Using STELLA to Create Learning Laboratories: An Example from Physics

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Abstract
STELLA is a new software program that has been designed to bring system dynamics to broad-based audiences. A series of books is being developed to disseminate STELLA and system dynamics into one of these broad-based groups -- the college educational market. The books center on a "learning laboratory" approach to learning. This approach uses STELLA as the basis for an experiential, learner-controlled learning process. One of these books, "Learning Laboratories In: Physics," is described in this paper. The book contains three sections: mechanics, thermodynamics and electromagnetism. Within each section are five to six lab sessions. The lab sessions progress from simple structural models of fundamental concepts to more complex models that integrate the work from the previous labs. A sample session on Newton's laws is presented to illustrate the approach.

Introduction

STELLA is a new software program that has been developed to enable very broad, non-technical audiences to conceptualize, construct and analyze system dynamics models. One of our goals in developing the software is to use the power of the system dynamics approach to enhance the learning process. To that end, we at High-Performance Systems are developing a series of books, or more appropriately "learning laboratories," that use STELLA as the basis for experiential, learner-controlled learning. This paper outlines the techniques we are using in writing these books and illustrates them with examples from my book, entitled "STELLA Learning Laboratories In: Physics." The book is intended for college level students taking introductory courses in physics or engineering. For a description of the learning laboratory approach in a different setting, refer to Steve Peterson's paper which describes the application of the STELLA learning laboratory approach to microeconomics.

I draw extensively on the work for my physics book throughout this paper. First, I provide some background material by briefly describing what STELLA is and how it is used. Next, I give an overview of the book and the learning laboratory approach. Following the overview, I present a sample laboratory session on Newton's laws to illustrate the techniques we are using to enhance the learning process.

A Brief Description of STELLA

STELLA is an icon-based modelling "language" that eliminates much of the technical effort typically spent in building a system dynamics model with DYNAMO. Taking full advantage of the graphical operation and radical-ease-of-use design of Apple Computer's Macintosh, STELLA enables even novice users to learn the technical aspects of model building in about one hour. To illustrate, if you were building a model with STELLA, you would merely select levels, rates or auxiliaries from a "structural tool kit," place them on the screen and "plug" them together. As you create the diagram, the necessary mathematical relationships that would be written explicitly in DYNAMO are generated automatically by STELLA according to the type of element and the interconnection made on the screen. So, in effect, the user is "drawing" a structural diagram while STELLA is generating the computer code simultaneously. In addition to the automatic generation of computer code, STELLA embodies knowledge of model-creation heuristics and analytical tools -- animation of the structural diagram and scatter plots to name two -- that make it a powerful tool for building and analyzing models of dynamic systems.

For a more detailed description of STELLA, refer to Barry Richmond's paper "STELLA: Software for Bringing System Dynamics to the Other 98%."

Overview of the Learning Laboratories in Physics

In most physics courses today, teachers use inherently static techniques to teach inherently dynamic concepts. Many problems in physics are dynamic in the sense that they are concerned with moving bodies or particles. However, many of the methods applied to these dynamic problems are static in nature (such as free-body diagrams and conservation laws). Also, these methods typically emphasize end-point solutions rather than on an understanding of the path or mechanisms involved. For example, consider the way students learn about collisions between particles. They are taught the principles surrounding the conservation of momentum and energy, then apply these principles to solve problems concerning particle collisions. Frequently, the student is given the particle velocities *before* a collision occurs and asked to solve for the particle velocities *after* the collision occurs. Little time is spent explaining or understanding the mechanisms by which momentum is transferred from one particle to another *during* the collision. The transfer mechanism is important for understanding how it is that momentum is passed from one particle to another and for understanding how energy is lost during the collision. Energy losses are usually ignored in such examples. While traditional static methods serve an essential purpose in teaching fundamental concepts, they are limited in their ability to give students an intuitive understanding of dynamic behavior and ignore many real world influences.

One important reason why dynamics have not played a greater role in the teaching of physics is that analytic tools like STELLA have never been readily accessible to students. I once demonstrated STELLA for a Dartmouth physics professor. After the demonstration, he remarked on the ease with which a student could include non-linear factors in a dynamic model. He also pointed out that because of the mathematics involved the most complicated dynamic problem covered in introductory physics courses was simple harmonic motion (i.e., a second order, linear system). A brief review of Halliday and Resnick's "Fundamentals of Physics," an introductory physics text, reveals that physicists make the most of simple harmonic motion. It is covered five times in the book: the spring and pendulum in mechanics, the motion of water in a U-tube and a wooden rod placed vertically in the water in fluids, and L-C circuits in electromagnetism. Given a tool like STELLA, physics professors will no longer be constrained from helping even the most casual student gain an intuitive feeling for dynamic behavior.

The world is dynamic and it is from this world that people like Isaac Newton distilled their theories. Using STELLA, we are creating an environment where students can explore the theories of many of the world's greatest scientists in a dynamic framework. For example, students studying mechanics can analyze the behavior of particles as they plummet toward the earth falling through different media. A student studying thermodynamics (underscore dynamics) can experiment with the output and efficiency of a running Carnot engine operating under different temperatures and pressures. In presenting the theories underlying such examples, I draw on a students dynamic intuition with carefully selected examples to reinforce their everyday experience and to avoid the unnatural context of a static, idealized world. Also, giving a student the ability to bring "alive" many of the static textbook treatises they are exposed to in class will provide natural motivation for learning.

Our goal in using the learning laboratory approach is to show its value-added. Therefore, my book is intended to be used in concert with, and not as a substitute for, a good physics textbook. In fact, the progression of the chapters and laboratories are closely modelled after two very popular physics texts, Fundamentals of Physics by Halliday and Resnick and University Physics by Sears and Zemansky. Since our focus is on value-added, I have left out of the book detailed descriptions of many fundamental concepts, such as force, mass, charge and temperature, which are treated so well in many of the physics texts, especially in the two I have just mentioned. Rather, I take these concepts as a "given" and concentrate on building a dynamic framework within which they interact to produce behavior.

There are three sections in the book: mechanics, thermodynamics and electromagnetism. Within each section, the individual lab sessions progress from fundamental concepts to an integration of the fundamentals into a more advanced topic. For example, in the first section of my book on mechanics, the first four labs cover Newton's laws, energy and momentum, conservation of energy and momentum, and gravitational attraction. The final chapter integrates these individual concepts into a dynamic model of collisions between particles that demonstrates all of the previously covered concepts.

The progression in the book is from simple to more complex concepts and from more to less "handholding." The very first lab sessions dealing with mechanics are very structured (the student is guided every step of the way) and relatively simple: a one level, one rate system is used to introduce momentum and force. As the labs progress, more advanced topics are covered, such as particle collisions and oscillations. By the time the student has reached the fourth lab on gravitational attraction, they both know how to use STELLA and have a base of knowledge of mechanics. Hence, the lab sessions become more complex and less structured. This process builds students' confidence and gives them freedom to be creative.

All the STELLA books are written to be used interactively with the computer. The format is that of a laboratory setting. The student prepares the "laboratory apparatus" (places the necessary structural elements on the computer screen with STELLA) from descriptions in the book, then performs the experiments as outlined. A priori hypotheses and results are recorded right in the book, creating a permanent reference document similar to a lab notebook.

The purpose of the STELLA lab sessions differs from that of the real-world physics labs. Physics labs are used more or less to confirm the theories presented in class. For example, students measure the length of time it takes a pendulum to complete "x" number of cycles and calculate its period to confirm the equations governing simple harmonic motion. (Of course, the existence of air resistance and friction violate the assumptions of this type of motion, making the results of the experiment close to, but not equal to, those predicted by the equations.) The purpose of the STELLA lab sessions is to present the student with an opportunity, not only to experiment with concepts presented in class, but also to extend these concepts and, ultimately, to create theories of their own. Referring back to the pendulum example, students, using

STELLA's graphical mode of operation, can quickly and easily construct a model of a pendulum, plug in the necessary parameters, and simulate or animate it to find its period. They can then superimpose non-idealized influences such as friction onto the structure to judge the marginal effect it has on the behavior. They can also tack on some "accounting" variables to determine how the pendulum's energy shifts from potential to kinetic, where energy is being lost, how much energy is lost, etc. The possibilities are limited only by the students imagination.

In designing the lab sessions, we wanted to create a series of "small wins" for the student to maintain interest and motivation. Therefore, each session is self-contained and takes only about one hour to complete. For example, Newton's laws, heat and temperature, kinetic theory of gases, and Coulomb's law are each covered in one lab session.

A major asset of the system dynamics approach is the discovery of certain behaviors and structures that occurs during the course of an analysis. Most system dynamicists would agree that this process of discovery is an invaluable way of learning. Carrying this approach into an educational context, one way for a student to learn is to discover concepts on their own rather than having the concept presented to them in class. Taking this to an extreme, one might imagine a professor sending her students out to sit under an apple tree to wait for an apple to fall in the hope they will discover gravity. The inefficiency involved in such a scheme makes it impractical, which is one reason why textbooks are written. However, using STELLA, much can be done to facilitate the discovery of knowledge by the student. One way we attempt to have students discover certain concepts is by presenting them with a number of different behavior patterns and then asking them to deduce the structure that produced it. This process is an excellent way for students to "relive" the experiences of people like Newton and Carnot. I give an example of the discovery process in the next section of my paper on the sample lab session.

We felt it important that, whenever possible, the examples for the learning laboratories be chosen on the basis of their relevance to the intended audiences' background and experience. Some of the reasons for keeping the examples relevant to the students experience are obvious, such as its easier to maintain their interest, it is inherently motivating, etc. A less obvious reason is the goal of having the student discover knowledge rather than being presented with it. By using an example they are intimately familiar with, we can ask them to be more creative in their solutions. Also, we can eliminate a lot of lenghty and boring description of the situtation that would otherwise be required. For example, in motivating the discovery of the reasons why a pendulum exhibits damped vs. sustained oscillation, I can ask the student to call on their own experience with swings in a playground and the fact that they had to pump their legs to maintain the motion of the swing. If I had chosen a less relevant example, such as a "generic" pendulum, 1) it would be more difficult to motivate the idea that energy is constantly being lost from the system and that it must be supplied by some external source to sustain the oscillation and, 2) I would have to describe all the attributes of a generic pendulum, which is abstract and not very interesting.

Sample Laboratory Session

Two techniques are used throughout the lab sessions to facilitate the learning process: hypothesis testing and synthesis of structure. The first technique, **hypothesis testing**, is used to get a student to exercise their mental models, i.e., think, about how a given structure will behave. The student is asked either to sketch their best guess at the behavior over time or to state what behavioral changes will occur as a result of a change in structure or parameters. Having been asked to take a stand on the outcome, the student would then check their a priori hypothesis against the result generated by the computer. If there is a discrepancy between the a priori and the actual behavior, the student is led to investigate the reasons for the discrepancy. This "closes the loop" on the learning process. If I were to present the results without first getting an a priori, it would be far too easy for students to convince themselves that they knew how the model would behave. Also, the active nature of the hypothesis testing keeps the student invested in the process.

The second technique, **synthesis of structure**, is the process system dynamicists go through when they sketch a reference mode and then try to synthesize the structure responsible for that behavior. The way I use this in the book is very similar to the reference mode approach. I present some behavior, from a physical setting of course, and then ask the student to make the structural changes or additions needed to reproduce the behavior. The behavior mode I choose is always within the context of whatever topic is being covered.

To demonstrate how I have implemented these two learning techniques, I have extracted parts of a lab session on Newton's laws from my physics book. The first half of the sample lab session focuses on the use of hypothesis testing.

Assume that you are standing on a frozen pond and your friend is sitting on a sled next to you. You are going to apply a force of 20 lbs. to your friend's sled for 15 seconds and then release the sled. The structural relationship between your applied force and the sled's momentum is shown in Figure 1. (Figure 1 was made with STELLA. Notice the "tool kit" of structural elements on the left side of the screen.)

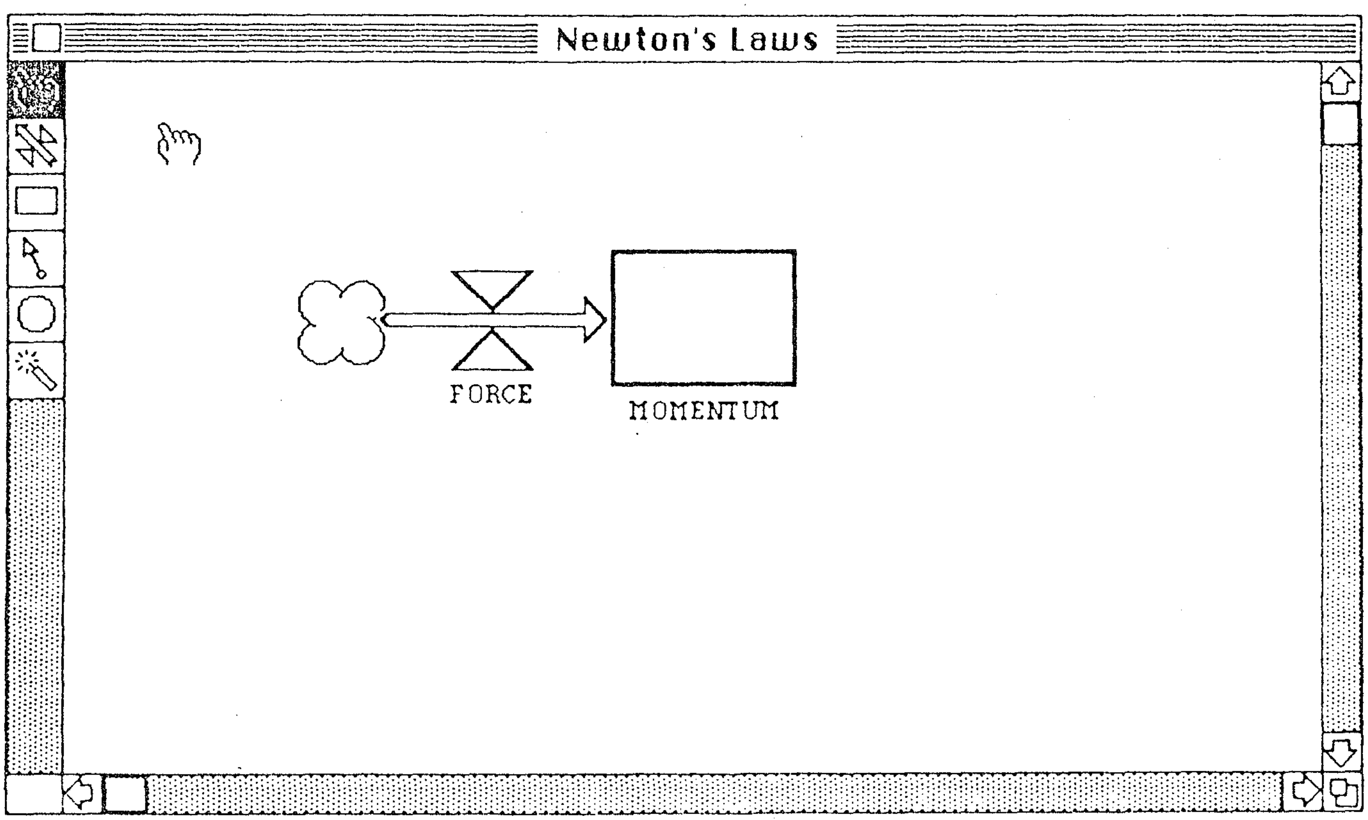

Figure 1: Structural diagram illustrating the relationship between force and momentum.

MOMENTUM is the momentum of the sled and FORCE is your 20 lb. applied force. Momentum is the integral of all forces acting on a body (Newton's second law). In this simple example, we are considering only one force. The structure I have given to you above is not given so easily in my book. Rather, I motivate the structural relationship between force and momentum by drawing on the student's experience with the physical world. Getting back to our scenario, if you apply the 20 lb. force for 15 seconds, how will the momentum of the sled change over time, assuming that initially the momentum is zero? Sketch your best guess at the behavior in the graph provided below.

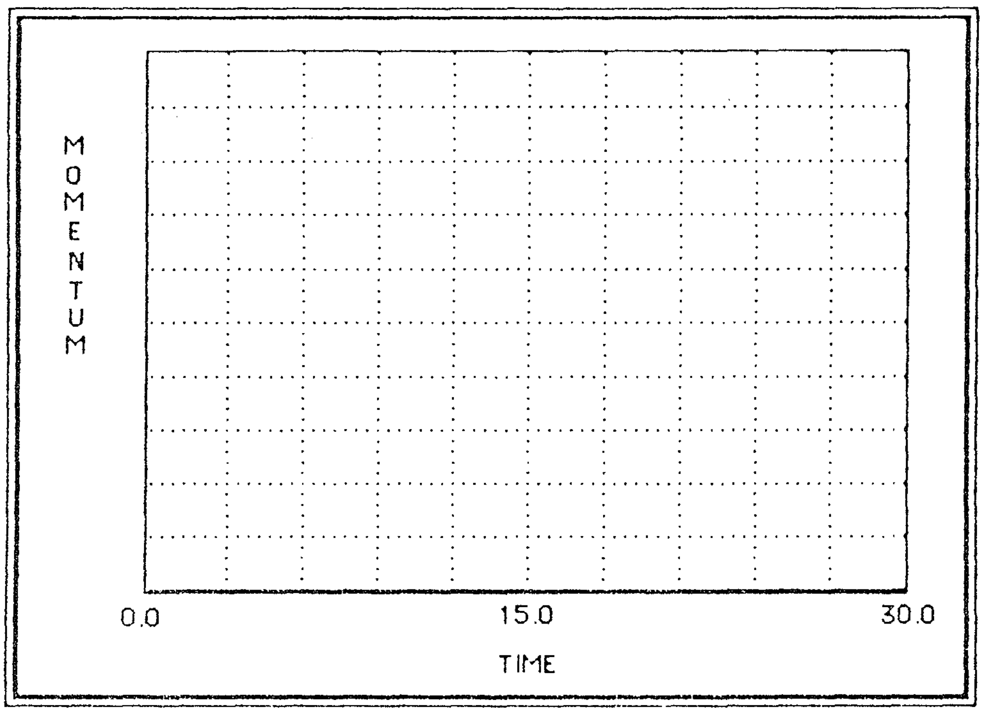

Figure 2: Blank graph for sketching the behavior of the sled's momentum over a period of 30 seconds.

Did your graph show momentum increasing linearly from zero at time=0 to 300 at time=15? At time=15, the 20 lb. force is removed and the sled's momentum remains constant at 300 forever. If you are an experienced system dynamicist, sketching the behavior for momentum in this one level system is very easy. If you are a student being exposed to physics for the first time, it is much more difficult. However, there is a tremendous amount of learning that occurs while trying to figure it out. The student is beginning to get an intuitive feel for the importance of integration and is learning about the structural relationship between force and momentum in a dynamic context.

Whether you are a system dynamicist or a student, you may not realize that you have just demonstrated Newton's first law, which states that "a body in motion tends to stay in motion and a body at rest remains at rest unless there is a net or unbalanced force acting on it to change its motion." As long as there is no net force applied to the sled, its momentum remains constant. This occurs prior to time=0 and after time=15 seconds. Having demonstrated Newton's first law, I would ask the student to test their intuition by making a few parameter changes, such as halving the applied force to experiment with how it effects the behavior of the system.

This next part of the lab session focuses on the technique of having the student try to synthesize the underlying structure of a system given a certain behavior mode.

Below is a graph of the sled's momentum over a period of sixty seconds. The 20 lb. force is still applied for the first 15 seconds. Notice that the momentum never reaches the same magnitude as in the first example and that after 15 seconds have elapsed, the momentum decreases sharply. What structural changes would you suggest to reproduce this qualitative behavior?

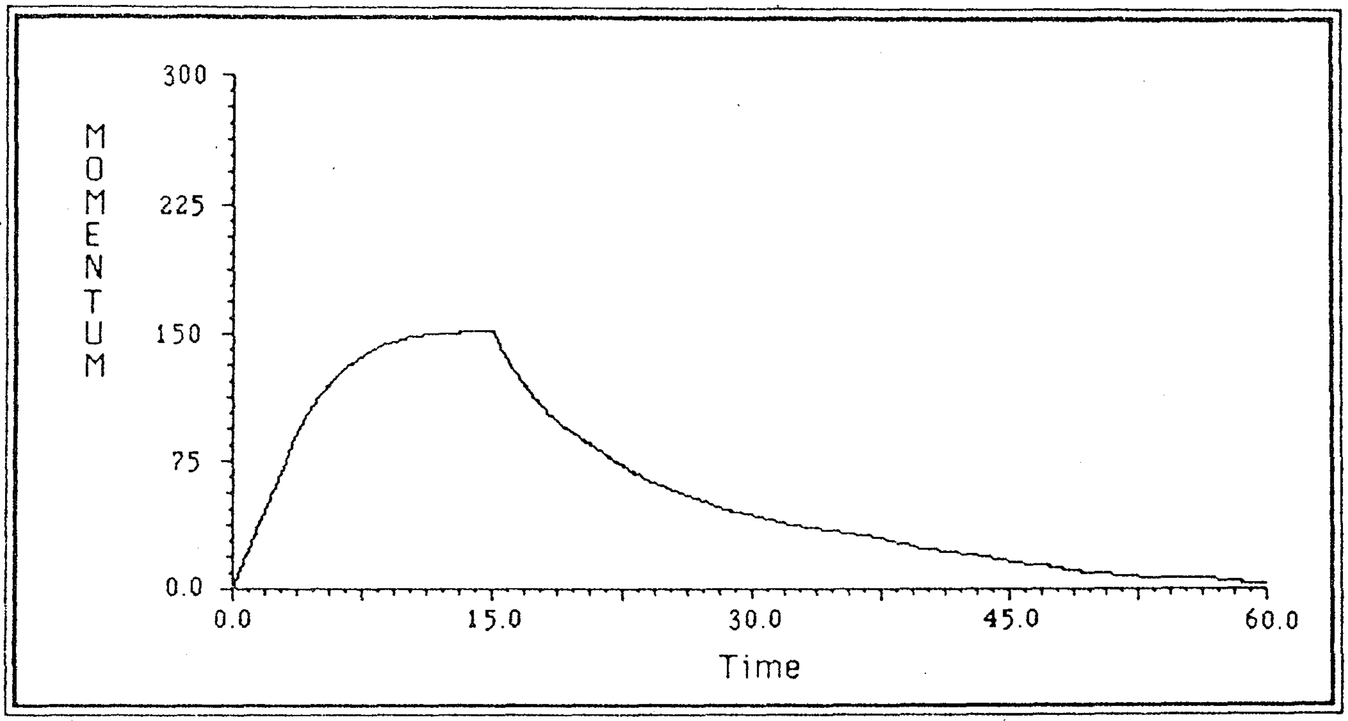

Figure 3: A plot of the sled's momentum over a sixty-second period.

What could cause the momentum of the sled to decrease and what would it depend on? Here is where "gremlins," those analytically-difficult-to-handle non-linear concepts like friction and air resistance, begin to play an important role. Having presented the "mystery," I would ask the students to draw on their own experience to deduce the structural changes required to solve the mystery. If they pushed a sled with a 20 lb. force for 15 seconds and let go, they know from experience that the sled's momentum and velocity (velocity is directly proportional to momentum) would begin to decrease. They also know that the reason the sled slows down is that there is friction and air resistance acting on the sled, even if they don't use those terms to describe it. Hopefully, they would have realized this on their own and then added an outflow from momentum with STELLA. As shown in Figure 4, I have modified the original structural diagram to include an outflow from momentum (DRAG), the mass of the sled, its velocity and an auxiliary for the fractional decrease in momentum from air resistance (FDMAR).

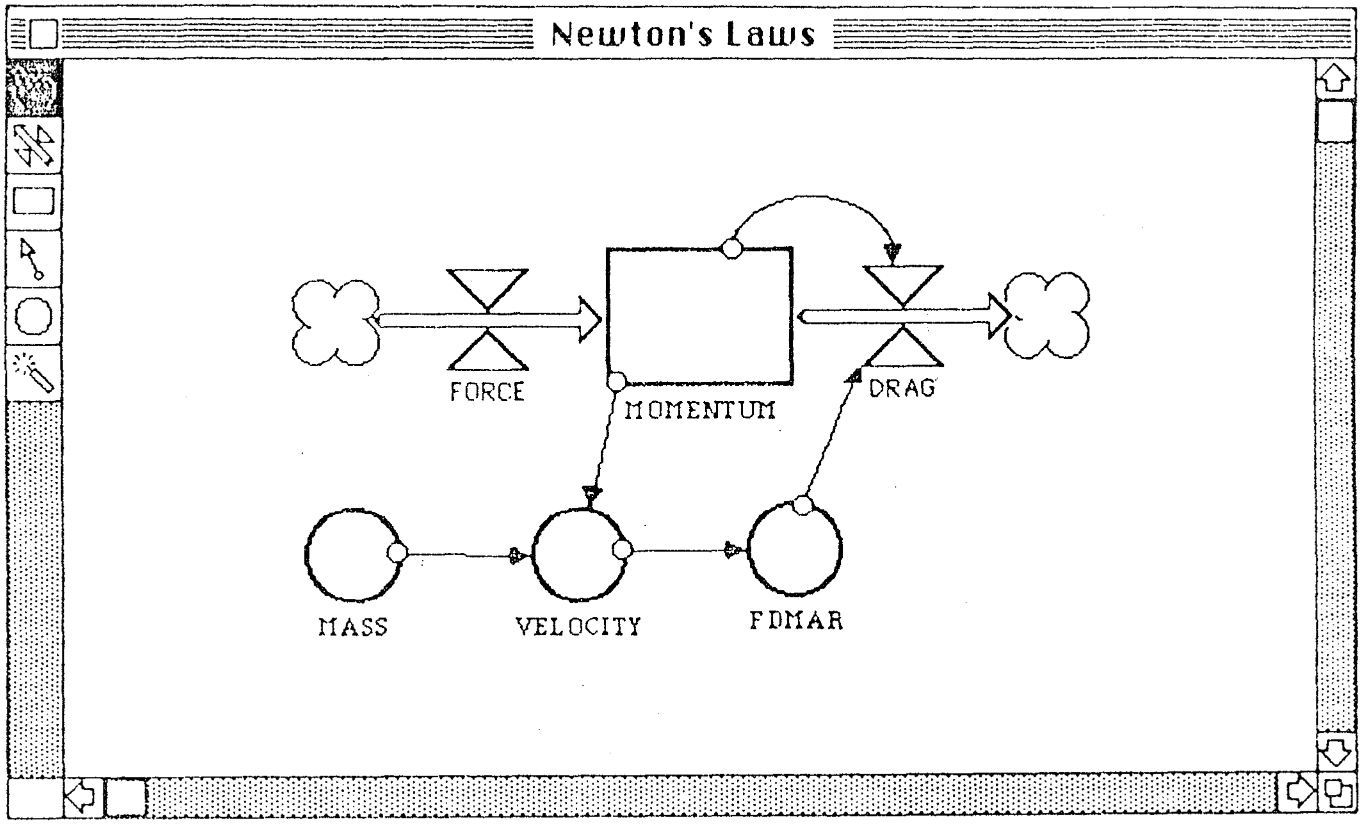

Figure 4: Structural diagram of momentum modified to include a drag force.

In attempting to reproduce the behavior, if the student added the outflow from momentum but did not parameterize the model to match the behavior exactly or did not know what to call the outflow, they still will have learned a great deal, i.e., 1) that there is an underlying structure responsible for the behavior and 2) that it is very easy to incorporate "gremlins," such as friction, air resistance, and other non-linear relationships in their analysis. Further, if they recognized that the drag force depended on the velocity of the sled, they will have added a feedback relationship -- another important learning experience.

In addition to plots of behavior over time, STELLA's scatter plot (x vs. y) capability provides a useful way of checking model generated behavior against empirical data. For example, Figure 5 illustrates the empirical relationship between velocity and the force due to air resistance.

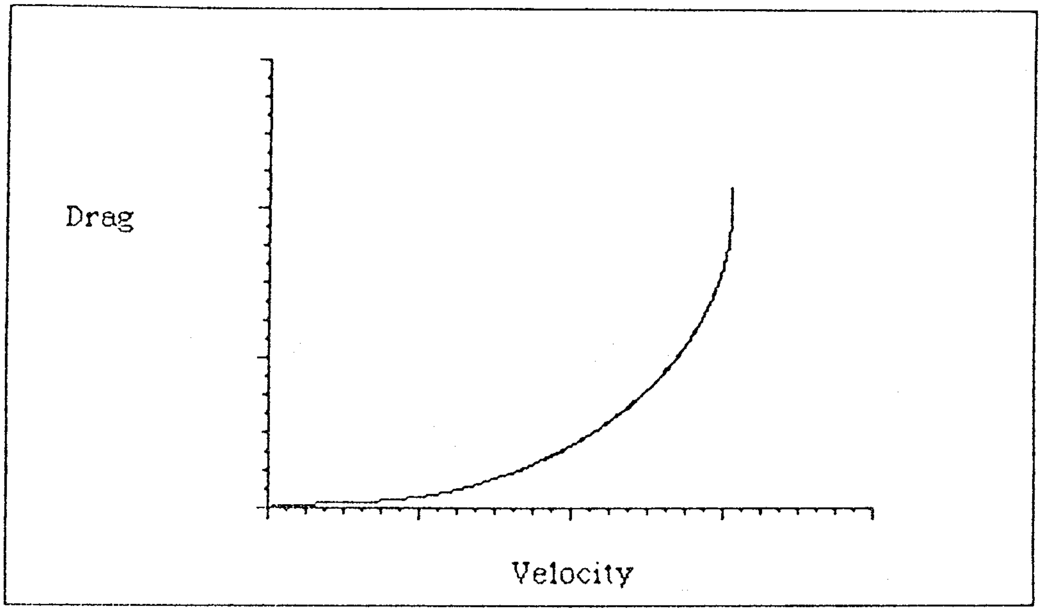

Figure 5: Graph depicting the relationship between the drag force due to air resistance and velocity.

The impact of air on a body travelling at a certain velocity produces a force that tends to decrease that body's momentum. The graph shown above illustrates a well known empirical relationship between this force, called drag, and the velocity of the body, where the force increases as the square of the velocity. (The numeric values of this curve depend on the shape and cross-sectional area of the body, i.e., whether it looks more like a rocket than a '55 Chevy has a significant influence on the *magnitude* of the resistance from the air but not the *shape* of the curve relating the drag to the velocity.) Whether or not the model reproduces this empirical relationship depends on the functional form of the rate equation for the drag force. For example, I have formulated the drag force, DRAG, as the product of momentum, MOMENTUM, and fractional decrease in momentum from air resistance, FDMAR:

DRAG = MOMENTUM * FDMAR

FDMAR could be made a graphical relationship that depends on velocity. The student then could experiment with different graphical relationships for FDMAR, such as curves A, B and C in Figure 6 below, and use a scatter plot to check the model generated behavior against the empirical data.

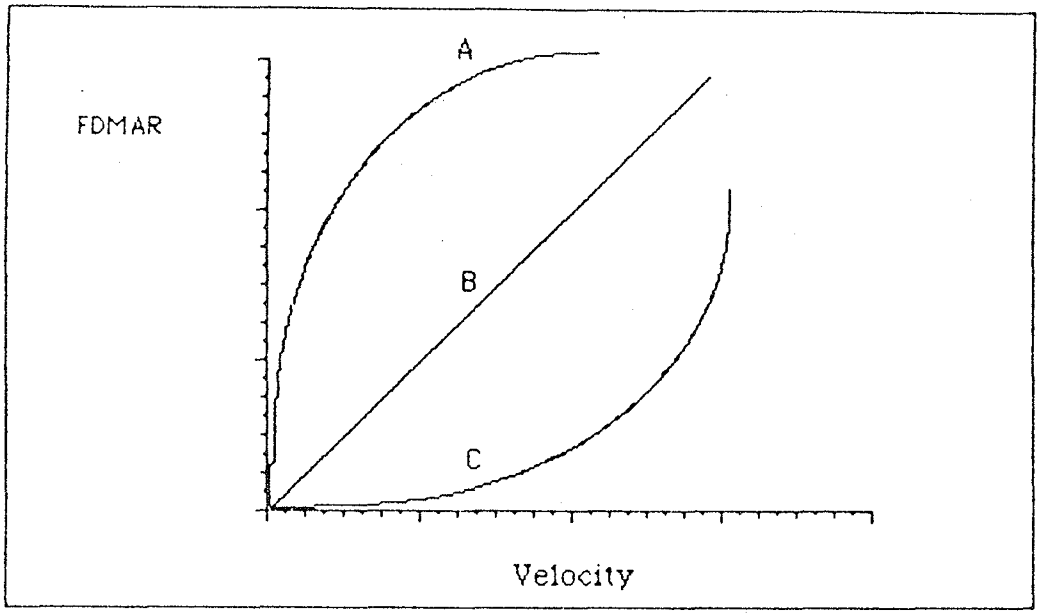

Figure 6: Graph illustrating three possible relationships between the sled's velocity and FDMAR.

The process of synthesizing structure by implementing and testing structural changes and parameter values (graphical relationships, constants, etc.) and comparing them to a reference mode facilitates the learning process in two ways. First, the process is *active* and involves the student in discovery of knowledge. This contrasts with the more traditional *passive* kind of textbook learning where much of the knowledge is presented rather than discovered. Second, the process is inherently motivating. The student is presented with a "mystery" in the form of a reference mode and asked to reproduce it. This challenges the intellect and offers an opportunity to be creative. (It is often the case that there are many "right" answers). In the beginning of the book the "mysteries" are relatively simple, such as the example of air resistance, but as the book progresses they become more complex.

A subtle advantage of the structural orientation of the laboratory sessions is its emphasis on understanding. In many physics and engineering courses, a lot of emphasis is put on getting the "right numerical answer." By contrast, if you look at the theories of Newton, Einstein or Maxwell, what they are describing is structure. To the extent that numeric precision is stressed over an understanding of the underlying process, the student is deprived of an important learning opportunity. A structural orientation can help to focus students' attention on developing understanding and insight rather than developing the manipulation skills associated with cranking out an answer.

Conclusions

System dynamicists have long since recognized the advantages of a systems approach to problem solving. The bad news has been that the limited availability of computers and the complexity of the technology required to apply the principles have impeded the use of "systems thinking" by such mass audiences as college level students. The good news is that many of these impediments are being eliminated. Recent advances in personal-computer technologies are providing a large non-technical audience with access to the power of the computer. At the same time, personal computers are rapidly being adopted as teaching/learning tools on college campuses all across the country. At Dartmouth College, 90% of all freshman and 86% of all upper classmen have purchased personal computers. The combination of rapidly advancing computer technologies and the large penetration of personal computers into the student market create a unique opportunity for achieving the goal of system's principles being integrated into the mainstream of college curricula. STELLA and the learning laboratory approach described in this paper represent one attempt at fulfilling this goal.

References

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