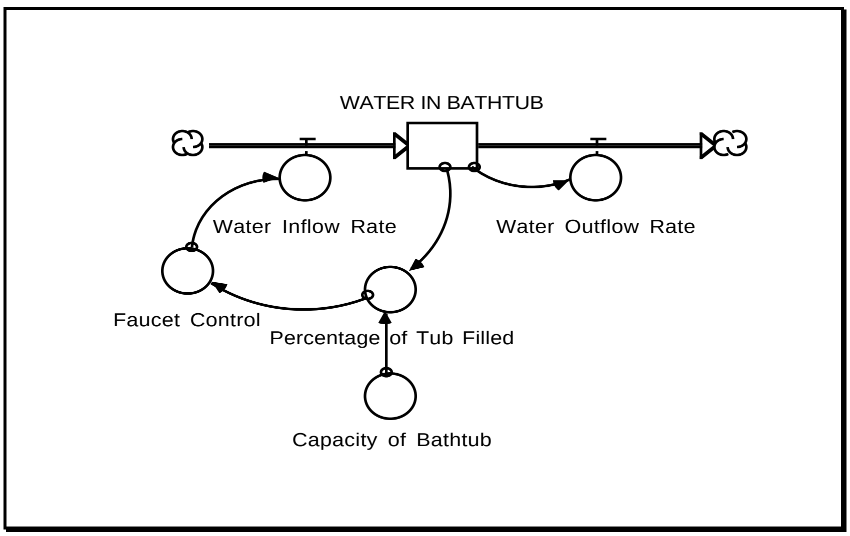
The First Three Hours

An Introduction to System Dynamics Through Computer Modeling



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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
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Table of Contents

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

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[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.

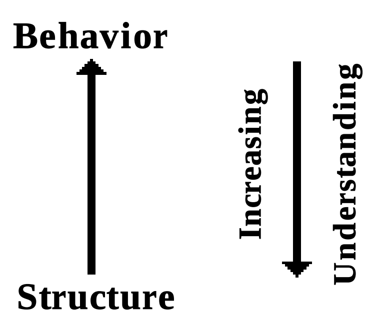


Figure 1: The Link Between Structure and Behavior

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:

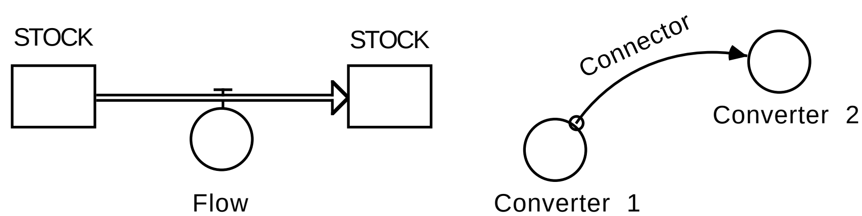


Figure 2: Representations of stock, flow, converter, and connector

[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.

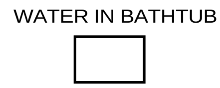


Figure 4a: STELLA Diagram of Stock Describing Water in a Bathtub

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.

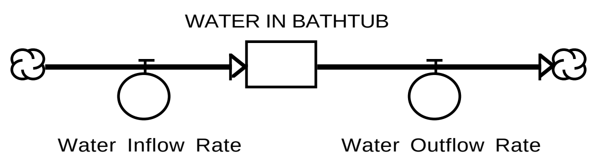


Figure 4b: STELLA Diagram of Stock and Flow Structure Describing Water in a Bathtub

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.

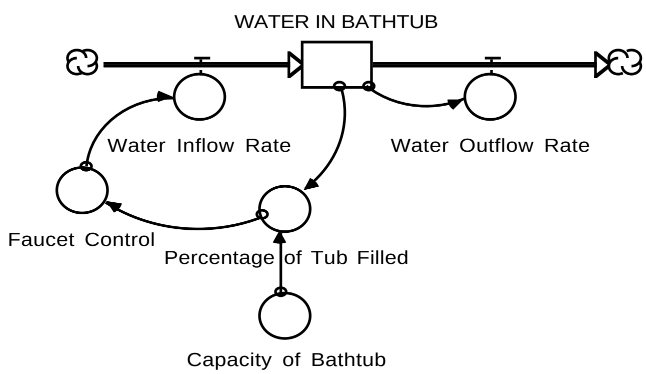


Figure 4c: STELLA Diagram of Inflow Control of Water in a Bathtub

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.

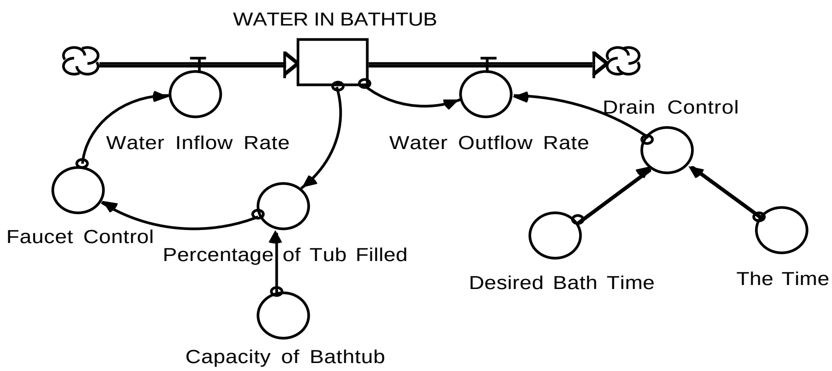


Figure 4d: STELLA Diagram of Water in a Bathtub

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.

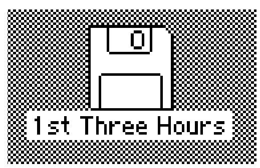


Figure 5: Macintosh Disk Icon

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.

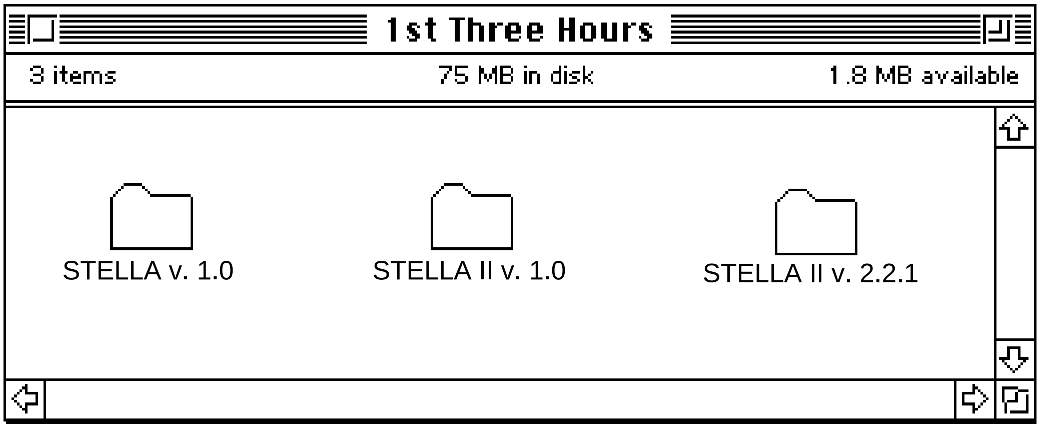


Figure 7: Window Showing Contents of First Three Hours Disk

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.

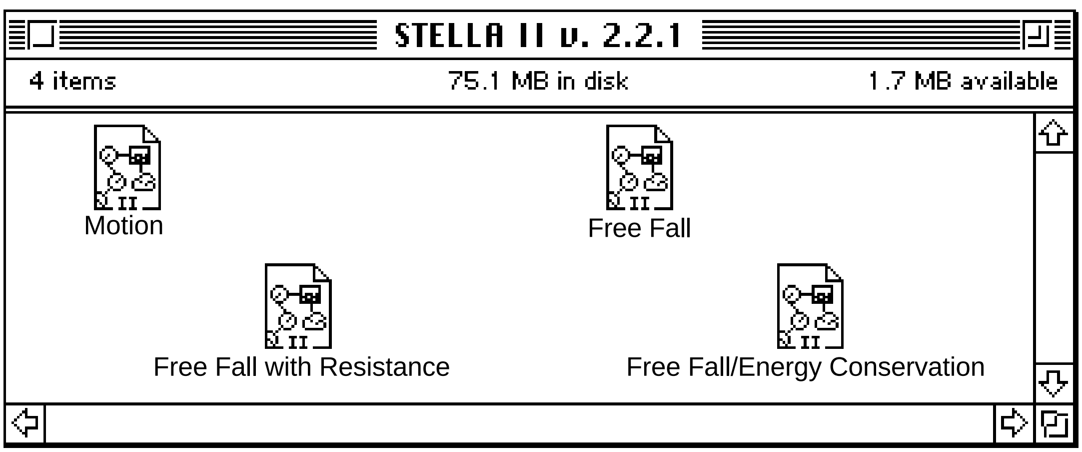


Figure 9: Macintosh Window Showing "STELLA II v. 2.2.1" Folder

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.

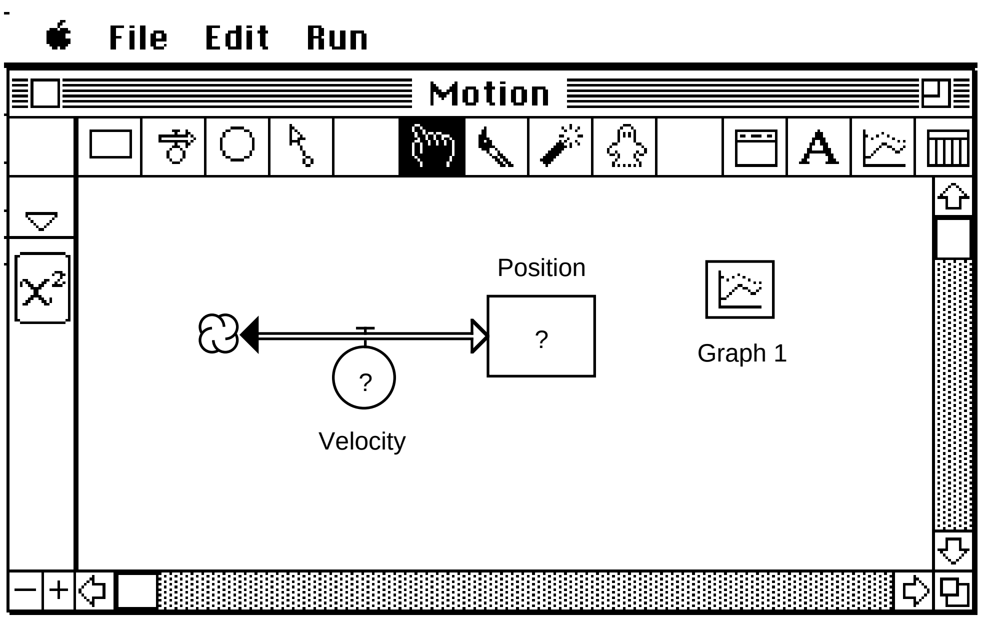


Figure 10: STELLA Diagram Window with Motion Model

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.

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***

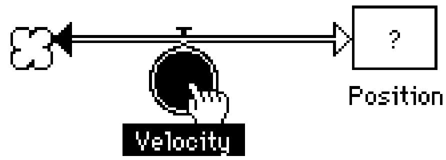


Figure 11: STELLA Diagram Showing How to Open Velocity Dialog Box

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

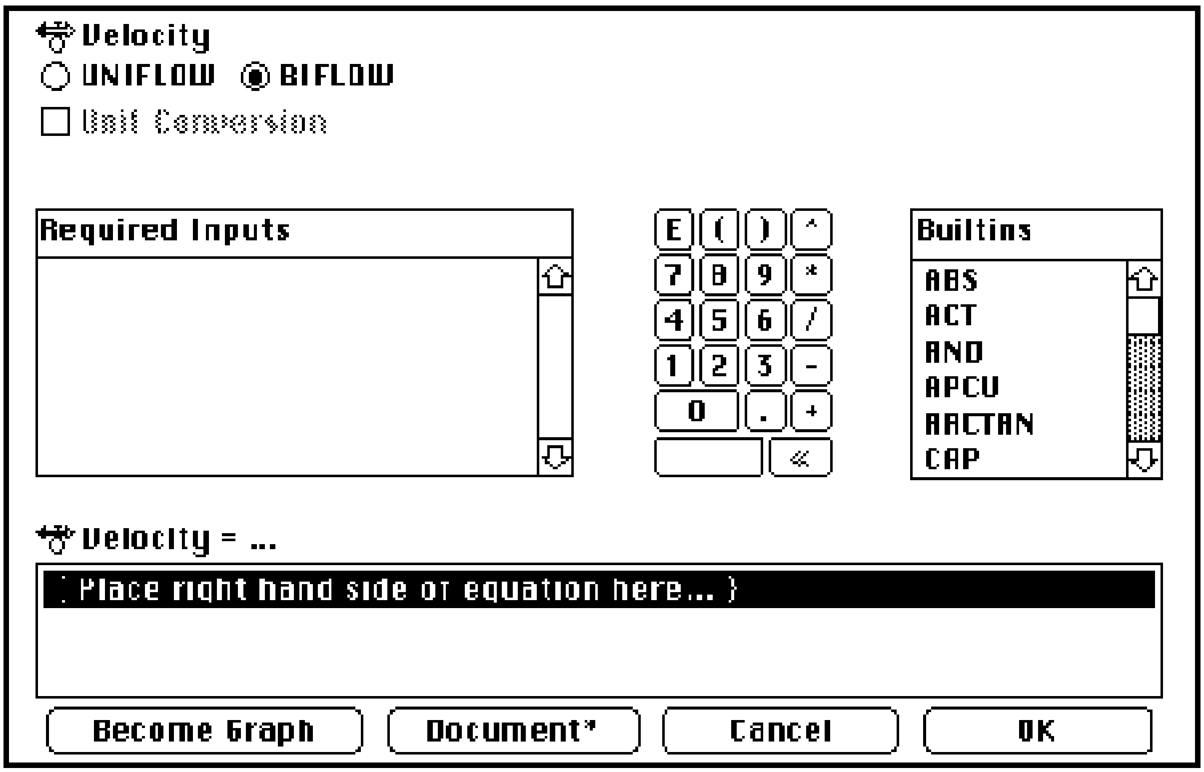


Figure 12: STELLA Dialog Box of Flow

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.**

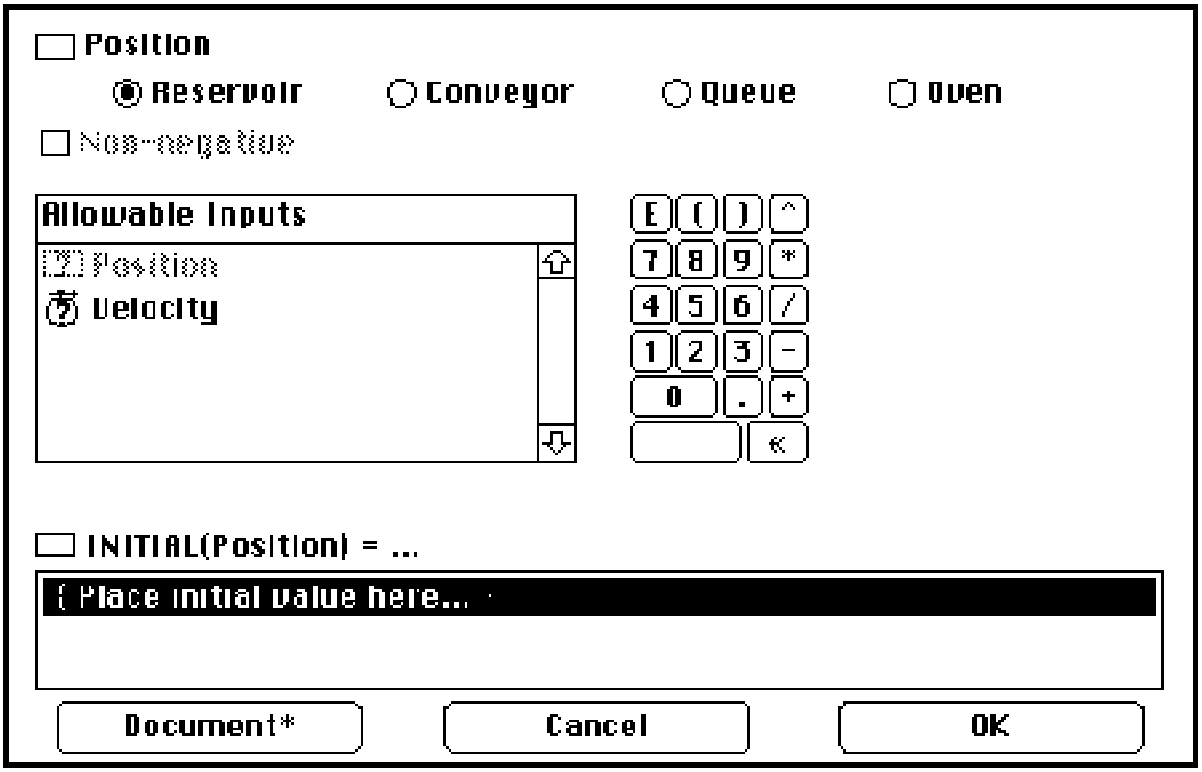


Figure 13: STELLA Dialog Box of Stock

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 <u>before</u> 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:

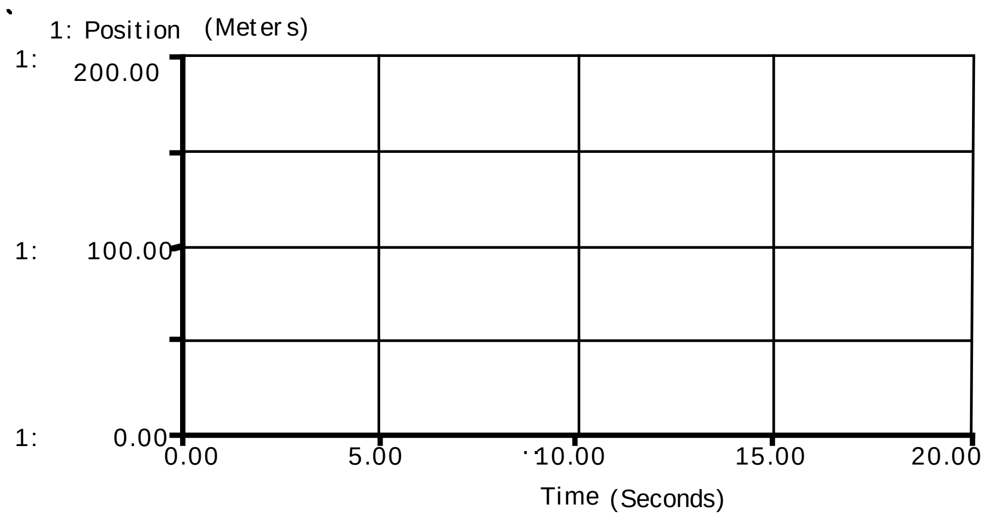


Figure 14: Mentally Simulated Behavior of Position over Time

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]

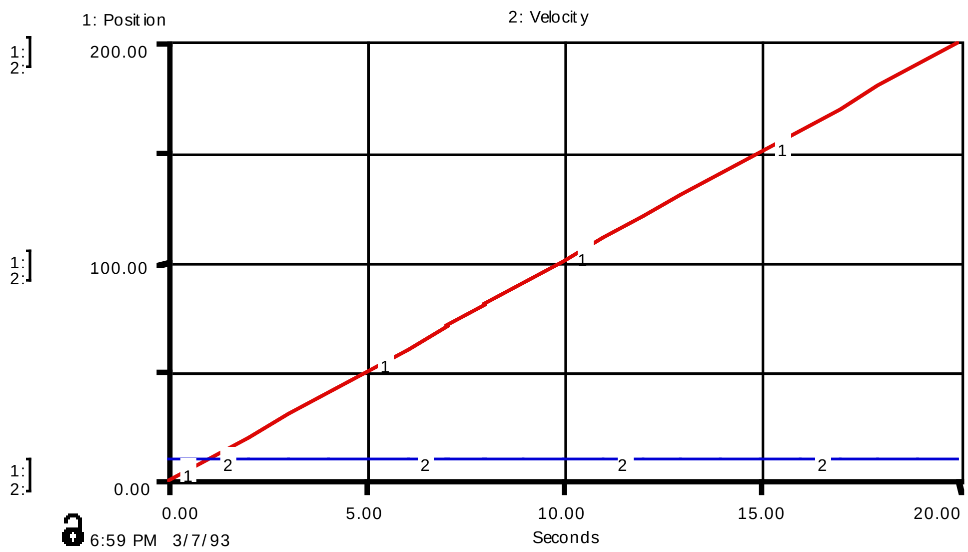


Figure 15: Graph of Position and Velocity over Time

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.

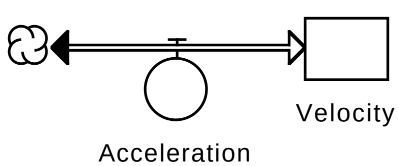


Figure 16: STELLA Diagram of Acceleration and Velocity

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.

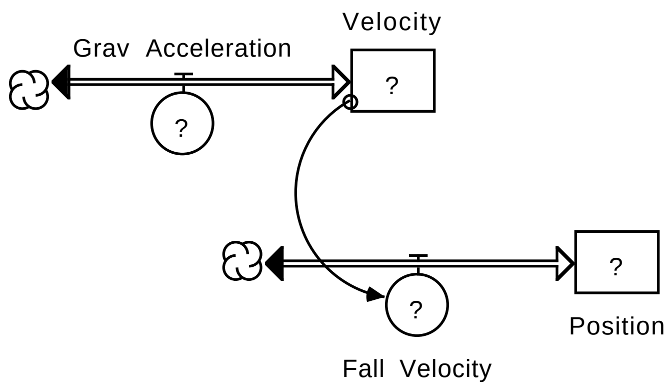


Figure 18: STELLA Diagram of Free Fall Model

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).

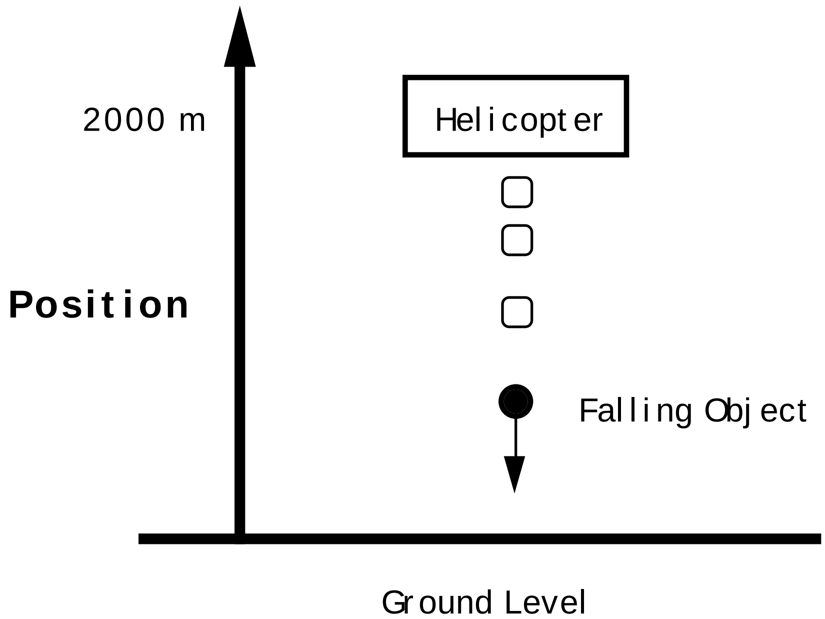


Figure 19: An object falling from a helicopter

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)**

To define the fall velocity:

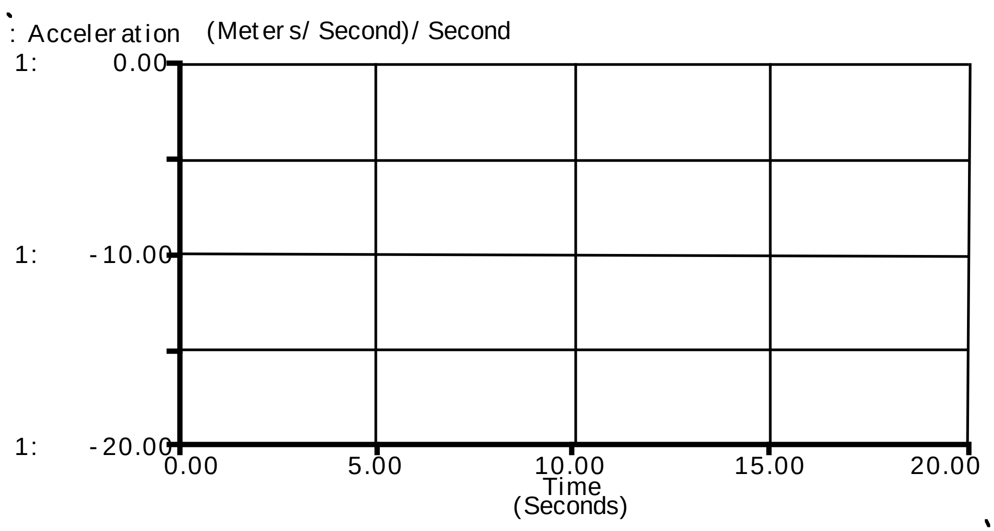
- **Double-click on the flow labeled *Fall Velocity***
- **Click on Velocity (under the required inputs list)**
- **Click on OK**

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



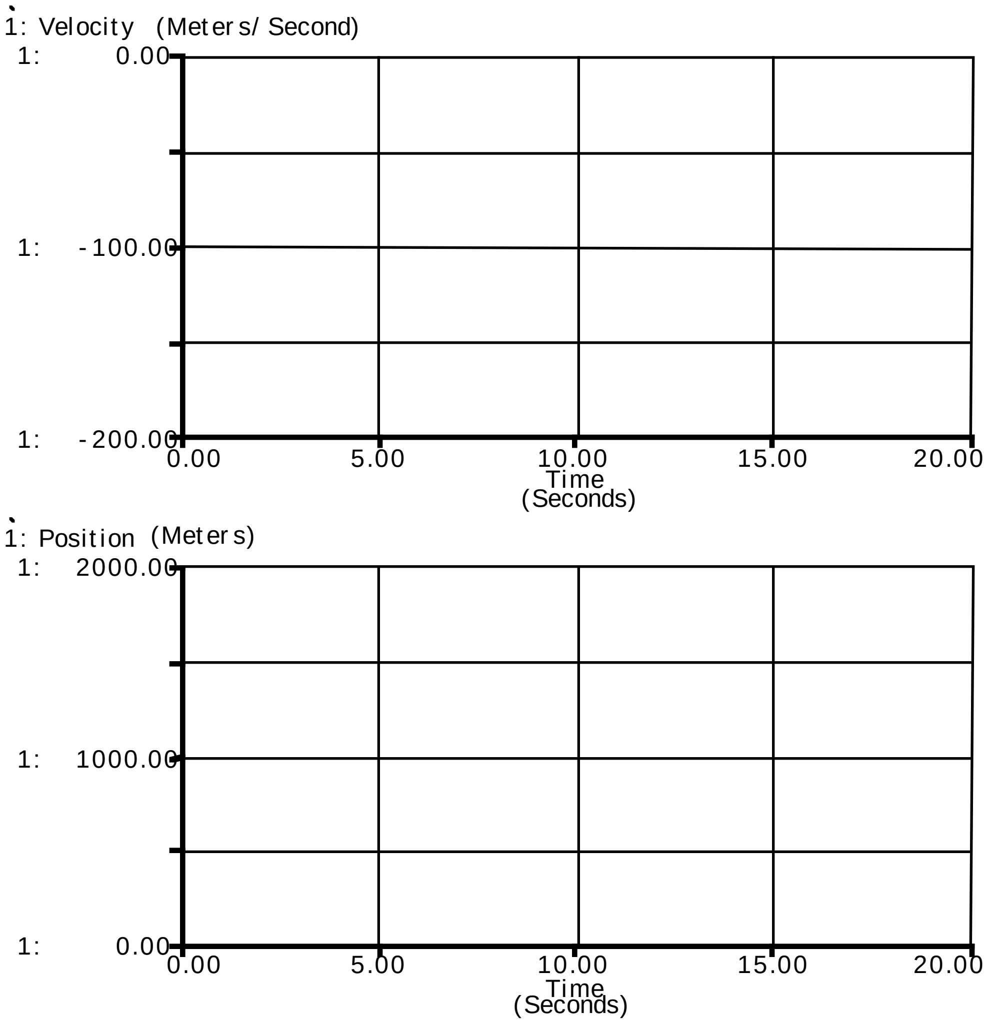


Figure 20: Mental Simulation of falling object model

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)

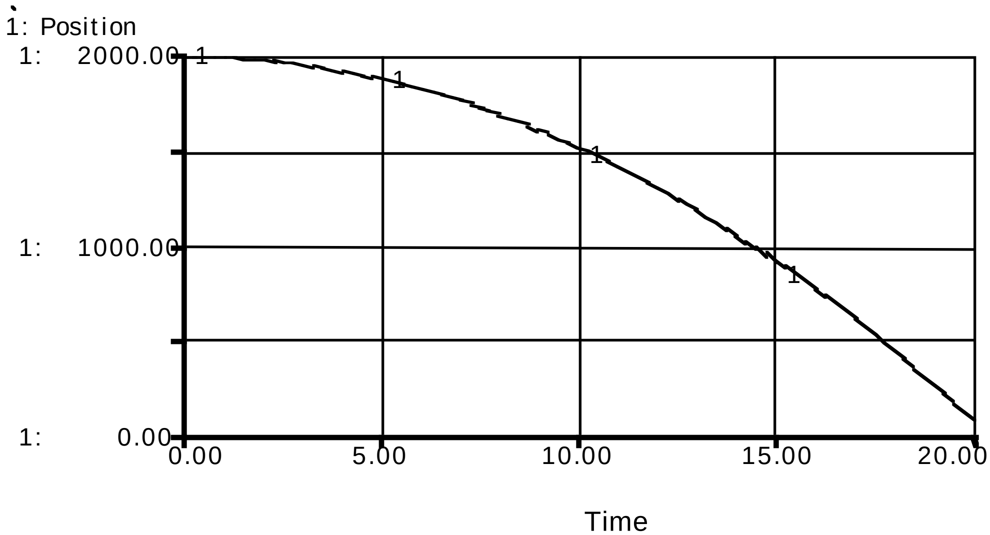


Figure 21: STELLA Graph of Position over Time

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.

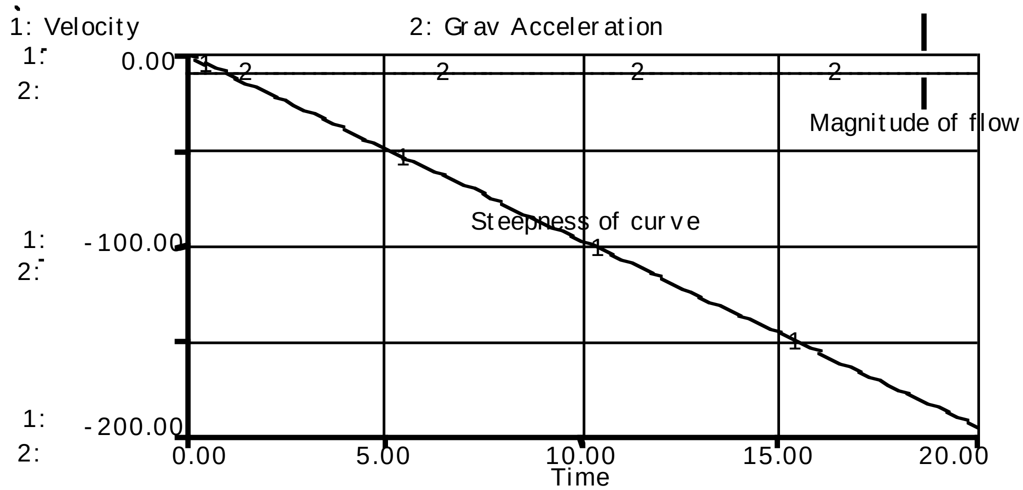


Figure 22: Computer-Simulated Graph of Acceleration and Velocity

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.

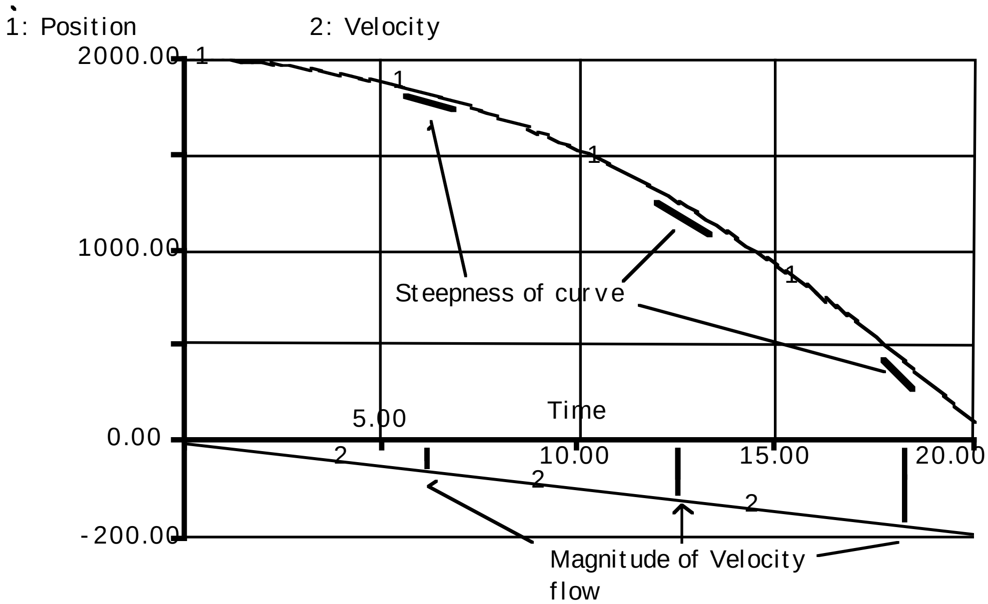


Figure 23: Velocity and Position Depicting Relationship between Stock and Flow

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?

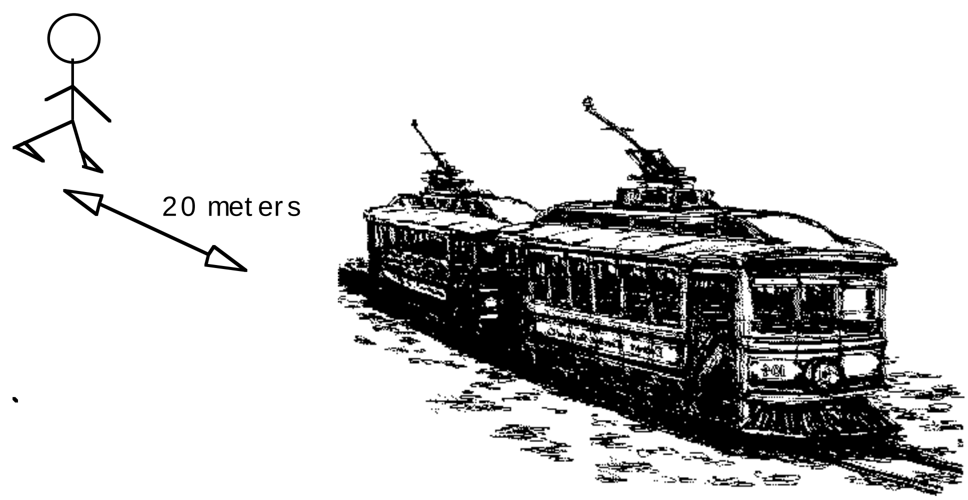


Figure 24: Illustration of "Catch a Train" Problem [6]

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.**

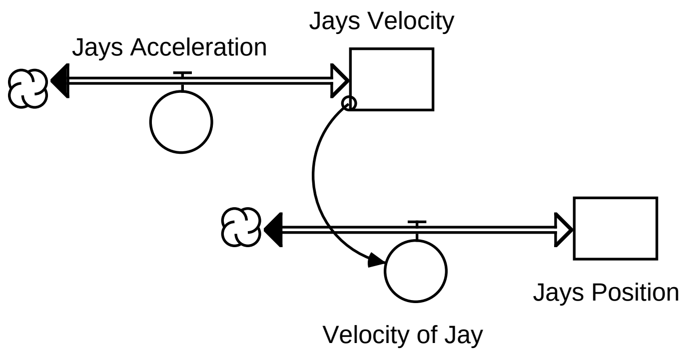


Figure 25: STELLA Diagram Depicting Structure of Jay in "Catch a Train"

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.

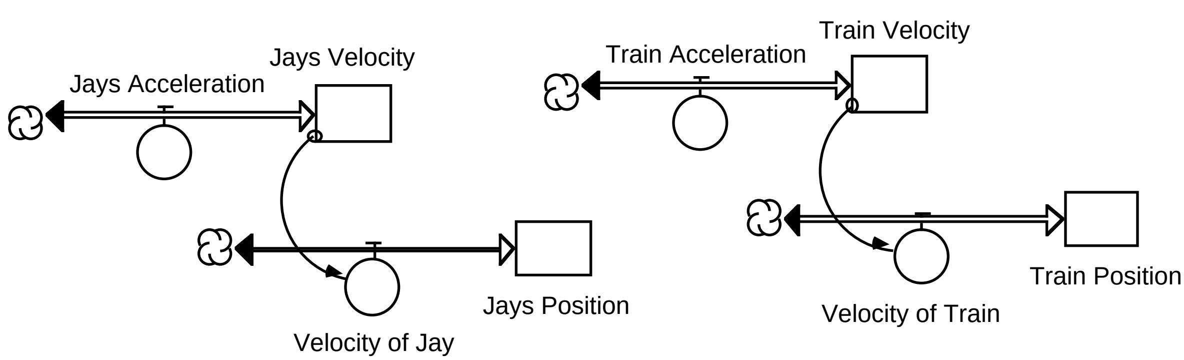


Figure 26: "Catch a Train" Diagram

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.

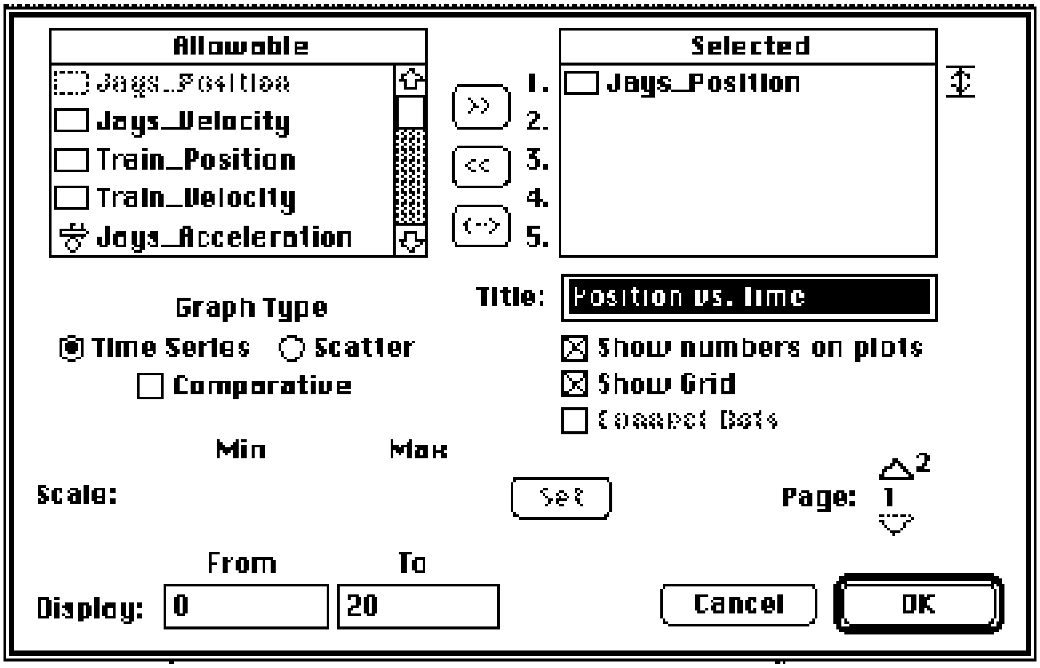


Figure 27: Graph Pad Dialog Box

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.

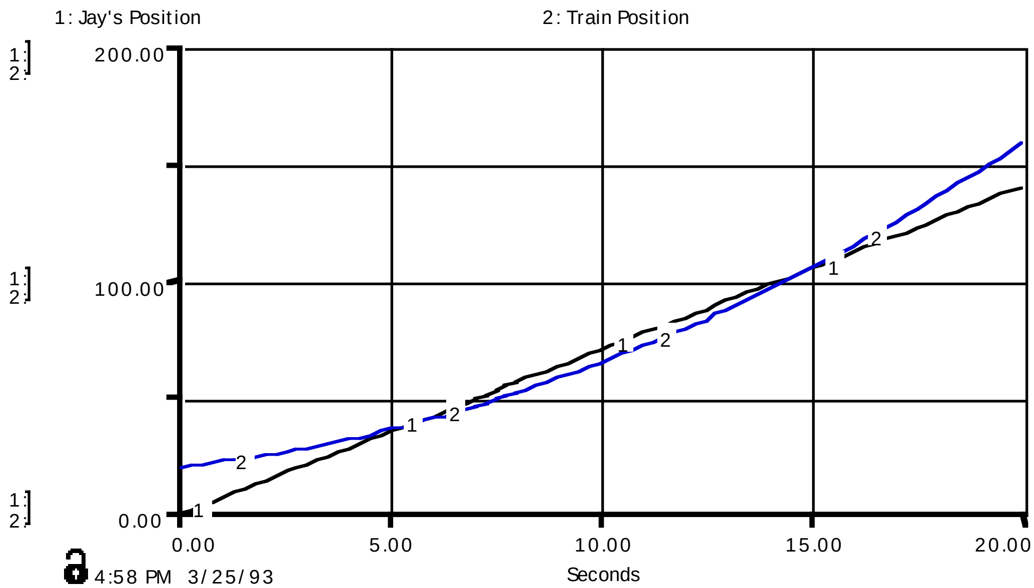


Figure 28: Simulated Graphs of Jay's and the Train's Position

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.

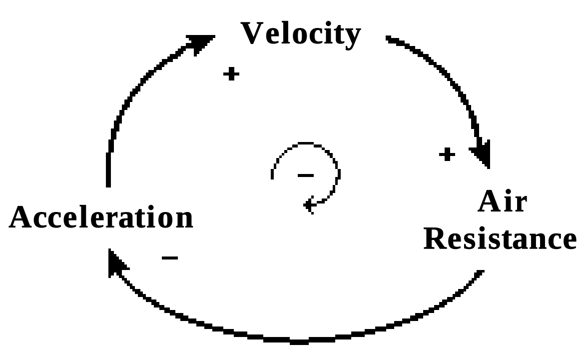


Figure 29: Causal Loop Diagram Illustrating Free Fall with Resistance

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.

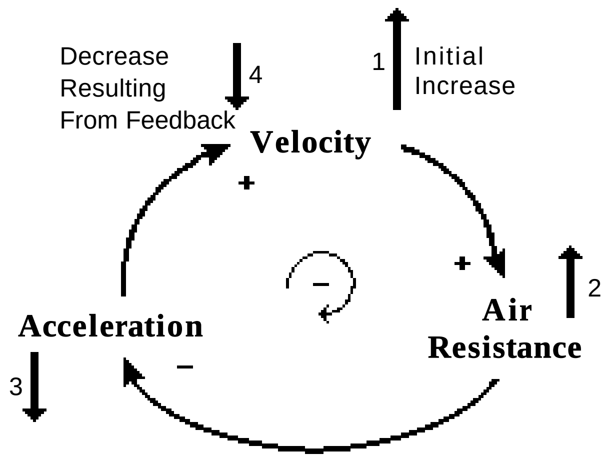


Figure 30: Causal Loop Diagram Illustrating Negative Feedback

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.

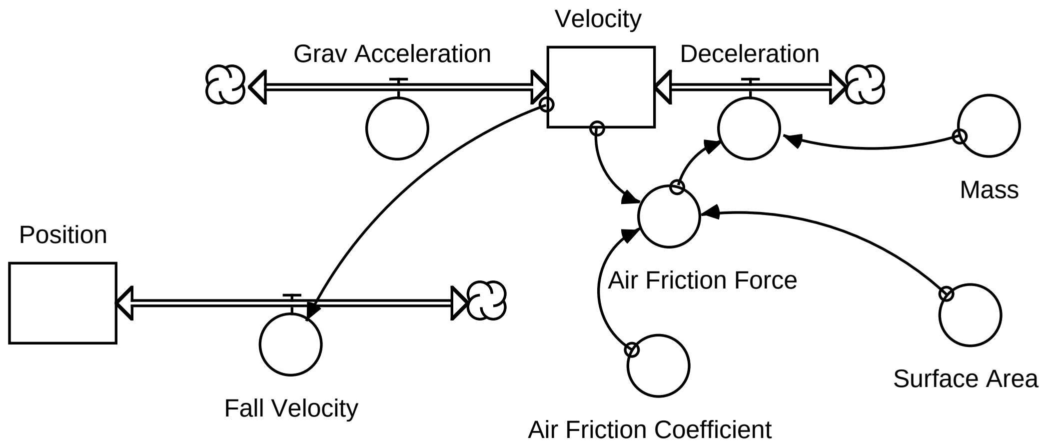


Figure 31: STELLA Diagram of Model Illustrating Free Fall with Air Resistance

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.

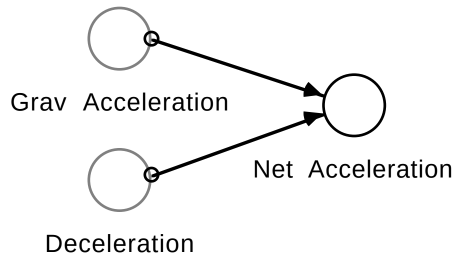


Figure 32: STELLA Diagram of Net Acceleration

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.

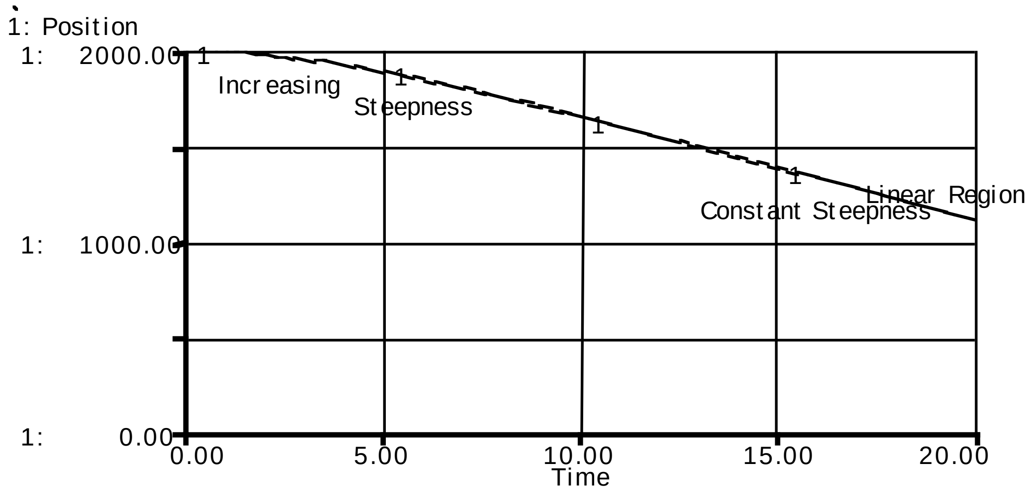


Figure 33: Graph of Position over Time

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.

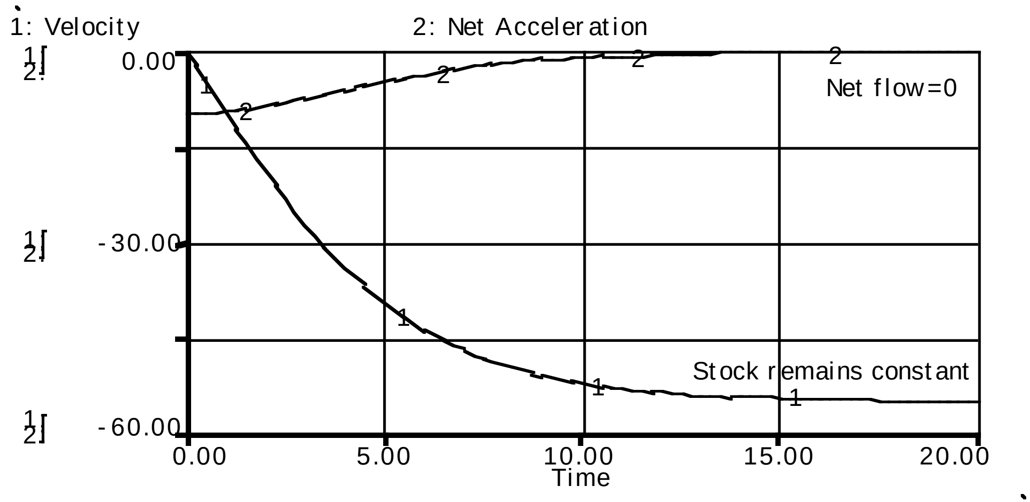


Figure 34: Graph of Net Acceleration and Velocity over Time

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**

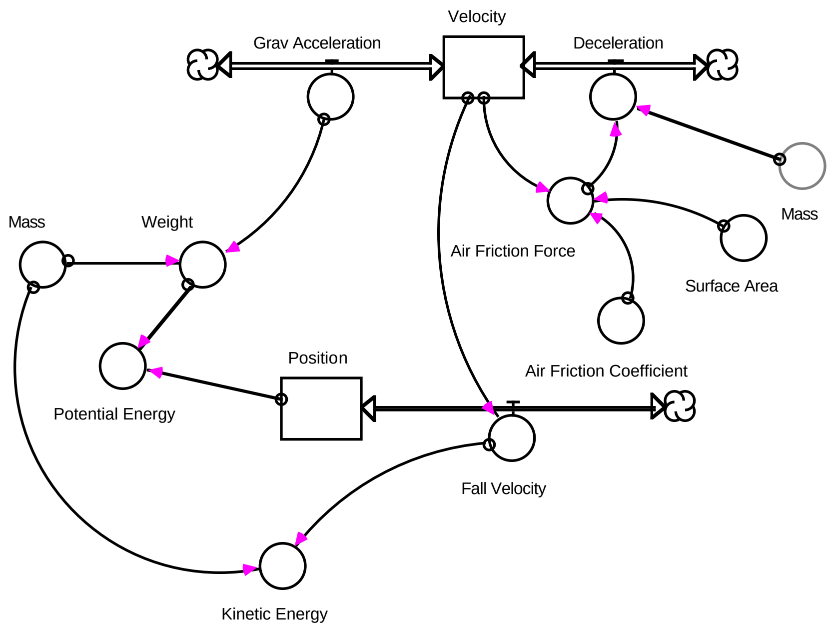


Figure 35: STELLA Diagram of Free Fall and Energy Conservation Model

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.

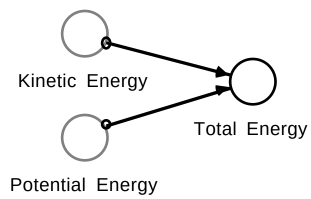


Figure 36: Total Energy Diagram

<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).

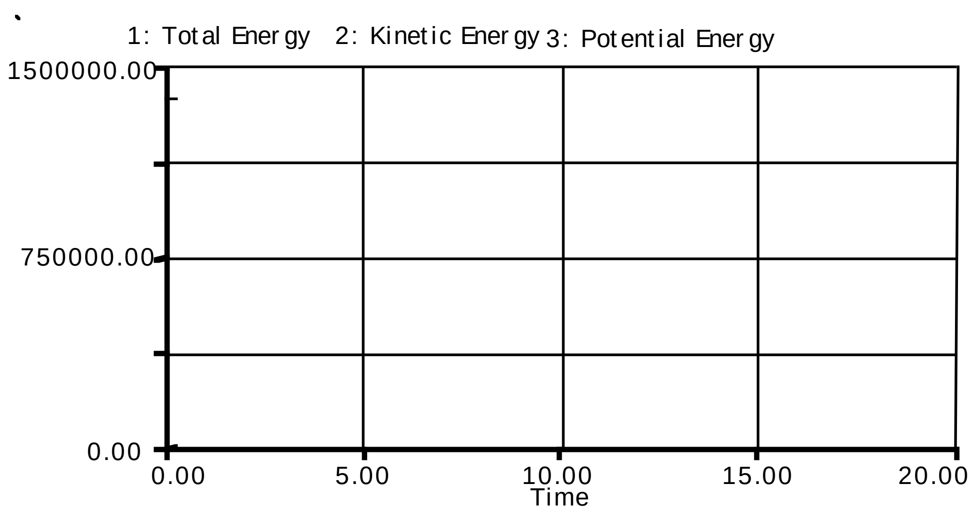


Figure 37: Mental Simulation of Total Energy, Kinetic Energy, and Potential Energy

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.

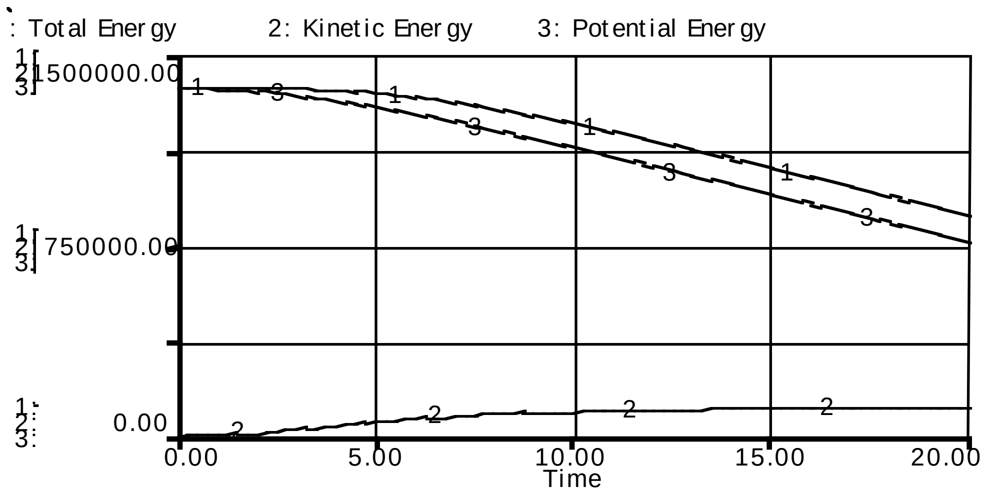


Figure 38: Graphs of Total Energy, Kinetic Energy, and Potential Energy

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.

[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.

$$Cl + O_3 \text{ -> } ClO + O_2$$
$$ClO + O \text{ -> } Cl + O_2$$

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:

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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