - Hyannis) restoration:
- prohibitively expensive ✗
- states refuse to subsidize ✗

If the Budd Cars are approved, more car-less tourist facilities need to be created. Namely, rental services. This keeps cars off the bridge, the ultimate goal.

If nothing is done, the traffic problem is sustained, but no negative changes will apply, either.

$3 MIL. and $2+ mil/year could be approx.

[Need a comprehensive plan for a slow, non-commuter railway and the systems to support the tourists on either side. If funding is unfindable, doing nothing is acceptable as it is not a time-sensitive problem. Yet.]

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Sep

Josh Weiss

A) There are two problems discussed in this article. One of which leads to the other. The first, and main problem is the travel time and congestion commuters face when going to Cape Cod. During the travel season the roads to the cape become jammed, and travellers have a very difficult time getting there. The other problem is that a railway will be environmentally unsafe for the area, and it would also cause more growth in the area, adding to the problems.

B) If I were to come up w/ a solution for this problem I would agree with Kennedy's plan. The plan is to refurbish the railways, and add some new ones, to make travel easier. The good idea that he really has is that it would be a long trip - using old trains that can only go so fast. In this way the trip may take longer than driving (barring traffic) and would cost more. That may make some travellers refrain from using the rails, so it would not affect the growth on the Cape very much if at all. Plus, if the rails are kept up and the environment is protected, the ecosystem will be able to remain in tact.

Sean Ting

Sep

a) The problem is that Kennedy wants to build a railroad system that would connect Cape Cod and to the rest of MA. It shouldn't cost the state very much, according to Kennedy, because of ~~distance~~ of old trains that he has purchased which have both a historic feel and are comfortable. He also is trying to sell it to environmentalists through regulations on it's speed that would make the trip so long it would be attractive only to tourists in the summer, keeping its impact minimal. However Turkington, a Falmouth representative, claims that in terms of government funds required to keep the railroad afloat, the plan's a bust, as it could eat up to $20 million a year. Also, upon arrival to cape cod, it is difficult to get anywhere without a car.

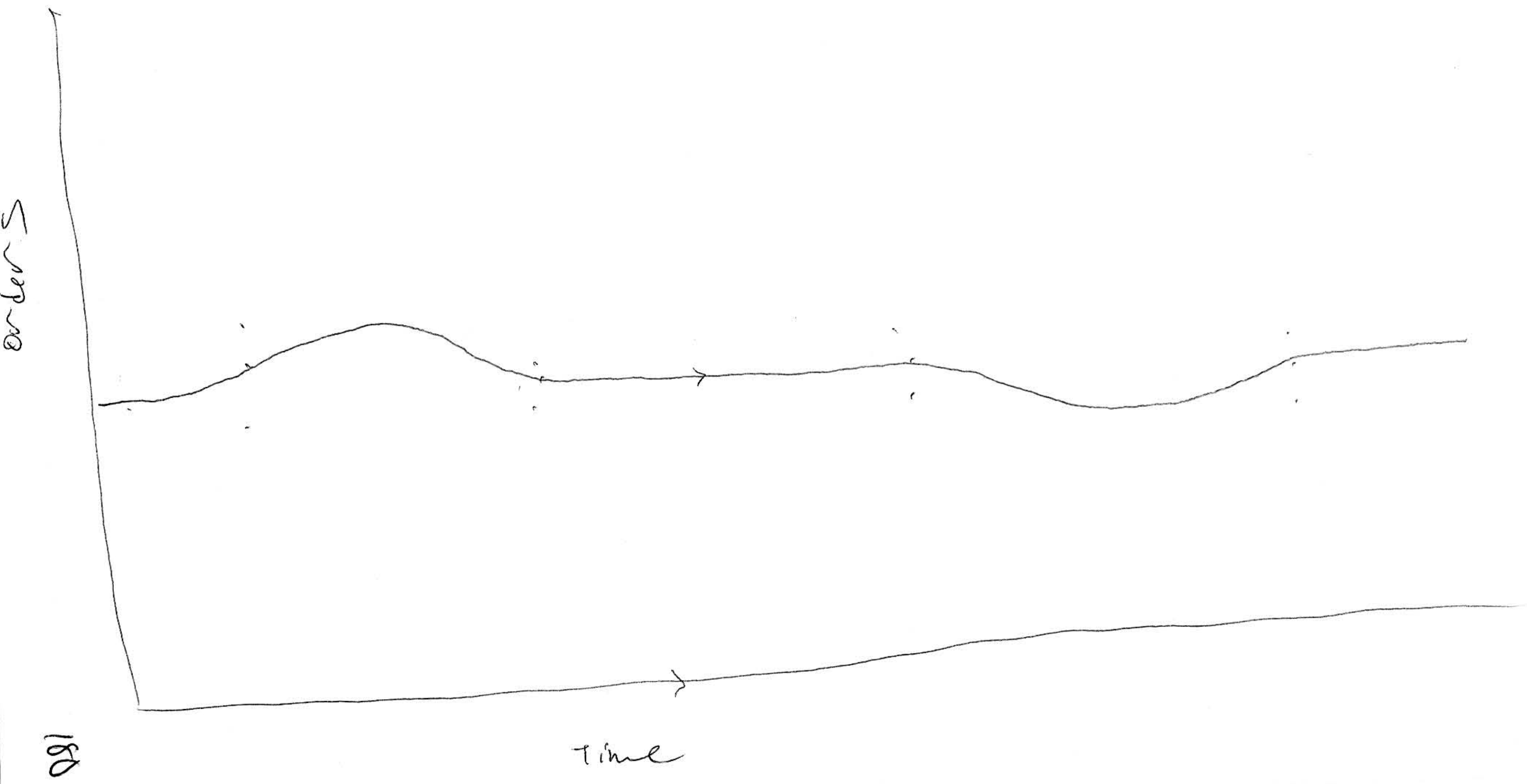
b) Don't build it. If it would cost the government $20 million ~~and~~ would hurt the environment to some degree, and wouldn't help passengers once they got to cape cod, what's the point.

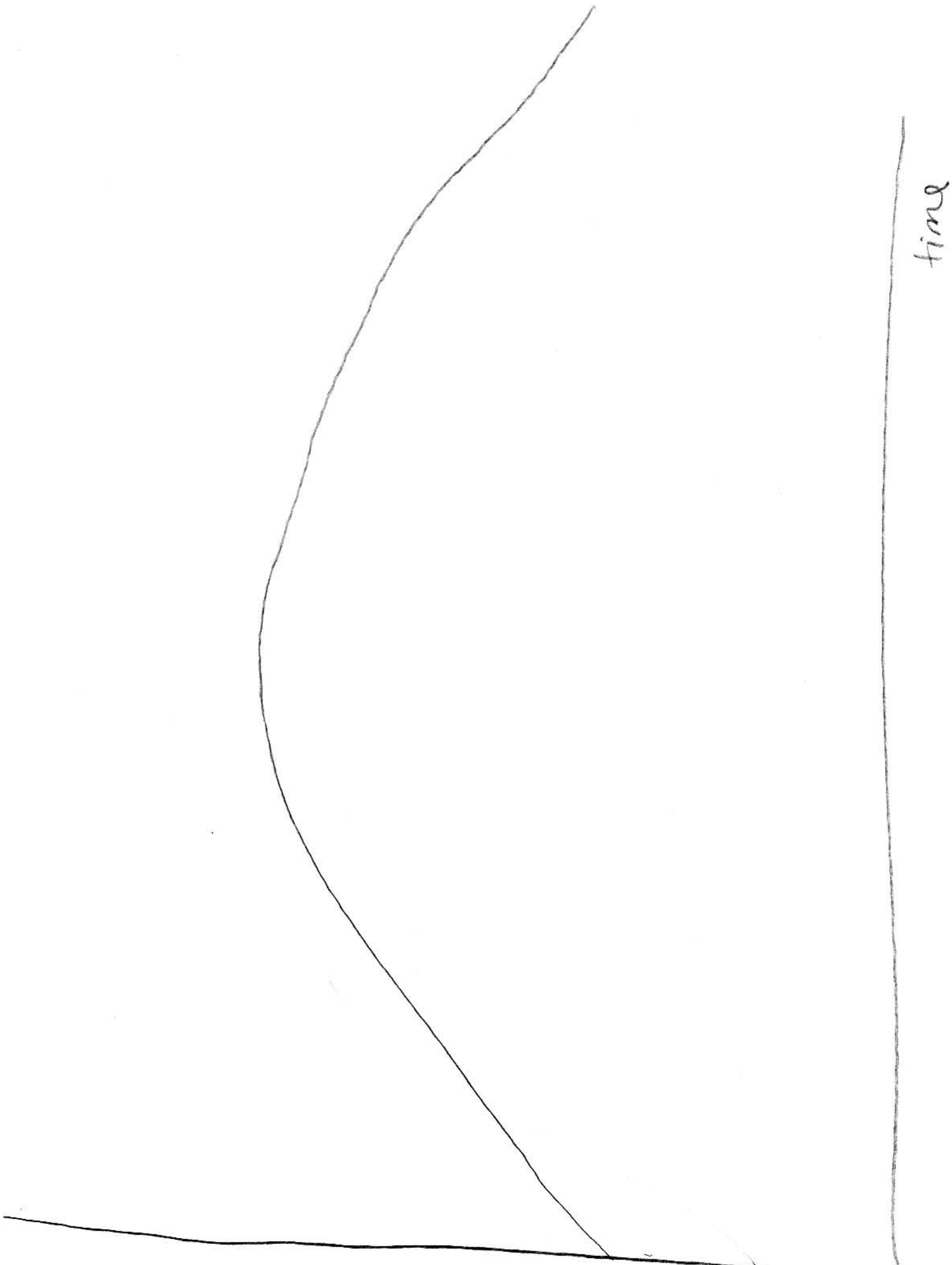
Appendix 11: Beverage Game Data

(September 24 student responses)

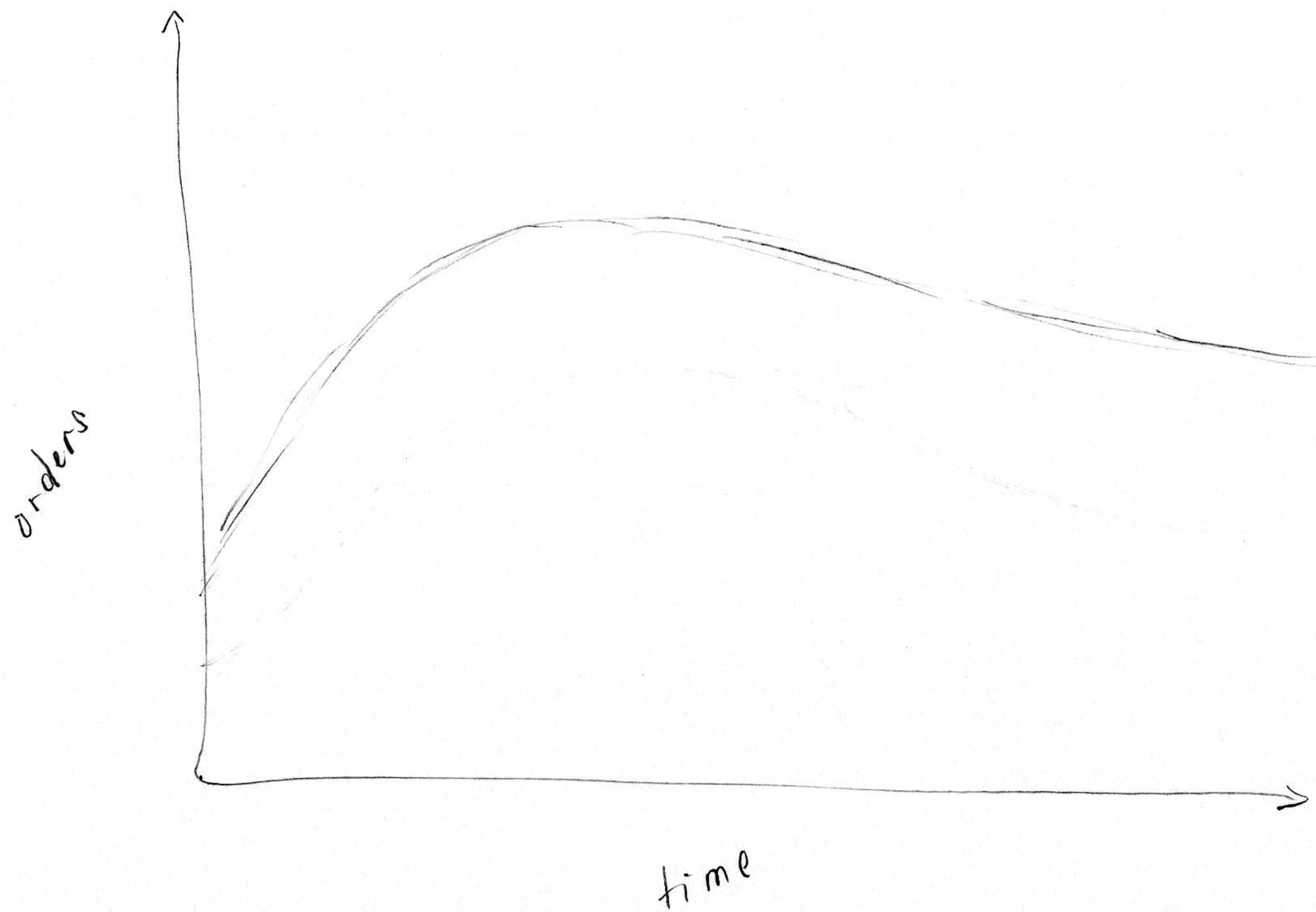
Summary:
This is the Beverage Game student output. Collected on September 24. Due to the nature of the game, there is no correct answer.

The elements Factory

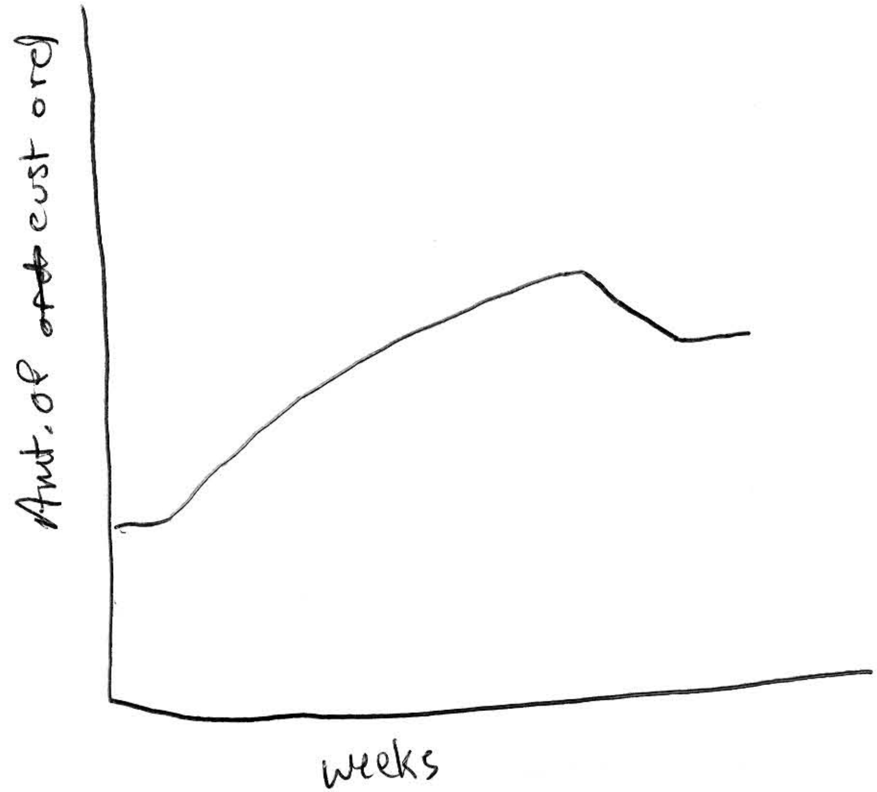



time
Orders

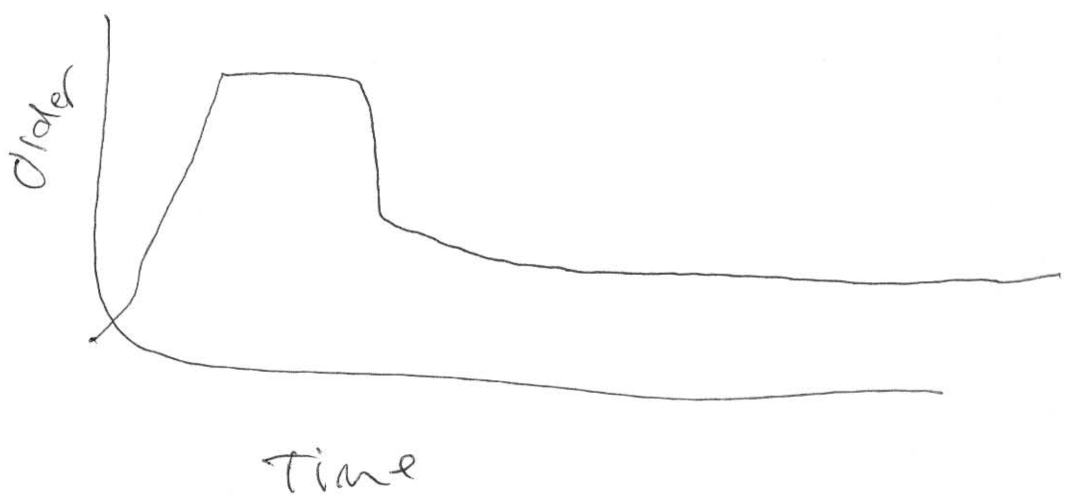
wholesaler



Factory



Whole seler



2
81
29
29
114
302
446

1 1
648
+1255
903
1160

2359

1179.5
600

2780.5

The rest of the Beverage Game data is fairly typical for this game. Therefore it is not included in this copy. It is available with the original copy with the SSPS department.

Appendix 12: Beginner Modeling Exercises

(September 27 student responses)

Summary:
This quiz was conducted on September 27. A set of possible solutions is available at Appendix 5.

Beginner Modeling Exercises

System Dynamics In Education Project
System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

Michael Shayne Gary
with help from
William A. Glass

March 8, 1993

Everything in the world around us can be represented by either a stock or a flow. As an exercise to help you begin identifying things around you as stocks and flows, the following problems should be completed.

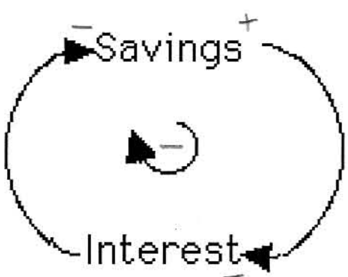
1. A) *Indicate whether the following variables are stocks or flows. Identify the associated flow or stock, that corresponds to each variable and draw a stock and flow diagram that represents the system you have in mind. Some of the variables can be either a stock or a flow, but the stock/flow diagram must be consistent with your choice of answers.*

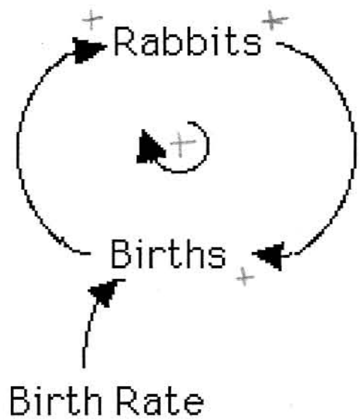
√ **population**	stock flow
√ **infected people**	stock flow
√ **factory production**	stock flow
√ **pollution**	stock flow
√ **interest**	stock flow
√ **salary**	stock flow
√ **distance**	stock flow
√ **electric charge**	stock flow

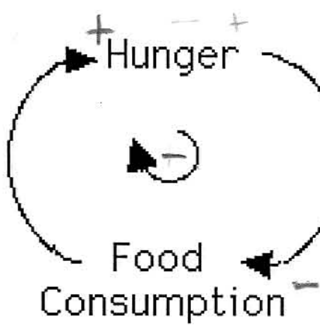
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

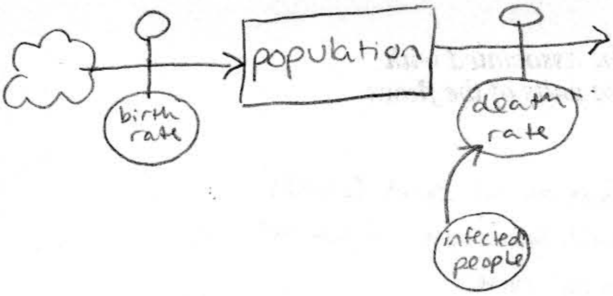
computers in a store → how many sold (sales)
nuclear weapons → increased death rates in world
books in a library → litracy rate
trees in a forest → # of animals
heat → # of (heat) strokes
distance → time
velocity → distance traveled

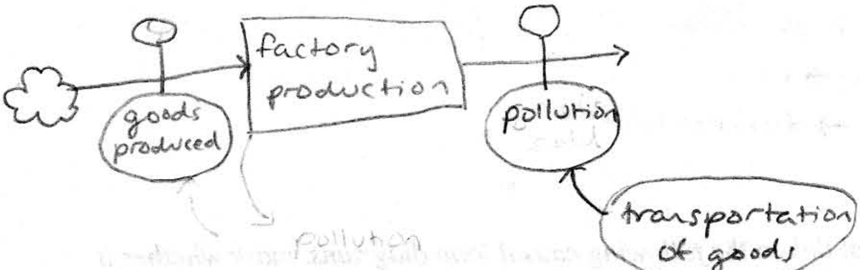
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*

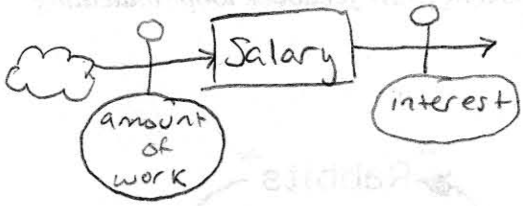


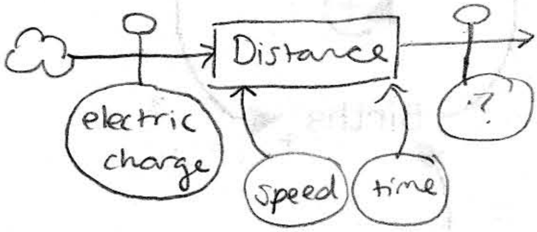


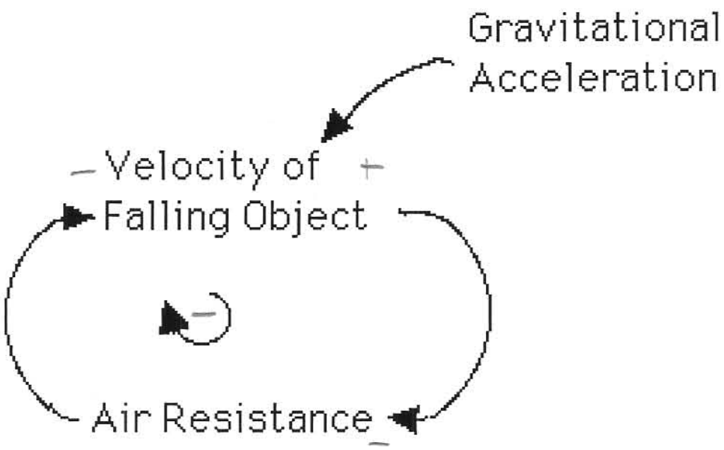


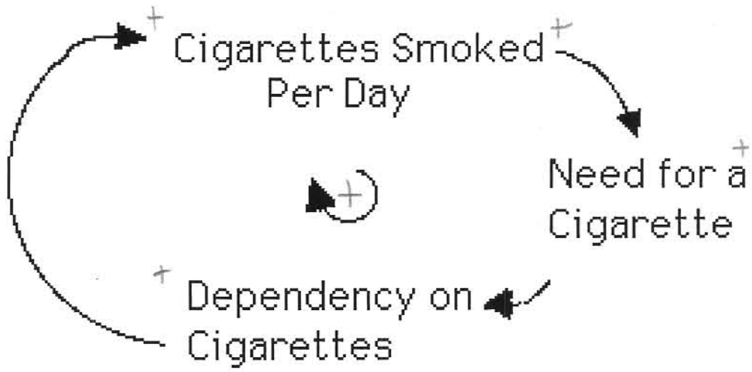

population
birth rate
death rate
infected people


factory production
goods produced
pollution
transportation of goods
pollution


Salary
amount of work
interest


Distance
electric charge
speed
time
?


Gravitational
Acceleration
Velocity of
Falling Object
Air Resistance


Cigarettes Smoked
Per Day
Need for a
Cigarette
Dependency on
Cigarettes

Beginner Modeling Exercises

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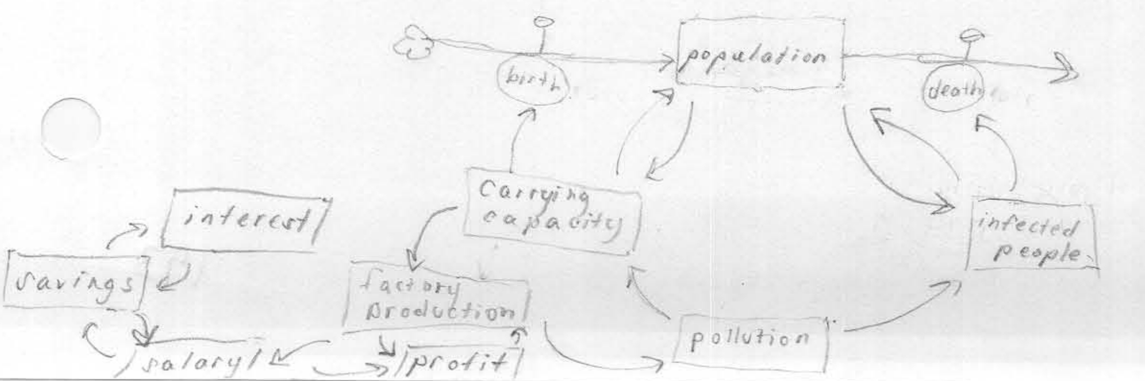
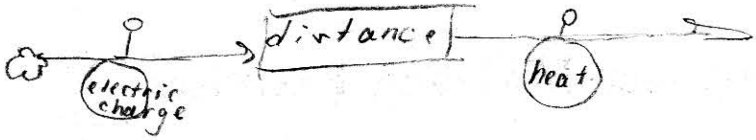
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow



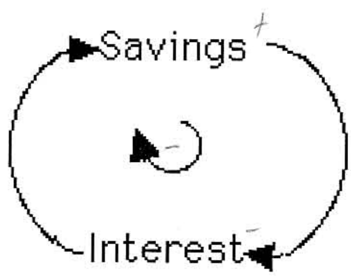


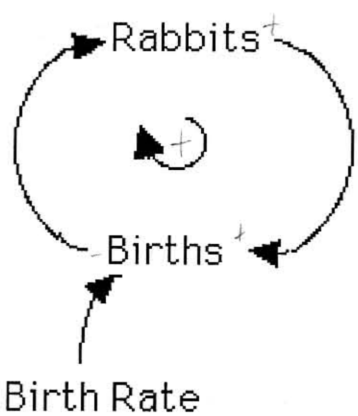
distance
electric charge
heat

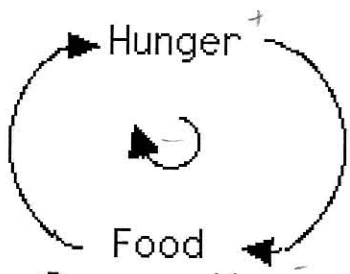
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

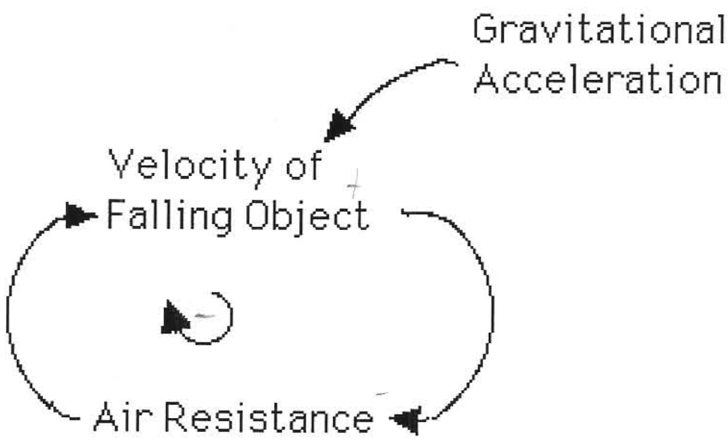
computers in a store - purchases / factory production;
nuclear weapons - production / detonation;
books in a library - books written / books discarded;
trees in a forest - growth / death;
heat - energy saved/energy released
distance - electric charge / energy released;
velocity - acceleration / deceleration; mi/h

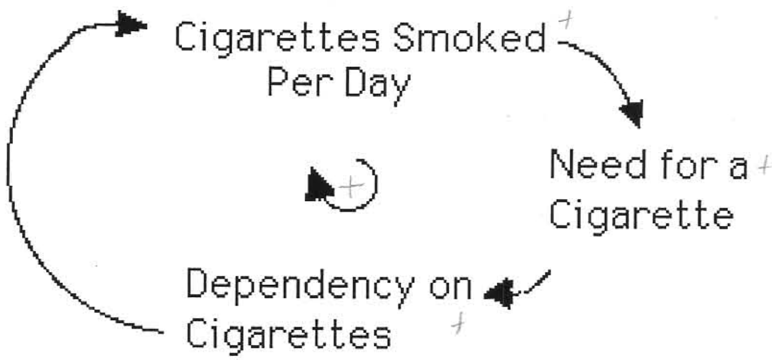
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational
Acceleration
Velocity of
Falling Object
Air Resistance
+
-
-


Cigarettes Smoked
Per Day
Need for a
Cigarette
Dependency on
Cigarettes
+
+
+
+

Joshua Carlson

Beginner Modeling Exercises

System Dynamics In Education Project
System Dynamics Group
Sloan School of Management
Massachusetts Institute of Technology

Michael Shayne Gary
with help from
William A. Glass

March 8, 1993

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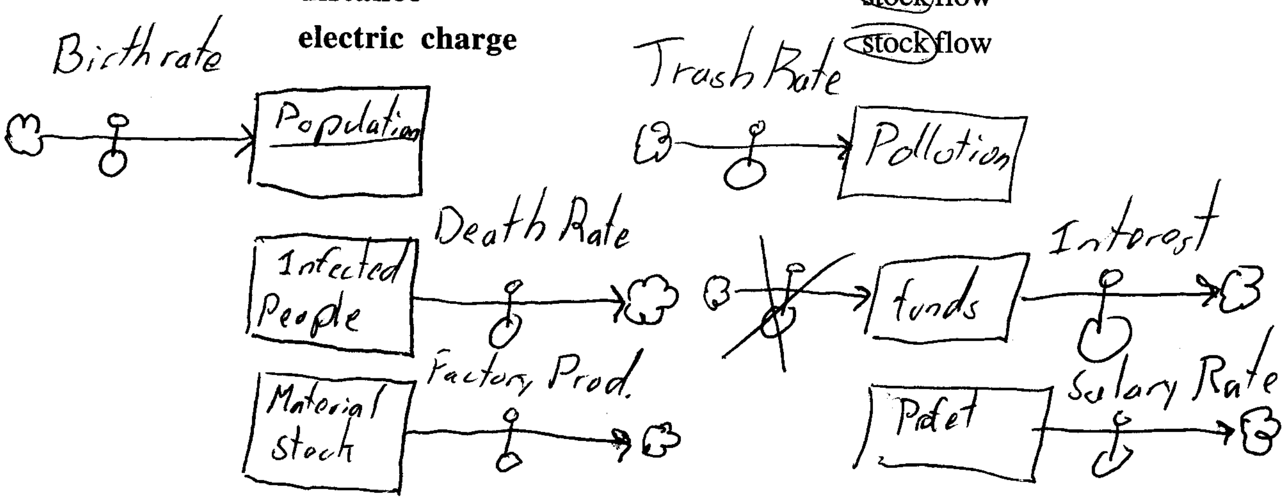
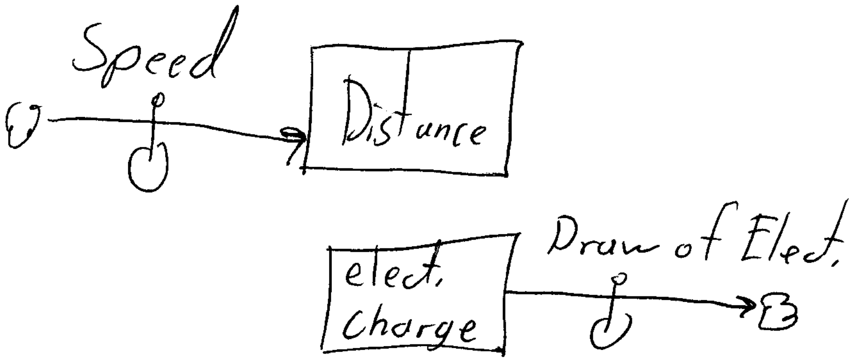
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow



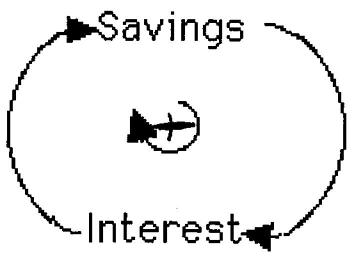
196

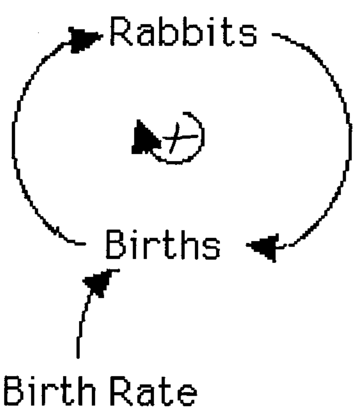

Speed
Distance
elect.
Charge
Draw of Elect.

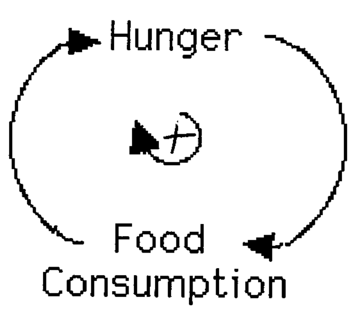
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

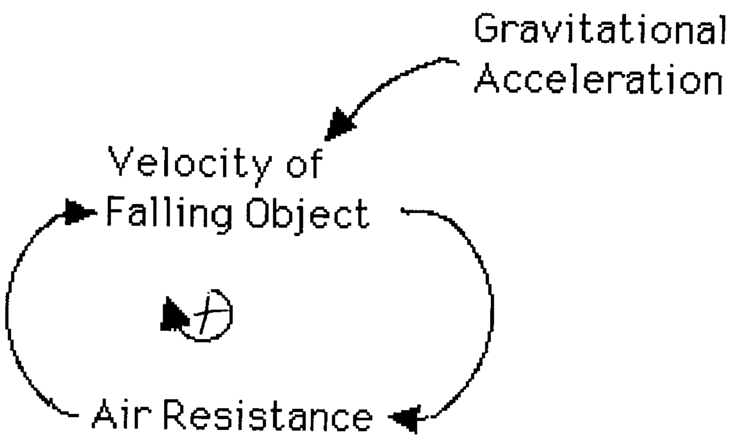
- **computers in a store** → Sale Rate
- **nuclear weapons** → Disarment Rate
- Donated Books → **books in a library**
- **trees in a forest** → Foresting Rate
- **heat** → insilation
- Velocity → **distance**
- **velocity** → Distance

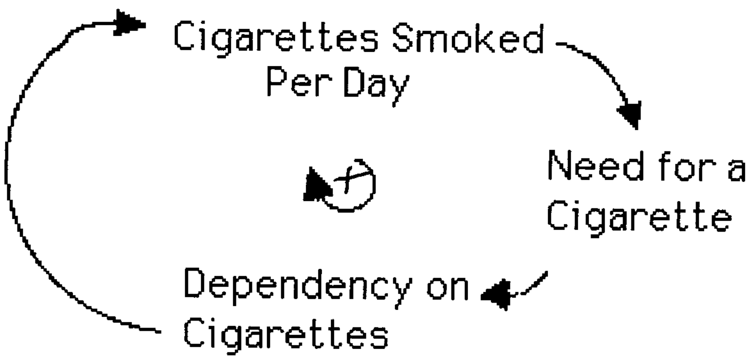
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational
Acceleration
Velocity of
Falling Object
Air Resistance
+


Cigarettes Smoked
Per Day
Need for a
Cigarette
Dependency on
Cigarettes
+

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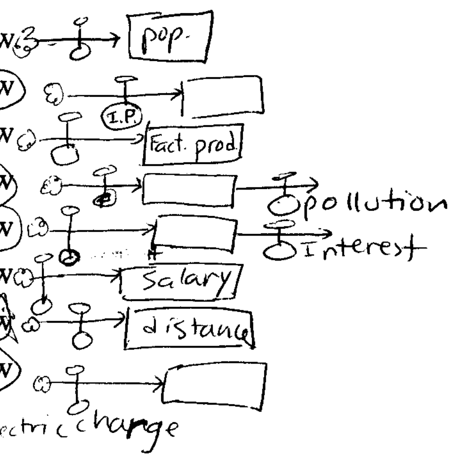
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

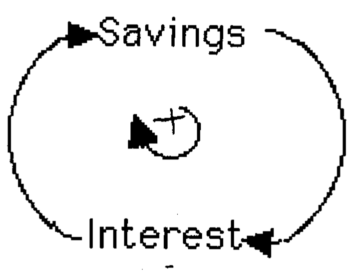


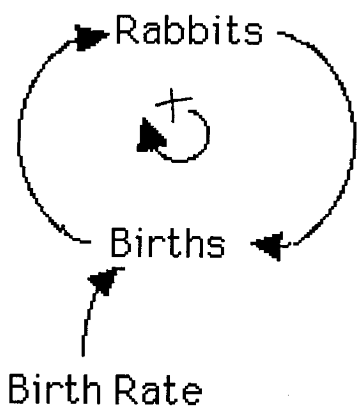
200

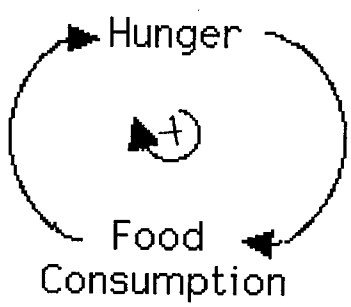
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

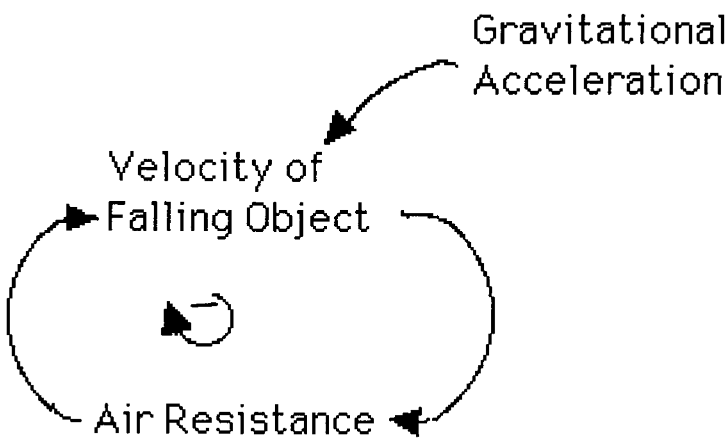
computers in a store price
nuclear weapons available resources
books in a library customer demand of books
trees in a forest forest fires
heat electricity
distance rate
velocity acceleration

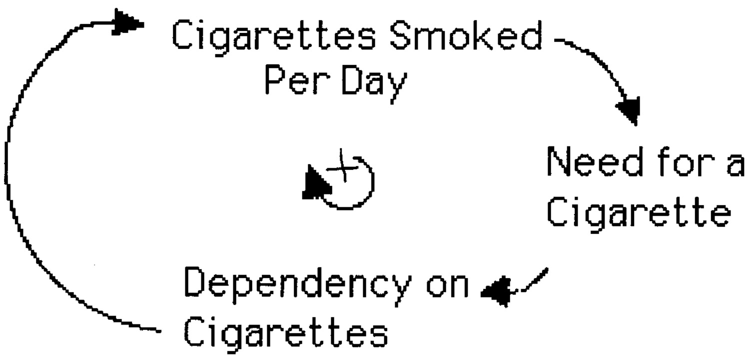
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational Acceleration
Velocity of Falling Object
−
Air Resistance


Cigarettes Smoked Per Day
Need for a Cigarette
+
Dependency on Cigarettes

202

 Mark Daniels

Beginner Modeling Exercises

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Michael Shayne Gary
with help from
William A. Glass

March 8, 1993

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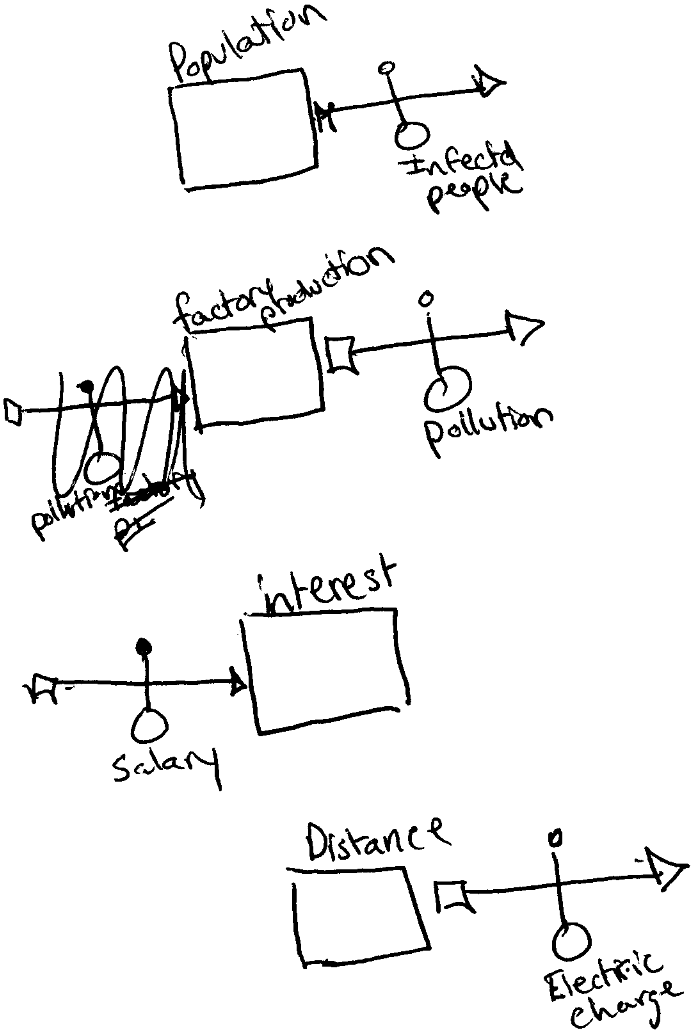
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

203

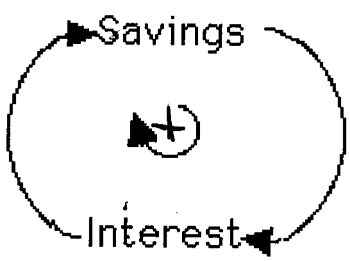


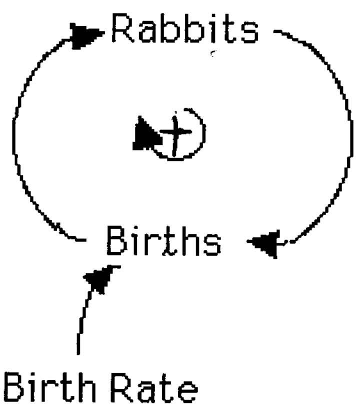
Population
Infected people
factory production
Pollution
interest
Salary
Distance
Electric charge

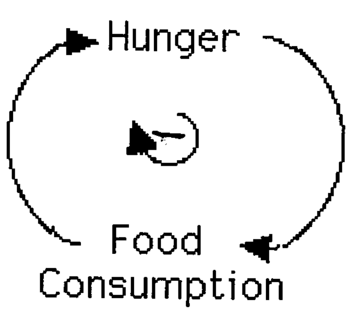
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

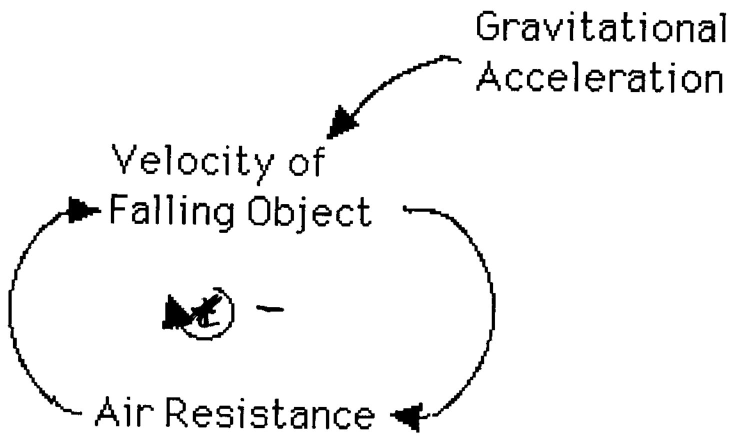
computers in a store	cost of computers (dollars)
nuclear weapons	
books in a library	size of city (population)
trees in a forest	wildlife (# of animals / sq. mi.)
heat	distance from sun (mi.)
distance	velocity (mph, m/s)
velocity	acceleration (m/s^2)

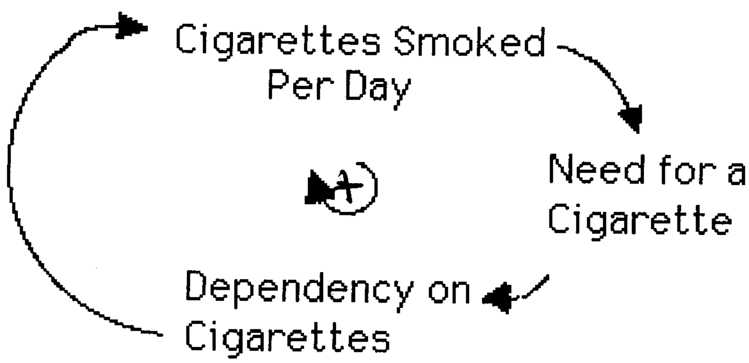
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational
Acceleration
Velocity of
Falling Object
-
Air Resistance


Cigarettes Smoked
Per Day
+
Need for a
Cigarette
Dependency on
Cigarettes

student SAM

N/A

207

Beginner Modeling Exercises

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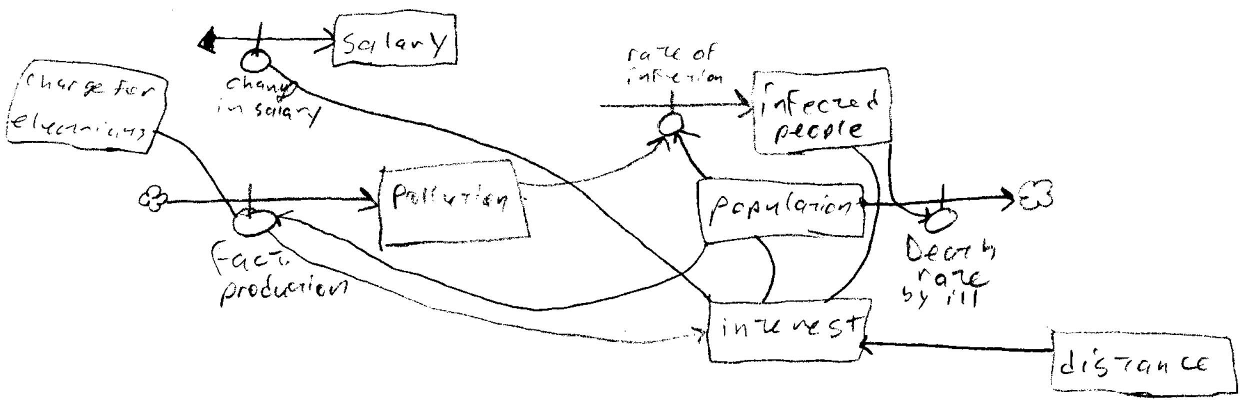
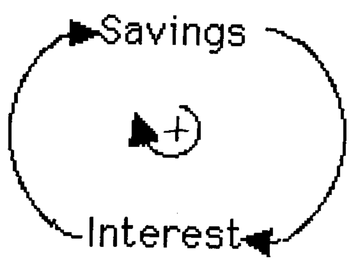
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

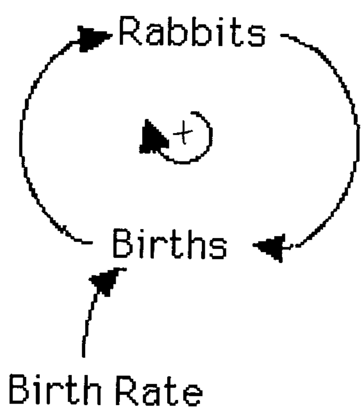


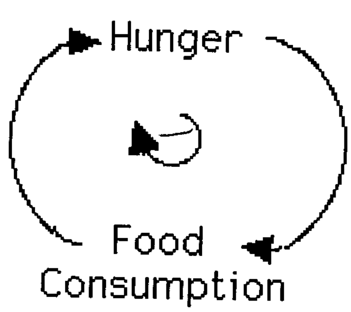
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

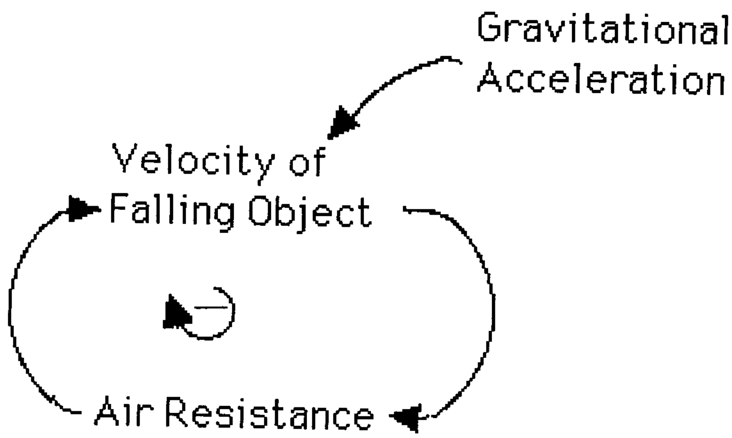
computers in a store Sales, purchases
nuclear weapons developments, production, launches
books in a library arrivals, borrowing, loans
trees in a forest growth rate, deforestation rate
heat photon flow ⇆
distance time, velocity
velocity acceleration ⇆

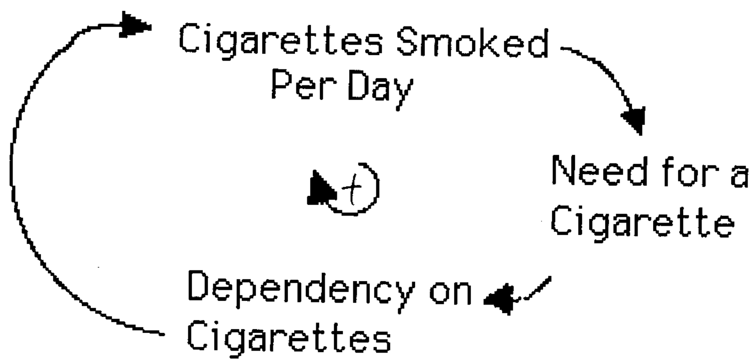
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*








Gravitational
Acceleration
Velocity of
Falling Object
−
Air Resistance


Cigarettes Smoked
Per Day
Need for a
Cigarette
+
Dependency on
Cigarettes

Josh Weiss

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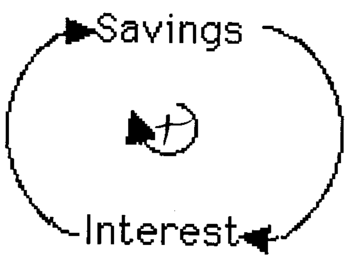
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

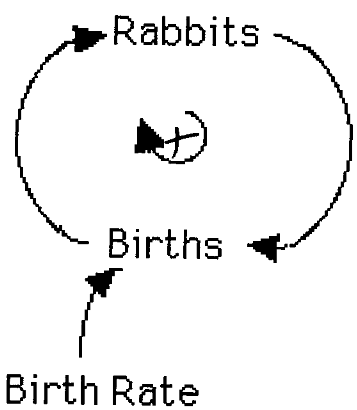
211

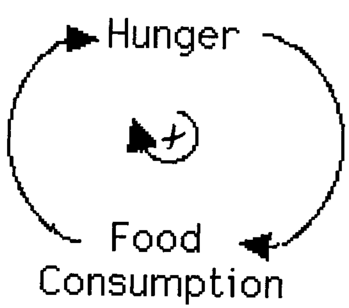
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

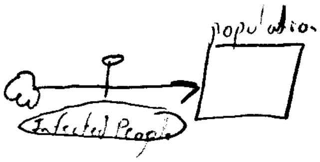
Velocity

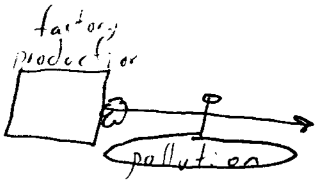
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*

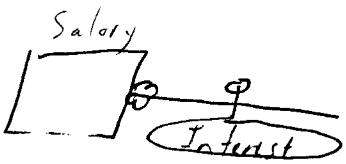


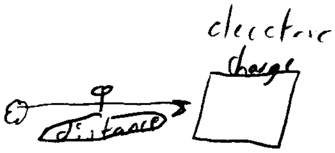


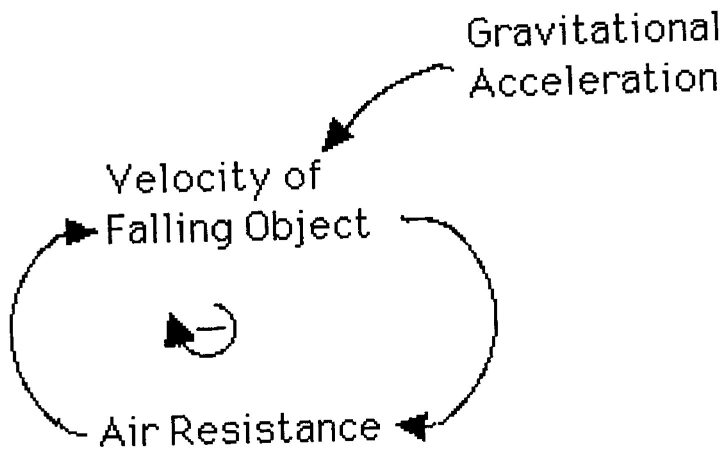


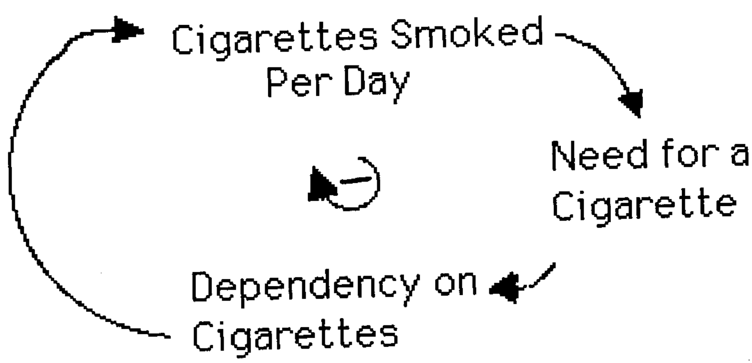

population
Infected People


factory production
pollution


Salary
Interest


electric charge
distance


Gravitational Acceleration
Velocity of Falling Object
Air Resistance
−


Cigarettes Smoked Per Day
Need for a Cigarette
Dependency on Cigarettes
−

Sean Ting 1

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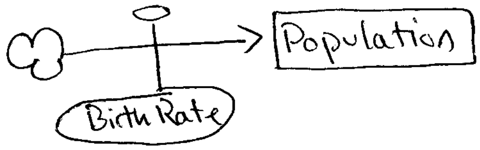
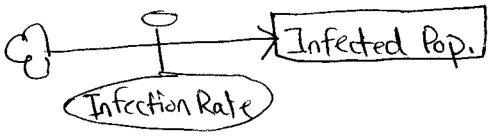
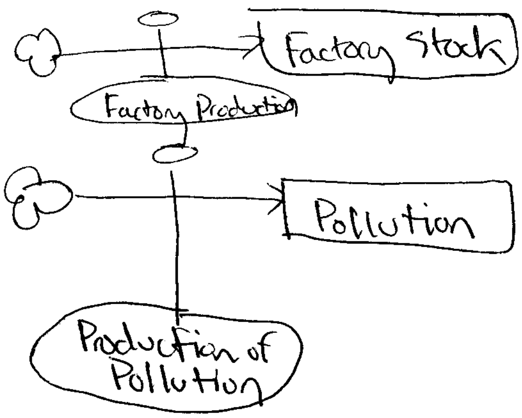
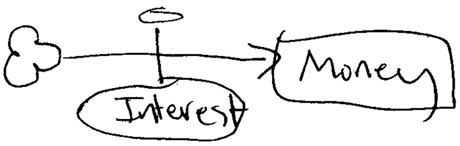
population	stock flow
infected people	stock flow
factory production	stock flow
pollution	stock flow
interest	stock flow
salary	stock flow
distance	stock flow
electric charge	stock flow

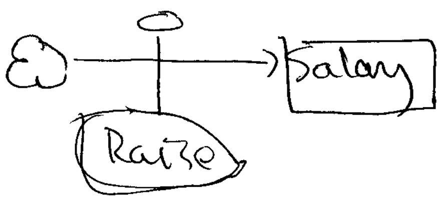
215

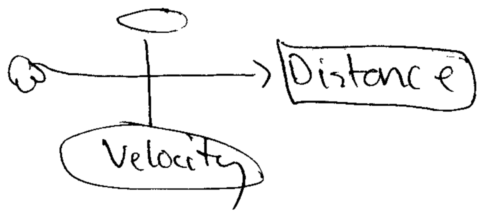

Population
Birth Rate

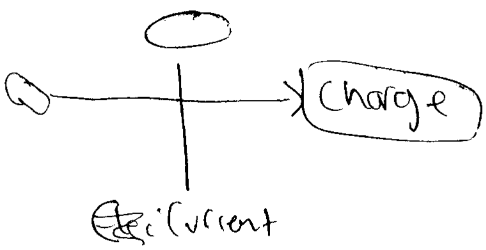

Infected Pop.
Infection Rate


Factory Stock
Factory Production
Pollution
Production of Pollution


Money
Interest


Salary
Raise

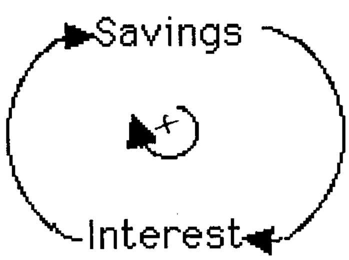

Distance
Velocity

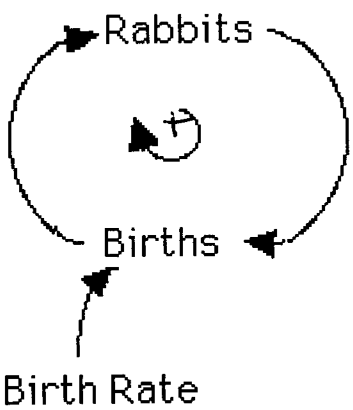

Charge
Current

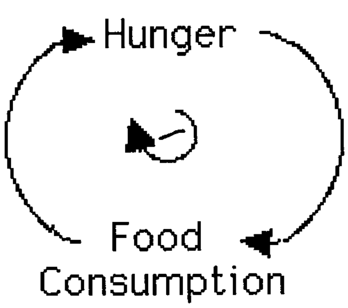
B) *What are some of the flows that might be associated with the various stocks below? What are the units of the flows and the stocks?*

computers in a store Orders
nuclear weapons Other countries production.
books in a library check-out/in rate, library budget
trees in a forest growthrate, deathrate, rate cut down
heat radiation in/out, convection in/out, conduction in/out
distance velocity, acceleration, jerk
velocity acceleration, jerk

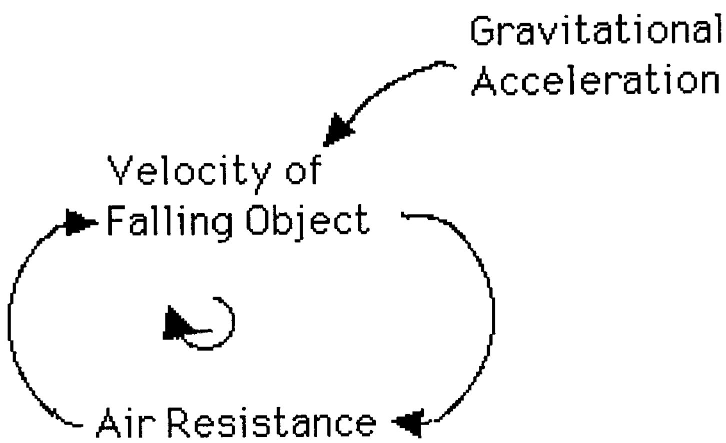
2. A) *For each causal link in the following causal loop diagrams, mark whether it should indicate a change in the same direction "+" or a change in the opposite direction "-". Put a "+" in the center if it is a positive feedback loop (associated with exponential growth), or a "-" if it is a negative feedback loop (indicating goal-seeking behavior).*

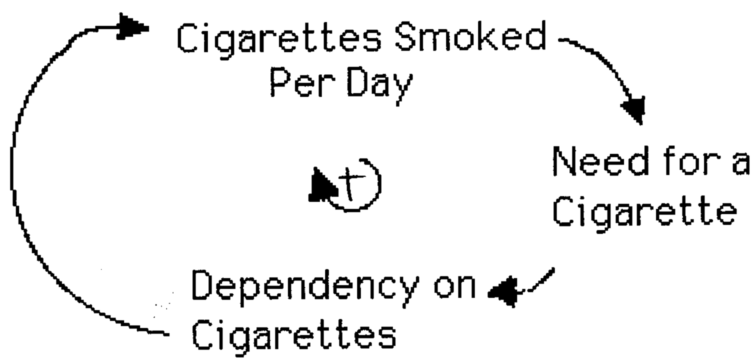






2/7


Gravitational
Acceleration
Velocity of
Falling Object
Air Resistance


Cigarettes Smoked
Per Day
Need for a
Cigarette
Dependency on
Cigarettes

Appendix 13: Drug Inventory Model Replication

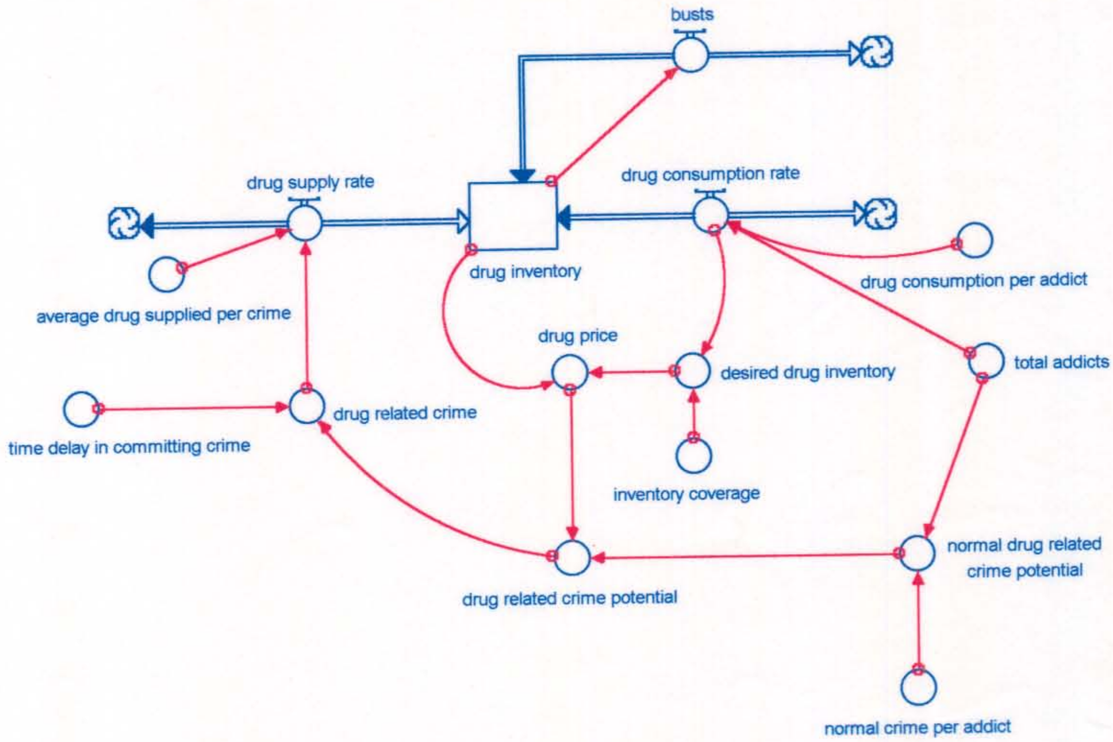
(October 15 student responses)

Notes:
This assignment was passed out on October 11 and collected on October 15.

Students were given Appendix 7 and asked to replicate the model, and provide printout of the computer model, its equations, and its simulation runs.

Only four of nine students passed in this assignment because of problems accessing the required software. The handout from the first student can be used as an example of a correct response.

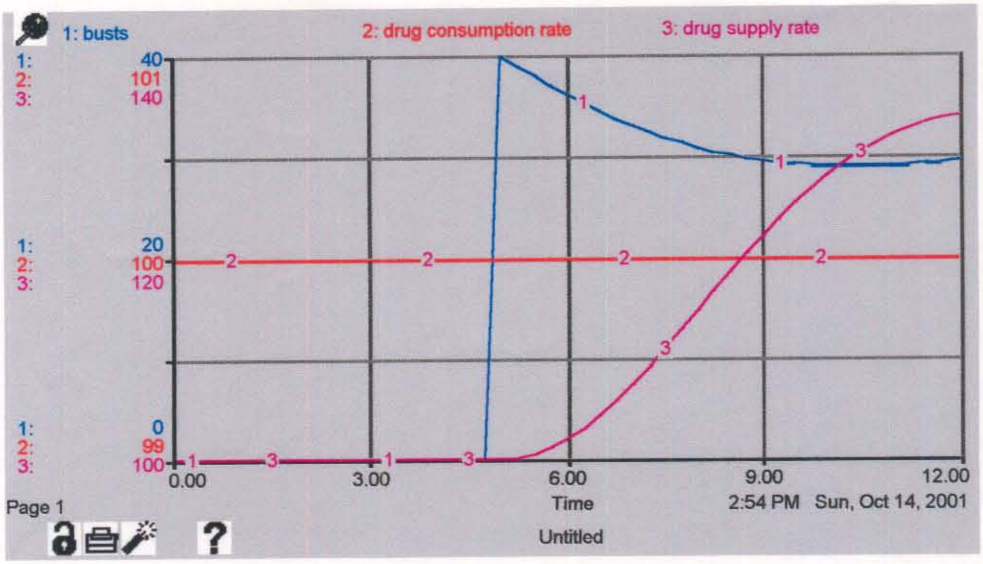
Meaghan O'Connell
Due: 10/15/01
System Dynamics – Drug Inventory Model



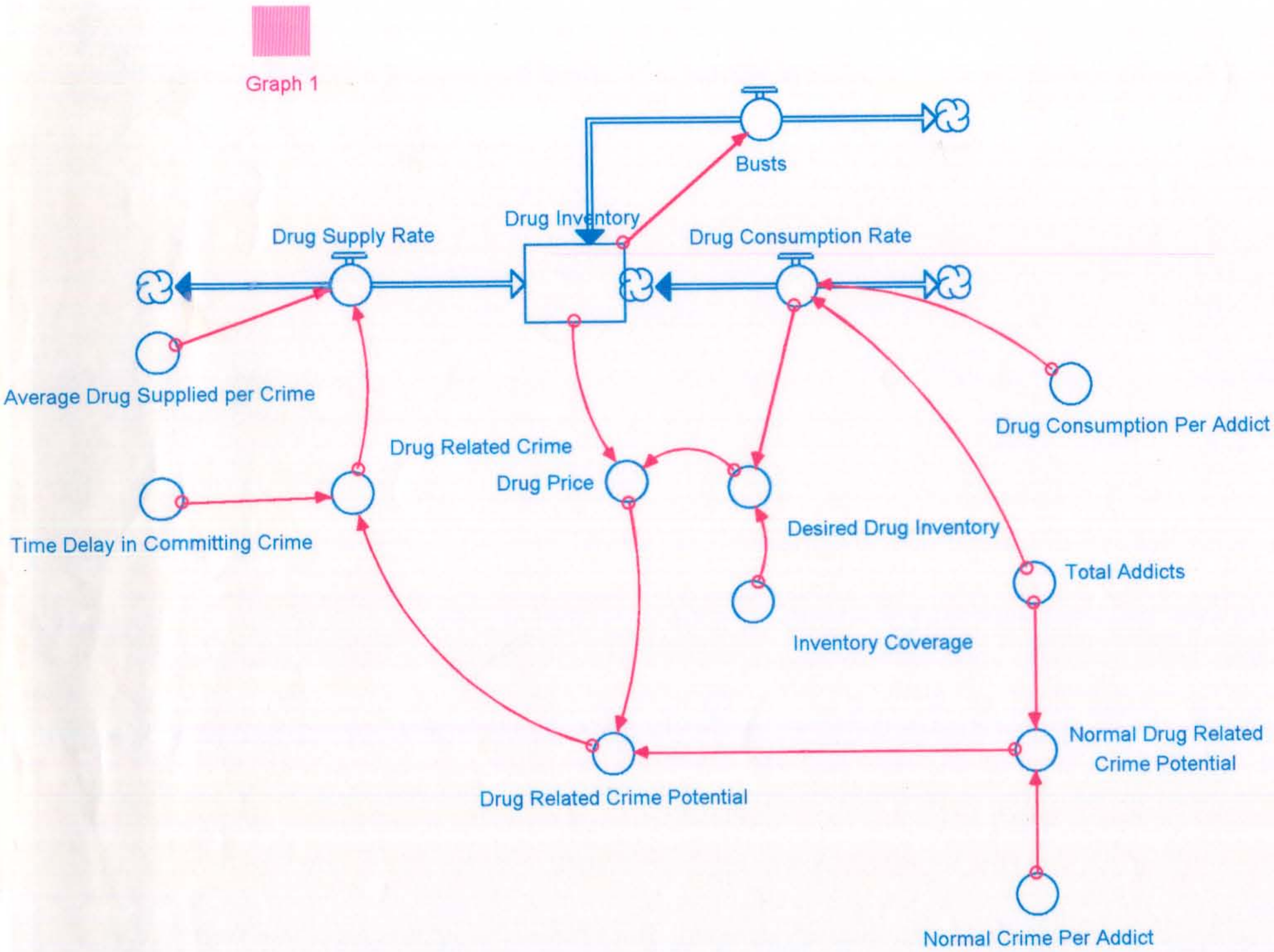
drug_inventory(t) = drug_inventory(t - dt) + (drug_supply_rate - busts - drug_consumption_rate) * dt
INIT drug_inventory = 400

INFLOWS:
drug_supply_rate = drug_related_crime*average_drug_supplied_per_crime
OUTFLOWS:
busts = drug_inventory*(0+STEP(.1,5))*1
drug_consumption_rate = total_addicts*drug_consumption_per_addict
average_drug_supplied_per_crime = 1
desired_drug_inventory = drug_consumption_rate*inventory_coverage
drug_consumption_per_addict = 1
drug_price = desired_drug_inventory/drug_inventory
drug_related_crime =
SMTH1(drug_related_crime_potential,time_delay_in_committing_crime)
drug_related_crime_potential = normal_drug_related_crime_potential*drug_price
inventory_coverage = 4
normal_crime_per_addict = 1
normal_drug_related_crime_potential = normal_crime_per_addict*total_addicts
time_delay_in_committing_crime = 2
total_addicts = 100

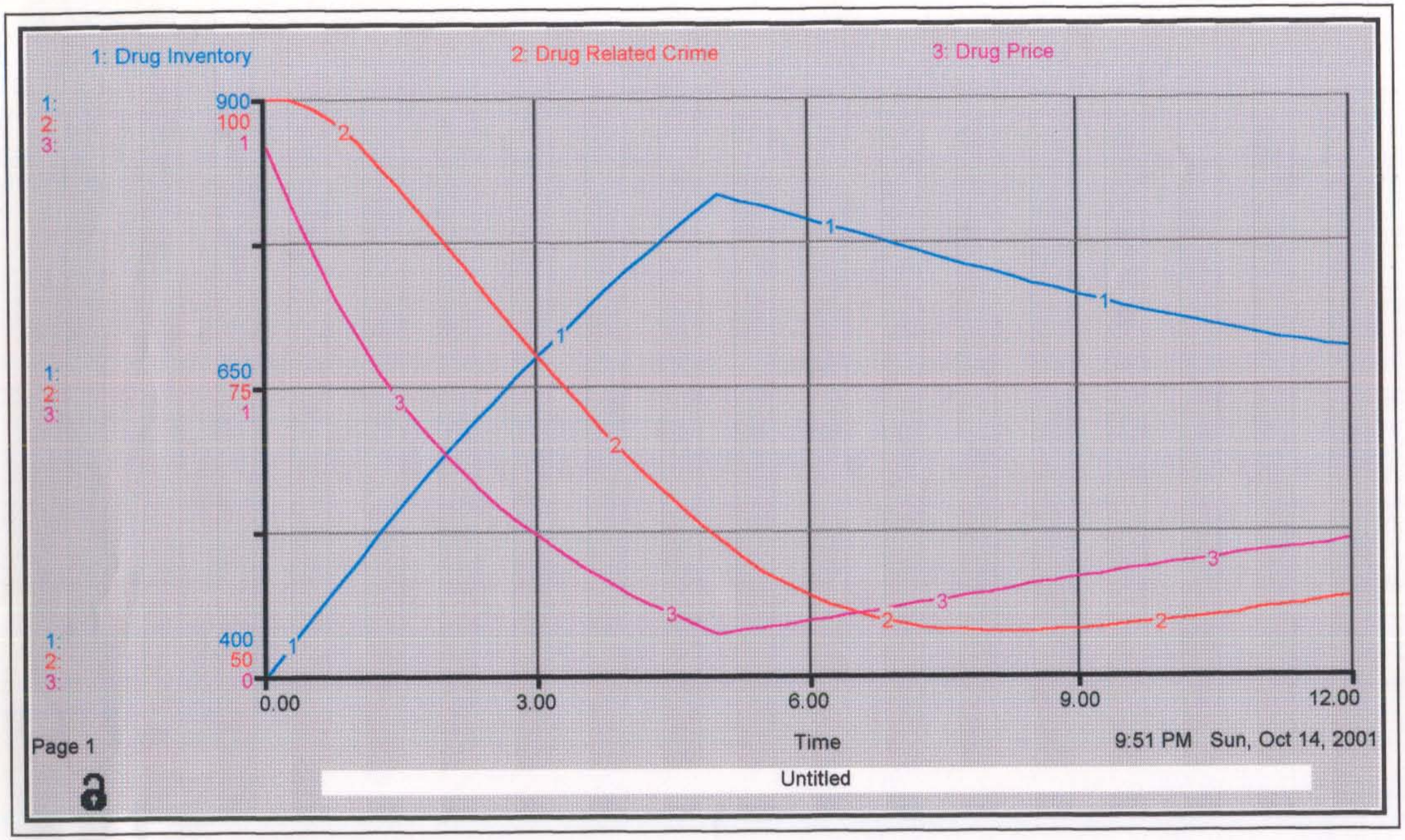
Meaghan O'Connell



Joshua Carlson



Joshua Carlson



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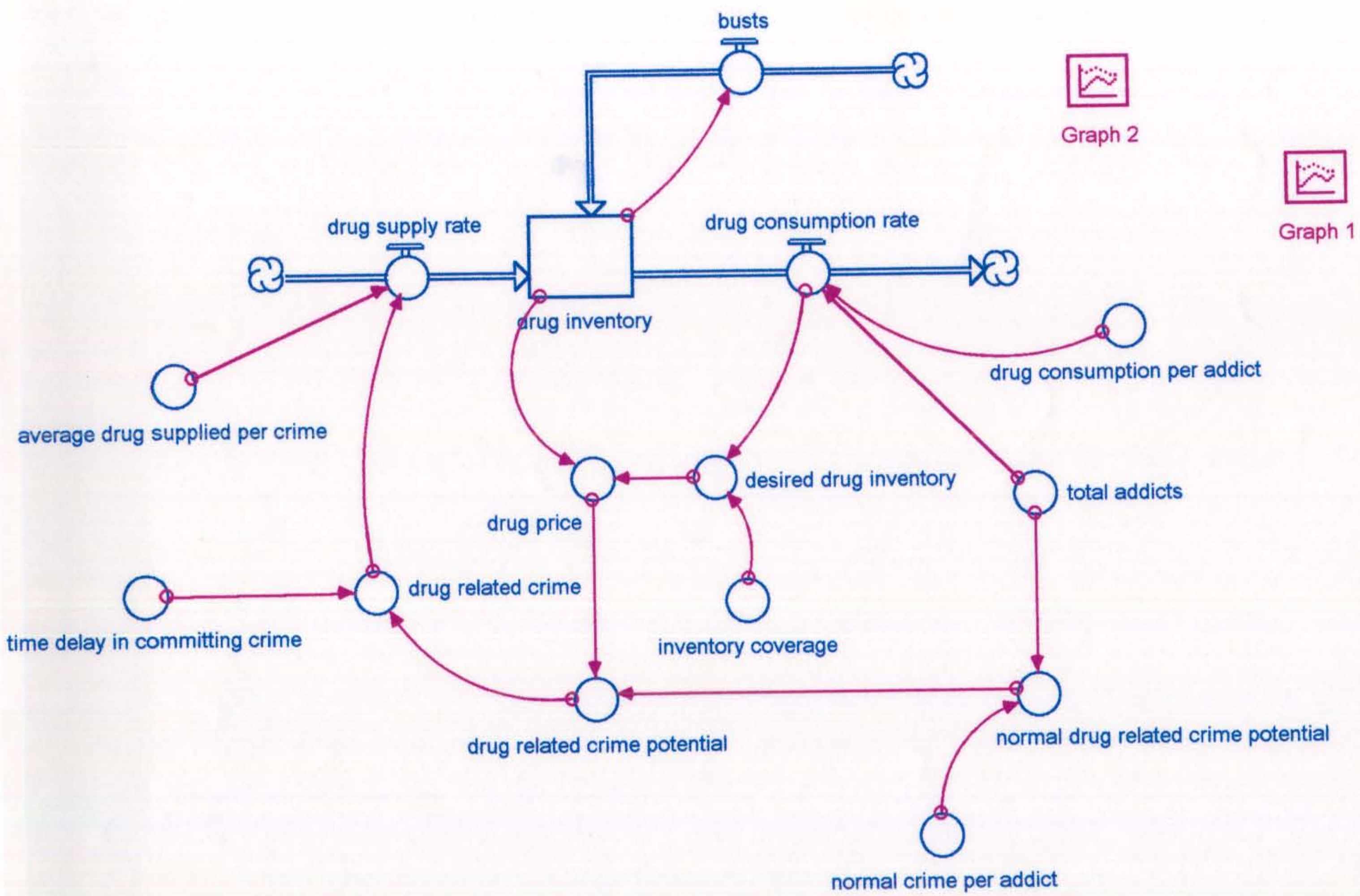
Marian Chaffe

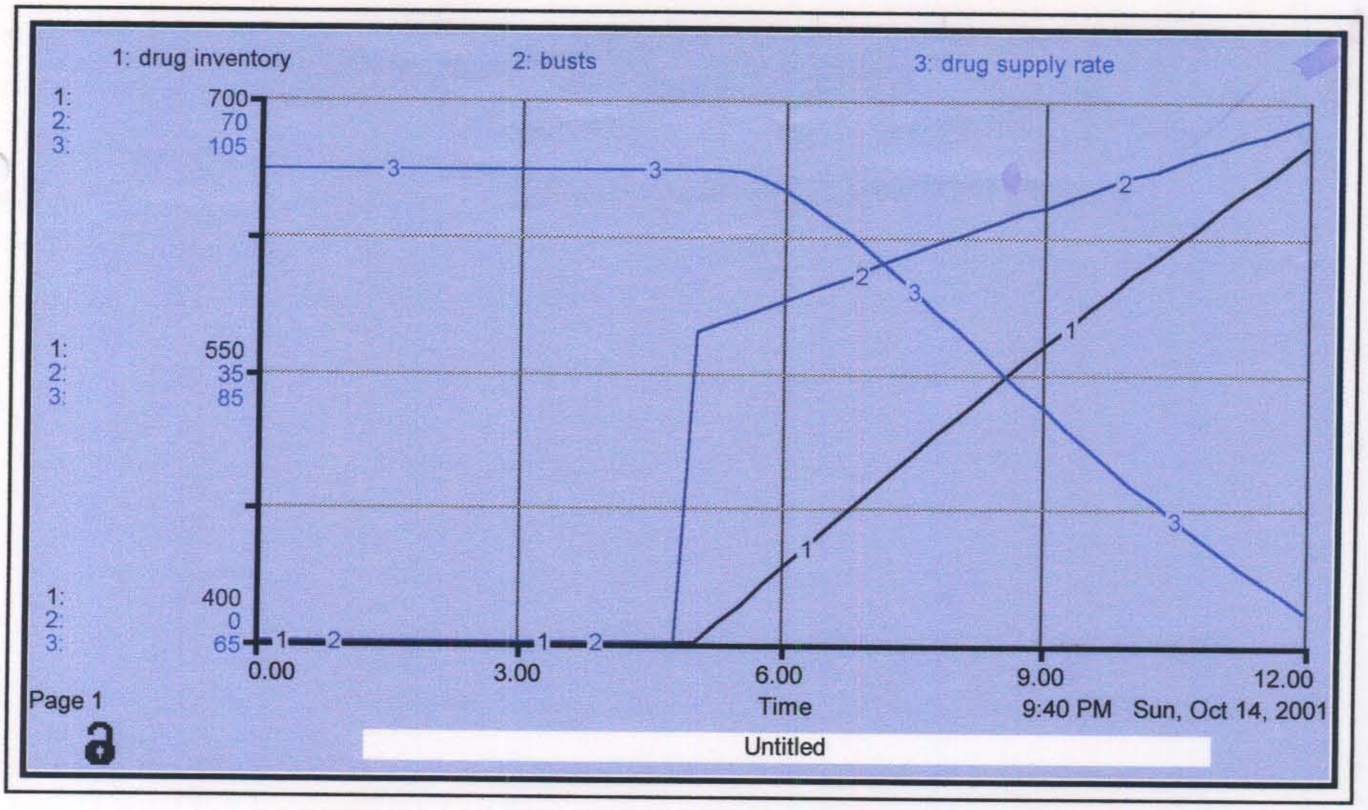


□ drug_inventory(t) = drug_inventory(t - dt) + (drug_supply_rate + busts - drug_consumption_rate) * dt
INIT drug_inventory = 400
INFLOWS:
drug_supply_rate = drug_related_crime_*average_drug_supplied_per_crime
busts = drug_inventory*(0+STEP(.1,5))*1
OUTFLOWS:
drug_consumption_rate = total_addicts*drug_consumption_per_addict

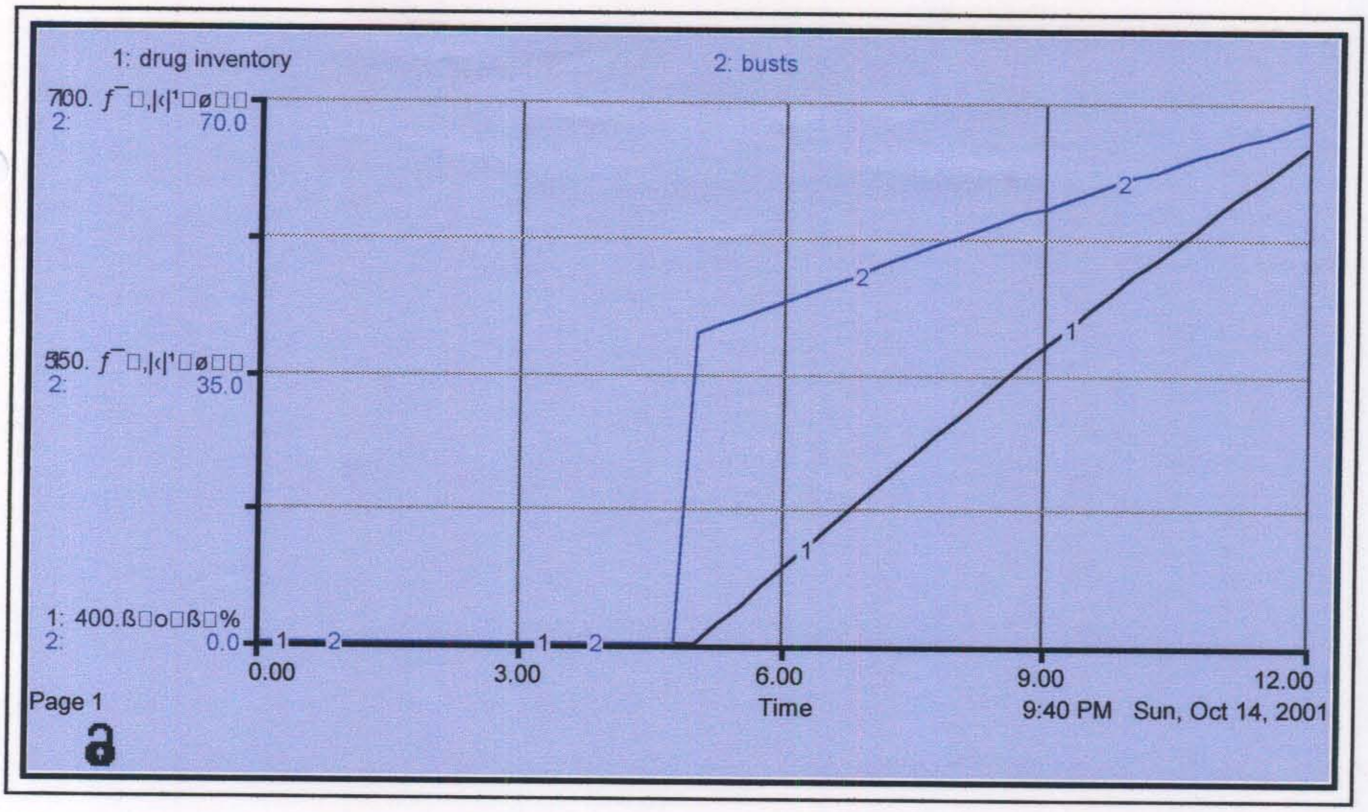
○ average_drug_supplied_per_crime = 1
○ desired_drug_inventory = drug_consumption_rate*inventory_coverage
○ drug_consumption_per_addict = 1
○ drug_price = desired_drug_inventory/drug_inventory
○ drug_related_crime_ = SMTH1(drug_related_crime_potential,time_delay_in_committing_crime)
○ drug_related_crime_potential = normal_drug_related_crime_potential_*drug_price
○ inventory_coverage = 4
○ normal_crime_per_addict_ = 1
○ normal_drug_related_crime_potential_ = normal_crime_per_addict_*total_addicts
○ time_delay_in_committing_crime = 2
○ total_addicts = 100

Marian Chaffe

Marian Chaffe

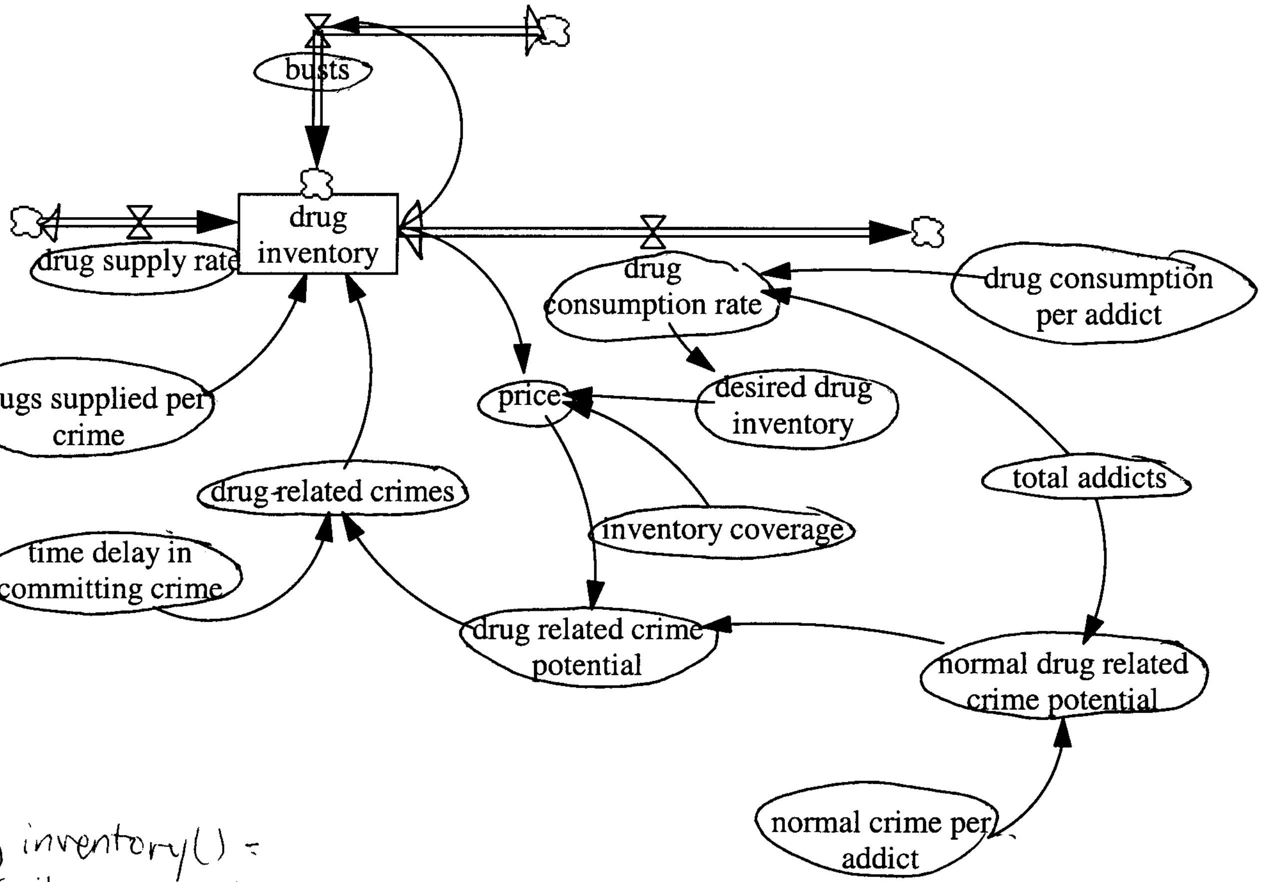


Marian Chaffe



Eileen Kosasih

Model: View: View 1



drug inventory() =
Init = drug supply rate * 1

Mon Oct 15, 2001 11:56AM

Appendix 14: Cape Rail Link Article Student Responses

(student responses)

Summary:
These were collected on November 16 from students who took the system dynamics course.

Nov

Meaghan O'Connell

a) The ride to the Cape is consumed with tourists, which means there are many traffic jams. Plans have been made that try to solve this problem, but these solutions lead to more problems. It has been proposed that the railways to and from the Cape should be restored. Kennedy purchased self-propelled Budd cars which he claims would not cost nearly as much as restoring all of the railroads. One of the problems is that people are questioning Kennedy's estimated price for the project; they think it would actually be much higher than his proposed cost. Another problem is that commuters will have no other form of transportation once they reach the drop off location in Hyannis, and making a car rental service is not included in the plan. Another problem with railways, which is not stated in the article, is the pollution of the environment.

b) I think that before making any changes to the Cape, a survey should be sent out to residents of Massachusetts asking them if commuting to and from the Cape is really that big of a problem and if it is, then would they prefer to take a train. This would take care of any problems that may arise with the residents after changing the forms of transportation on the Cape.

After this is done, and if the community/residents vote for the railroads, I think some type of fundraiser should be held in order to help pay for the railroads and help with the money situation. The problems that are going to arise once the railroads are built is the decay of the environment and the transportation after the drop off. So, based on all of these problems, tourism on the Cape would decrease due to the decay of the environment and the lack of convenience for the tourist. My solution would be to not use trains as a form of transportation on the Cape - they only lead to more problems for residents, tourists and the state/government.

(Nov)

Marian Chaffe

#3

a. The problem addressed in the article is how to install a railway service to reduce traffic problems at the Cape. Kennedy has bought 7 self propelled train cars that travel up to 60 miles per hour. The trip from the Cape to Boston and vice versa takes about 2 and ½ hours. Kennedy has admitted that he will need at least $2,500,000 the first year to get the railway started. The Central, today's tourist trains serves up to 60,000 passengers per year. Kennedy has highlighted the fact that Cape Codders do not want too much more moving into the area; and this new service might not only increase pollution, but also bring more unwanted industry and visitors into an already crowded area. Finally, I would find a way to address the lack of funds needed to begin the rail service.

→

b. To solve this problem, I would make a kind of model to illustrate all of these factors. Once I had formed a model, I might try forming a graph that would represent the change in traffic flow caused by the installation of the railcars. From this graph, I would generalize the situation.

I believe that doing this would provide numerical and statistical support for installing the rail car service. In doing so, traffic might not back up so often and passengers would enjoy a quiet train ride. The only issue that would be difficult to address is to find the funds to support this and that would be solved by donations and taxes from residents. The state funds would provide enough until profits from ticket sales became enough to keep up the service.

NOV

Joshua Carlson

a)

In the article "Cape debates impact of rail link," I was able to ~~see~~ discern what the main problem was. The problem is that traffic jams caused by too many people heading to the cape is getting to ~~be~~ be too much. This is especially true for the summer week-ends. Its a simple matter of too many people trying to get to one place.

The Cape is not a very big place yet large amounts of people vacation there. There are only so many ways into the Cape and these ~~get~~ get clogged very quickly. One solution was to put in a train system. However, there are ~~problems~~ problems and concerns with this idea. Some of these concerns are the fear that a train system would spark further development and ruine the ~~co~~ Cape. Another is that it will cost too much, and finaly how will this affect the environment.

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b) To solve this problem I would most likely use ~~Kennedys~~ Kennedy's idea with the train, but modify it a ~~bit~~ bit. The goal is to alleviate traffic into the Cape while being cheap and ~~env~~ environmentaly friendly about it. To do this I would ~~match~~ first match the number of cars on the train to the number of tickets sold. With the room left on the train I would put frieght cars. On the trip back out of the Cape I would take crafts, fish, produce, ect. back out. This would help pay for the train system. Hopefully this ~~will~~ won't spark growth.

There is one thing I can't control. That would be how this train system will affect the environment. The is already one train making the trip. Before building the train I ~~can~~ would run a study on the environmental effects of the train.

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(Nov) 11/20/01
Eileen Kosasih

a) Hyannis is a town at the bank of Cape Cod Canal which is clogged in the summertime. The problem is to find a system that lets tourists in and out of the Cape faster (more efficiently). Several ideas are proposed, but each has factors that backfire; such as cost, environmental issues, and landscaping problems.

b) I would go with the Budd cars. They are appealing because; they cost much less than (re)opening a railway service, so the government would approve; they can travel to specific locations, carrying only a certain number of travellers, so it appeals to tourists, Maintenance seems easier, therefore cheaper; and tourists are encouraged to take planes & buses more often, since they can be transported there, decreasing traffic flow and upping other transportation services' profits. Also, they don't take much away from the landscape, like railway stations, and are not as hazardous to the environment.

(Nov)

Mark Daniels

a) John Kennedy wants to build a railroad transportation system using existing rails and adding cars to expand on the system. Opposers say this would lead to overdevelopment and an increase of tourism which would harm the environment in Hyannis

b) I do not think this is a good idea, at least not at this point in time. According to the article, commuters would not have adequate transportation once they arrived in Cape Cod. This additional form of transportation may reduce traffic initially, but a reduction in traffic will cause more people to want to make the commute by car.

This addition to tourism will result in an increase of development. One can assume that one of the reasons tourists travel to the Cape is to see the beaches and environment. Overcrowded beaches and increased development will cause a decrease in the level of serenity that many people enjoy. When this environment is affected adversely, this may cause a decrease in tourism. There fore, a commuter train to the Cape may eventually have adverse effects on not only the amount of tourism, but the environmental conditions and industry that already exists.

(Noo)

Samuel Gurewitz 11/20/01

Rail Link.

3. A. The problem, as I understand it, is of transportation and development in Cape Cod. Currently, the Army Corps of Engineers is finishing restoring one of the three bridges across the Cape Cod Canal, which is a thirty million dollar project. With this restoration, a campaign has been made to open the brigde to passenger trains. However, with more and faster transportation could possibly spawn unwanted development and pollution.

B. I would go along with the proposition of the institution of seven Budd cars. Hopefully, with the cars, commute times will be lowered. More people in the cars will also mean less people on the road. Since there are not many Budd cars and because they are relatively slow, not much development will occur. The Stella Systems Dynamic Model (as I remember it) that we created) seems to support this model pretty well.

In the model, the impact of the Budd cars is discussed. In the future, we feel that the Budd cars will grow in popularity and ticket price will increase. As a result,

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the Budd-car proprietor, John Kennedy, will make a great deal of money. As a result, he will want to utilize more cars, eventually causing a problem with development and pollution. Therefore, we have to put a cap on the number of trains he can ever implement.

(Noo)

Mark Sherman

a) The main problem is that there is more ~~a~~ traffic trying to pass on and off of Cape Cod at peak times. This results in huge traffic jams which are very undesirable. A train service to the cape would relieve the roads of many vacationer's worth of cars. However, a high-speed train service would supposedly trigger increased economical growth, which the Cape could not handle. Ultimately the goal is to find a balance of trains, rental car agencies, and other tourist transportation systems to minimize both traffic onto the cape and economical development on it.

b) The Budd Cars, from John Kennedy's Cape Cod Central Railroad, would probably help the situation, except that they would require huge government subsidation. My solution involves a little "give" from everybody. First, get some car rental ageneies in Hyannis. From there, any number of mass transportation ideas will work, because the people will still be mobile once they get off the train. The state will have to subsidize the Budd cars, but only the bare minimum of them are to be run. People will be willing to put up with the long train ride because it is easy and still shorter than a bad day of traffic. The Budd cars also should interface easily with Amtrak and the rest of the state's transit, so even long trips to the Cape are covered.

NOV

Josh Weiss
11/20/01

Train Problem

1. In this article there is a problem. This problem is that there is too much traffic on the way to Cape Cod. The way to solve this is to use trains, or is it? There are advantages and disadvantages to this plan. For one thing, it is thought that by using trains, it will cut down on traffic, making the trip easier for travelers. This will lead to increased population on the Cape though, where there is no room. By increasing population, you will "decrease," or ruin the environment, and that is why most people go to the Cape. Also, if more people go to the Cape, more services will be necessary to accomodate all those people, further disintegrating the environment. So, the traffic problem needs to be solved, but the environment and population must be kept stable.

2. There is a solution to this problem. If I had the choice, I would allow the trains to run. There would be definite specifications to this solution though. To begin, I would

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only allow the seven trains to run, but never increase the number of trains. This would keep the number of travelers constant on the trains. Since the trip takes longer by train than by car, I would think that more people would travel by car then by train. This would keep the number of total travelers constant. By doing this, the environment would stay pretty "healthy," if, the train company was forced to pay to keep it in good condition. Also, by keeping travelers constant, services would not have to increase, the environment would stay clear, and traffic would decrease.

Nov

Sean Ting

a) The problem is whether to build a commuter rail into Cape Cod. Benefits include (depending on your stance) less people driving to Cape Cod, less polution from cars, less traffic, more tourism in Cape Cod, and smaller benefits. Disadvantages include government costs, environmental damage due to pollution from the train, and lack of services available to those who arrive by train.

b) I just wouldn't build the train. If it's expensive, would damage the environment, and possibly not provide full services to commuters, it doesn't seem sensible to build it.

Appendix 15: Cape Rail Link Article Student Responses

(student responses)

Summary:
These were collected on November 16 from the control group – a class of students who took a mathematical modeling course.

John Hollis

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) The problem is that the Cape is overcrowded. There are too many cars, not enough road. If a train where available or some other form of public transportation was available, then there would be less traffic. However, another problem arises from that. Because the train would probably lose money, the Cape can't afford to keep it running.

b) I think that the best option to alleviate the traffic ~~at~~ the Cape is to pollute all of the beaches so no one wants to go there. Although I'm just kidding, that would work. Seriously, I think a more energy efficient train so the state wouldn't lose as much money on it. Also if more people were interested in using the train, it would pull in more money and could maybe even turn a profit, which would make the train worth it's while. Also, many people wouldn't take the ~~train~~ Budd cars because it takes 2½ hours to get to Boston, where a bus takes 1¾ hours, making the train a much slower trip. If the train were able to go faster or somehow make better time in it's journeys, people would be more apt to use the train to get to Boston as opposed to other forms of transportation such as a car or bus. The main difficulty with the Budd cars is the length of time it takes, which makes them unattractive to consumers. Combine that with a fuel burning diesel engine and you have a transportation device that won't pull in a lot of revenue. Maybe the Cape should look into alternate energy sources.

247 JB

20 September 01

① Write your name on the paper   Michelle Boudreau

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) The problem is that there is a crowded area in Middleborough during commutes, there is a lack of public transportation available to riders arriving in Hyannis, and the money needed ~~to~~ to fix this problem is a large amount. Kennedy (president of Cape Cod Central Railroad) runs tourist trains called Budd cars from Hyannis to the banks of the canal and proposes to deploy more trains to help the traffic problem. To do this plan you need up to 2 million a year to run, and $500,000 to refit bus stations, so he says. However, others believe it would cost up to 30 million dollars. So the question is what can the government do to solve the traffic problem ~~and~~ at a low price and not encourage movement into that area.

b) Because the number of people choosing to ride on the Budd cars has increased to 60,000 passengers, 25,000 more than last year, and 43,000 more than its first year it can be seen that there is a high profit in this industry. If the government can set the train prices up enough so that enough money could be made to equal the cost to build and maintain then this industry would work. Therefore the traffic in Middleborough would decrease because more people would be riding on the trains and there would be a minimum cost to run.

248   JB

Jennifer Goscila 20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) This article explains how people are thinking of solutions for the enormous amount of traffic in Cape Cod. The solution explored is the train. The worry to residents and environmentalists though, is that the train would allow more people to move to Cape Cod and become a highly developed area, ruining its tourism business. John Kennedy believes that if you give the train a minimum speed so it may actually take longer, then less people would use it, especially for commuting to and from work. The problem then would be having enough money, which tres in the state. He believes the should provide some money for this project, because he doubts they would make any profit at all.

249 JG

b) This isn't a black and white issue, yes they should, or no, they shouldn't. You have to find some way to better the idea, maybe even create a new one. For many families Cape Cod is an easy and less expensive vacation. Making the assumption that they wouldn't want to pay not only for the train, but also the car rental, counts out a lot of tourists and expected customers. If there was a way to make the train be a part of the vacation and have it end in a easily accessable spot, where buses could pick the people up, then more people would use it. This may mean that new buses need to be instituted and bus routes may though. There is no simple answer, the priorities must be weighed.

Nicholas Muzzolillo

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b.) Identify & discuss your solution to a)

a. The problem I see here is that the government wants to reduce trafic to the cape. But there are some troubles. One of course being money and another being the destruction of an ecosystem that is already frail. They intend to do this by renovating the rail system, but here is another problem. One being that once people get to the cape they want have a car to use while they are there and the public transportation at the cape is poor.

B. My solution to the problem is to build another bigger and wider bridge, look at it this way bridges are cheap to maintain. people who go will have car when there and the ecosystem along the rails wouldnt be harmed. This is what I believe is the best solution because once it is built it is cheap to maintain. So this way congress would have less trouble funding it. So overall I say build a bridge

251 JB

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

Sylvie Boiteau

a) A bridge that has never been used for passengers could possibly be opened up for them. This could mean there will be more development which would hurt the land, and make traffic worse. These passenger trains are powered by diesel fuel, which is bad for the environment. They could have a high speed commuter rail, or a slower set of self-propelled cars; being attractive to commuters or tourists. They could also restore the Cape Codder. Running this service would be expensive and tourists might find it hard to get a bus ride once off the train. A passenger rail service could lower the amount of cars going to the cape and make use of the bridge.

b) I do not think passenger trains should be used on the bridge instead of garbage trains. If people are upset about too much traffic going to the Cape, then they just shouldn't go because they end up making the traffic worse, anyway. A commuter rail would be horrible for the environment. Some land should remain undeveloped. Everything should stay the way it is.

252 JB

Annie Jane Allan

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) The problem in this article is that the Cape is trying to attract more tourists, and the roads are very clogged & jammed w/ cars. Some would like to solve this problem by restarting the train service on the Cape. Many oppose these ideas for different reasons, such as:

1. bringing in unwanted development.
2. maybe worsen traffic
3. not being able to make a profit & not be able to pay for it w/out taxes
4. Costing too much money
5. A car rental place would have to be set up

Other people like the idea because:

1. They feel it won't bring in too much development because not all tourists will be interested because it would be a longer journey than taking the bus
2. People won't bring their cars (won't add to crowding)
3. Don't think it will cost too much

253 JB

↓ ↓ ↓

b) My solution would be to set up car lots at different locations in the cape, & at the beggining, and have trollies / bicycle available in the towns, & encouraged. Parking could be fined by the hr, discouraging people from parking. I think that this will solve the problem of crowding the Cape w/ cars.

20 September 01

Rogacz

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) The problem at first seems to transportation: reducing the number of traffic problems by providing rail service to the Cape. It is, in actuallity a problem dealing with money. No state government wants to subsidize a losing business, yet commerce at the Cape wants as many people there as possible. Mr. Kennedy proposes a privite business to connect Hyannis to Middleborough doesn't seem to be realistic. $500,000 to refurbish rails and stations?! No wonder local politicians support him! But with no way of getting around once in Hyannis, I think people will try to avoid Mr. Kennedy's line in the future, and instead sit through the traffic.

b) Squeezing more people onto Cape Cod is not only foolish but irresponsible. To solve the problem of how to maximize the tourist population, I would forget about a new rail service, which would only serve people from the Boston area who think that $2\frac{1}{2}$ hours by train (without problems at the overcrowded Middleborough station) is better than $1\frac{3}{4}$ hr by car (without traffic), and who have a means to get around the cape once they are there. (After all, there are no plans for a car rental place). For years, Cape residents have supported the building of a Canal tunnel, useable to Cape residents with a sticker

JB
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for the tunnel. This would aid in the facilitation of people onto and off of the Cape not only for residents but for tourists as well. I beleive that the solution to the problem of how to get more money from tourists (meaning attracting more tourists to the cape) is to alleviatate the traffic woes of Cape Cod. Of course I personally have a great dislike for and a bias against increased tourism on the Cape; an ecological gem that is slowly being eaten by a continually increasing tourist population, development projects, and an increasingly longer tourist season.

20 September 01
Daniel Young.

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a.) Kennedy wants to put a rail system in that connects the (Hyannis) Cape with Boston. The trip by train was said to take 2½ hours and a drive w/ no traffic is 1 hour 45 minutes But when there is traffic there ~~[illegible]~~ is a greater time for the trip. This rail is said to keep tourists of the roads so they can fly to Boston and take a train down to the cape rather than drive with the large number of vacationers who drive down to the cape ~~for~~ the weekend. The question is if this rail line would be worth while.

b.) I believe this rail line will be worth while, even though the expence ~~[illegible]~~ of the operation. If they have the money this would be a great addition to re-furbish the rail lines. If the 20 million that is estimated is in fact the price then that would be a bit expensive, but if it keep tourists off the roads, ~~and~~ people ~~[illegible]~~ going to the cape will be much satisfied with the decreased traffic. And also because of the decreased amount of cars there will be less pollution, less gas being used, and also less traffic which alows cars to keep moving which also lowes the pollution.

In the article it was said that the impact on the fragile ecosystem would be "astronomical," but I think that is highly over estimated in that opinion. A rail line cutting through a vast amount of ecosystem would not be as much of an impact as the person made it out ~~to be~~, a development in the ecosystem

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JB

would be astronomical due to the fact that there would be people living there and the constent interaction between them and the forest, but if it is just a train that passess through the ecosystem allday it is a far less interaction between man and an ecosystem.

Andrew Witman 20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b.) Identify & discuss your solution to a)

a) The cape is such a popular tourist area that
heavy traffic makes it extremely tedious to get
to and from the cape. John Kennedy has proposed
refurbishing existing rail lines so tourists could
to the cape by rail. Other plans have been go
proposed but they cost too much money and would
not break even. What the cape needs is an inexpensive,
environmentally friendly transportation system that
would help eliminate the current traffic problem.
b) Since cost and the environment are the two primary
concerns, I think the best solution is to let the
public deal with it. If they want to go to the
cape, they should be prepared to deal with the
heavy traffic. Why is the cape so popular anyway?
Perhaps if there continues to be such a great
number of tourists the beaches will get so
crowded and polluted that noone will want
to go there anymore. How's that for a
cost effective solution? If people insist

JB

the traffic problem must be solved, I think the Cape should only allow a certain number of people to enter. This would cut down on traffic and damage to the environment. It may not sit well with the people making money off of tourists, but what better way to keep people off of the cape. Even better, charge people a fortune at the tolls! The state would make a fortune and keep people off of their peninsula. In any case, I still don't see the attraction of the cape.

Reid Vancelette

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a. The problem discussed here is the crowded situation to Middleborough. Meaning that they need to find another way of getting in and out of the cape. So, John Kennedy wants to rennovate and refurbish a train system that goes from Boston to Middleborough.

b. The situation that I think is best would to rennovate and refurbish the railway. I think this would be best because I know that during holidays and summer there are so many people who go to cape cod. And by using the railroad it will allow another possibility to get there. Which will allow less trafic. I know that the train didn't work before, but there are more people now who go to cape cod before. Cape cod is already a big tourist place, train will allow it to be easier accessable.

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JB

Joslyn Foley 20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b.) Identify & discuss your solution to a)

a) The Cape's traffic problem keeps it from be coming over-developed, but it also hurts tourists. They want to use trains that appeal to tourists and not commuters to get to and from the Cape. Some people are afraid that it will not make a profit and destroy the environment, and it won't be endorsed. Other trains have been shut down because there wasn't any profit.

b) My solution would be to ask people whether or not they would use this service, if enough say that they would to make a profit then continue Kennedy's plan, but use the most efficient and environmentally safe trains possible. Ask the people what they want.

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JB

20 September 01

Justin Duffy

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) John Kennedy wants for run a train line from Boston to Plymouth on Cape Cod. However, state Representative Eric Turkington is strongly opposed to this idea, as he believes it would be both costly and environmentally detrimental. What is the solution?

b) As I see it, the two issues at hand are cost and the environment. Mr. Turkington is concerned (rightly so) about the effects of such a train service on both the fragile ecosystems of Cape Cod, and the Massachusetts tax payers wallets. In my opinion, all public transportation should be run by the government, and should eventually become a source of state revenue (similar to the European transit systems). The main problem with this system for Americans are our enormous automobile and fossil fuel corporations (along with their other profiting industries.)

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JB

These companies have fueled a system in which the average American car is no longer a four or five seater, but a single occupancy vehicle. Public transportation has become a derelict relic of the past in the US (with the possible exception of air travel), and it's time to revive it. Now for the second part of the problem, something a little closer to home: the environment. How can we alleviate environmental damage to the Cape caused by commuting trains? First of all, if the trains running through Cape Cod are well used, this means there will be less traffic on it's interstate's and highways. CO_2 emissions could be cut drastically be trains, as well as the 'highway sprawl' of fast food joints, convience stores, etc. that inevitably follow highways, but not train tracks. Secondly, an increased public awareness about the ecological impact of private vs. public transportation could generate the capital needed for the ongoing research into alternate energy sources.

I'm going to stop now, because I've run out of space on the page, and I'm feeling sleepy.

Elizabeth Palumbo

20 September 01

① Write your name on the paper

265

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) John Kennedy has proposed a passenger train revival on the Cape. The Army Corps of Engineers are working to complete a $30 million restoration plan on the canals and this campain by John Kennedy would cost the state a fraction of what it would cost them to bring back rail service. John Kennedy wants to use self-propelled train cars buit in the 1950s, to bring back the "good old times" feeling that Cape Codders have. The main problem is that this proposal caters to tourists and other ideas just catering to tourism and the tourist market were crossed out. If the state isn't going to make any money off of a proposal, they won't use it. However, there is a lack of public transportation, and overcrowdedness in Middleborough which would increase the usage of this service.

b) Since Kennedy would only need $2 million a year to run his service after the stations and such are refurbished (@ costs he says will run no higher than 500,000$) this would prevent the fear a high-speed commuter rail line would trigger even more development. I say to let the people of Cape Cod vote. If they would like to have a train run through their town, and pay for any possible reprucussions, the

JB →

they will know full well what they're getting into.

20 September 01

① Write your name on the paper Adam Broders

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② Read the article Done

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

3.) a.) The main problem that I can see is traffic. The bridges to cape cod are always stock full while another train bridge only lowers for a trash train. They have stated many ways in which to fix this including running the old railroad as a public transportation option, but that seems to have a lot of problems.

b.) I have been on those bridges and I know they get very very busy. But to tell you the truth I always see the traffic only for a few miles on the bridge and either side of it. If they are going to need millions to refurbish this mode of transportation it had better get busier than what I have seen at those bridges. If it does then I still see all the tall walls that John Kennedy needs to climb in order to make the ~~islan~~ peninsula acessible from there, not just for comuters. If he shared a VERY detailed outline to his restoration and future processes then refurbish the bridge to relieve traffic (making sure not to destroy Cape Cod in the process.) Otherwise leave it as is. A place like that is worth a little traffic.

JB

Rachel Rynick

20 September 01

① Write your name on the paper

② Read the article

③ Write:

a) Identify & discuss the problem as you understand it.

b) Identify & discuss your solution to a)

a) With increasing commuter & tourist traffic in Cape Cod, an alternative mode of transportation must be found. One idea is to utilize the railways for commuting from Boston to the Cape.

b) I think that Kennedy's plan, with a few minor adjustments, would work well. One of the main issues is money. His current plan does not include taxing the residents to pay for the service, and that might do the trick. Overall, though, I think this service would be good for Cape Cod, Boston, and everyone going in between.

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JB

Appendix 16: Entry into a Mathematical Contest

(Extracurricular)

Summary:
After the course was over, a group of students choose to use system dynamics to build a model for their entry into a mathematical modeling contest. It was brought to my attention on November 14.

For office use only
T1 ______________
T2 ______________
T3 ______________
T4 ______________

For office use only
F1 ______________
F2 ______________
F3 ______________
F4 ______________

4th Annual High School Mathematical Contest in Modeling (HiMCM) Summary Sheet
(Please attach a copy of this page to each copy of your Solution Paper.)

Team Control Number: 205
Problem Chosen: B

Please type a summary of your results on this page. Please remember not to include the name of your school, advisor, or team members on this page.

Using Powersim, a system dynamics utility, the problem was modeled graphically. To design this model the interaction structures were carefully analyzed and were written based on multiple simple equaitons, primarily of the form distance is equal to rate multiplied by time. Once this interactive model is functioning, any value can be altered or manipulted with ease and the final result of the enitre system is changed instantaneously by the program. This flexibility allows for a total understanding of the problem and results to be derived based on the change of any one vairable, or the manipulation of many. This model can also be expressed numerically.

Based on the given times of evacuation, , the tallest possible building that is dimensionally equal to a World Trade Center tower except in height can be found. The results are:

Time (minutes)	Maximum Height (stories)
15	50
30	108
60	223

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Problem

A skyscraper-class building is to be evacuated. The elevators are rendered inoperable except by specific rescue personnel. The goal is to model the evacuation over a specified period of time, represented by X minutes. The model must include the height of the building, its floor area per story, occupation, and any other factors involved with the efficiency of the occupants removing themselves from the building.

Background and Assumptions

The building is assumed to have been designed and constructed in accordance with the Uniform Building Code. It is further assumed to have been built with reasonable dimensions, meaning it is able to support its own weight and function stably when a natural or artificial disaster situation mandating evacuation is not present. To simplify the problem it is assumed that the same number of people are on every floor of the building, each floor has equal area, and reaction time of the occupants is practically instantaneous.

The Uniform Building Code states that every building must remain in a state of free-flow in emergency evacuation conditions. A building is in a state of free-flow when there is no major congestion of personnel escaping at any point. To establish this state there must be sufficient stairwells and exits for all of the proposed occupants to escape easily. For example, take a small, simple building which appears to, based on number of exits and their location, be able to support 130 occupants with full regard for their safety. However, congestion would occur if more than 110 people attempted to exit the building at any one time through the main door. Therefore, the capacity is set by the local

Department of Public Health and Code Enforcement at 110 people in the building at any given time despite the existence of other exits.

Because all personnel should be unrestricted during their exit the total time for evacuation is determined by how long it takes for the person farthest from the exit to leave the building. This time includes how long it takes him to walk across the floor, get down the stairs, and run the mandatory 500 feet away from the building to be considered clear of the site. Federal engineers estimate the speed of a walking human to be 4 feet per second and that of a running human 10 feet per second. In additions, the Uniform Building Code defines standard dimensions for stairs as 11 inches horizontal distance and 7 inches vertical distance for each stair.

Solution and Generalizations

The time for the evacuation, x, can thus be represented as the total distance between the person farthest from an exit, divided by the average velocity of the person during his escape. This is true since time is equal to distance divided by rate. The distance is a function of the building's length, width and height. Assuming the worst-case scenario, that being a person in the opposite corner from the stairwell, the distance from the person to the stairwell is equal to the square root of the sum of the squares of the width and the length of the building. To this, the distance down the stairwell must be added. This is equal to the total distance down a stair multiplied by the number of stairs. The distance down a stair is equal to the sum of the vertical distance and the horizontal distance. The number of stairs is equal to the height of the top floor divided by the height of each stair. As the height of the stair is defined as 7 inches and the distance per stair is defined as 18 inches, the distance involved in descending the stairs is

$\frac{\text{height of top floor}}{7\text{ inches}} \times 18\text{ inches}$. Therefore, the total distance involved in getting out of the

building is represented as $\sqrt{length^2 + width^2} + \frac{height}{7} \times 18$. This time must be added to

the time required for a human to run the 500 feet away from the building. At ten feet per second, that takes 50 seconds. The total time for the building to be evacuated, in seconds,

is thus $\frac{\sqrt{length^2 + width^2} + \frac{\text{height of top floor}}{7} \times 18}{4\text{ ft/s}} + \frac{500\text{ ft}}{10\text{ ft/s}}$.

Additional Solution techniques

Modern technology offers many new divisions of science that in the past could not have existed. One of these fields is system dynamics, which is, in the words of Professor Michael J. Radzicki, "…a computer modeling technique that has its origins in control theory, cybernetics, organizational theory, behavioral psychology, economics, and digital computer simulation. It is used to build models of systems that are experiencing problems and/or exhibiting behaviors that are not well understood." The benefits of system dynamics, Radzicki then continues, is that models are problem-based, not system-based. With the supreme computational power of the modern computer, values and interactions within a problem can be modeled graphically and then calculated rapidly, regardless of the level of complexity. One such computer program is Powersim Studio Express, which was used to model this problem.

The first step in any model is to establish what variables are associated with the problem. Using the free-flow method of evacuation the following variables must be integrated:

- Number of floors
- Width of building
- Distance to stairs along horizontal
- Total distance to staircase (derived from width and horizontal distance)
- Distance down stairs
- Distance from bottom of stairs to "clear zone"
- Velocity to walk to stairs
- Velocity during descent down stairs
- Velocity while running to "clear zone"
- Time to get to staircase
- Time to descend stairs
- Time to run to "clear zone"

Each of these variables can be represented, for the purposes of this problem, as a constant or an auxiliary. Constants, represented by a diamond image in the diagram, represent values that will not change within a building, such as how many stories tall the building is and how high each story is. The auxiliaries are circles, and represent rates of change and values that are dependent on other values. A full diagram is in the Appendix 1. This model is the second built for this problem, the first of which did not work.

Every variable is connected with a link, drawn by a line with an arrowhead on one end. The data generated in one variable is used in a calculation in the auxiliary which it is linked to. The calculations are based on the mathematics explained above.

Based on this model and the given times to evacuate the building, the tallest possible building that is dimensionally equal to a World Trade Center tower except in height can be found. The results are as follows:

Time (minutes)	Height (Stories)
15	50
30	108
60	223

Not included in these calculations is the delay time that would occur in a real situation. Also not included are any actions by emergency personnel which would function to reduce the delay time.

Sources

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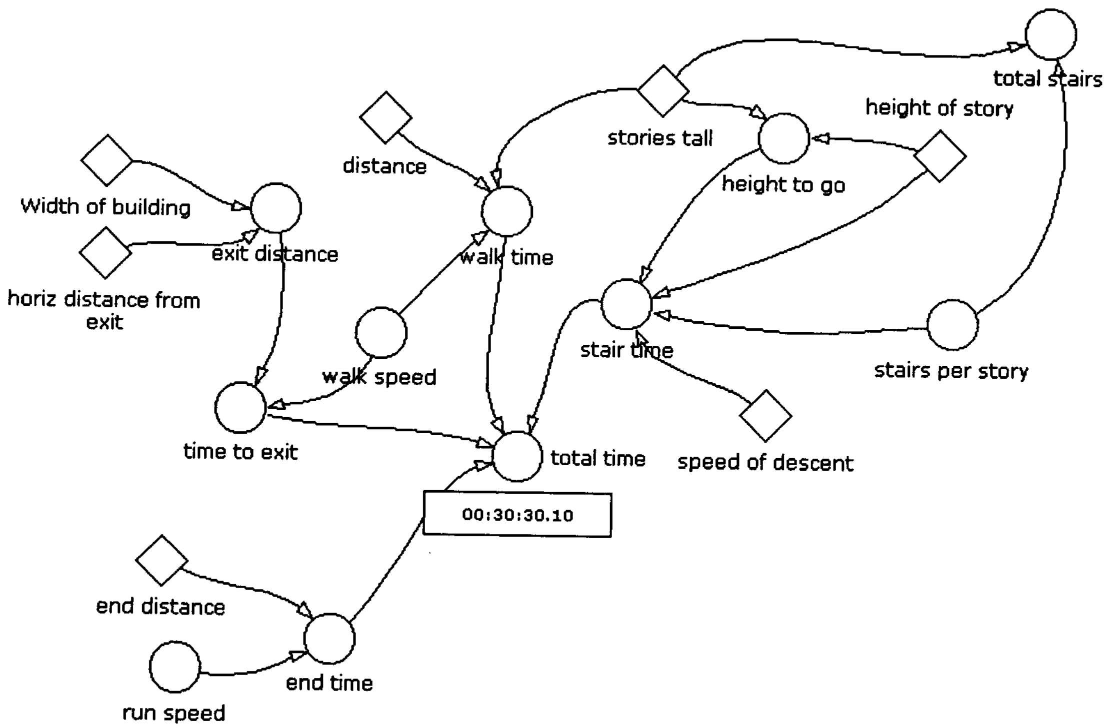
Appendix 1


total stairs
height of story
stories tall
distance
height to go
Width of building
exit distance
walk time
horiz distance from exit
stair time
stairs per story
walk speed
time to exit
total time
speed of descent
00:30:30.10
end distance
end time
run speed