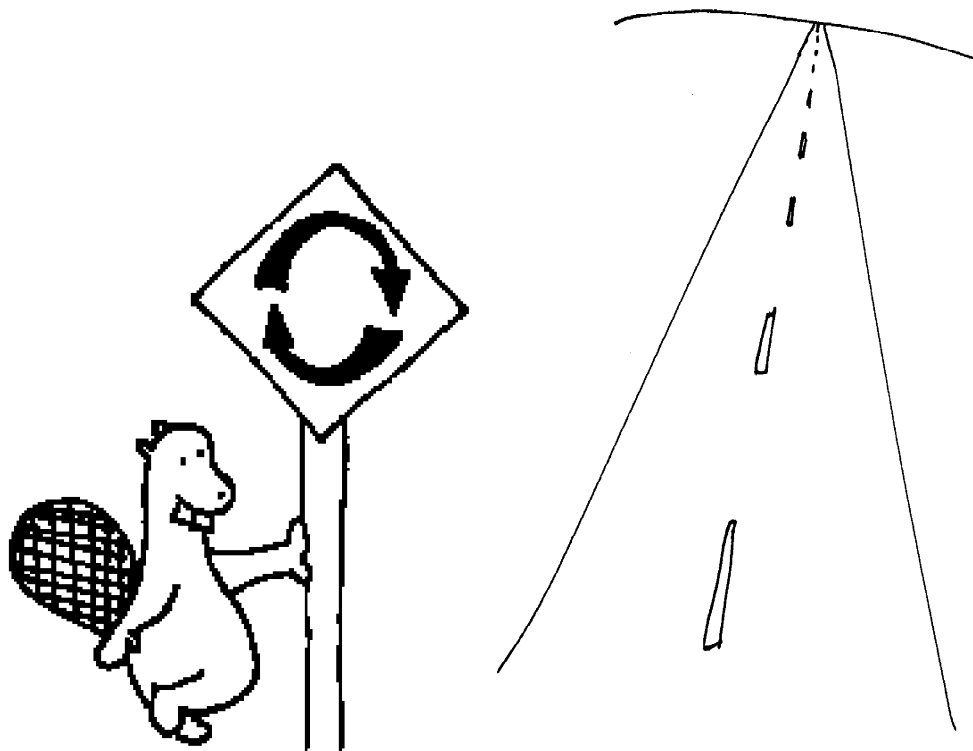


Road Maps **2**

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 2

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

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Welcome to Road Maps Two!



Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Two is the second in the series of chapters in Road Maps. In Road Maps Two, you will begin to model simple systems using STELLA II™ (Systems Thinking Educational Learning Laboratory with Animation) software. STELLA is an easy-to-use software package that allows the user to create and run models on the computer.

Road Maps Two continues to expand on the concept of feedback loops introduced in Road Maps One. It also introduces graphical integration and the concepts of levels and rates, as well as the relationship between feedback loops and levels and rates.

Topics Covered in Road Maps Two

Introduction to Computer Modeling

- *The First Step* (D-4694)

by Leslie A. Martin

- *Beginner Modeling Exercises* (D-4347-6)

by Leslie A. Martin

Feedback

- *Introduction to Feedback* (D-4691)

by Leslie A. Martin

Graphical Integration Exercises

- *Graphical Integration Exercises Part 1: Exogenous Rates* (D-4547-1)

by Alice Oh

Levels and Rates

- *Introduction to Computer Simulation*, Chapter 13 Levels and Rates

by Nancy Roberts et al.

Things You'll Need for Road Maps Two

Modeling Software

In order to complete Road Maps Two and subsequent Road Maps, you will need to have access to modeling software. The Road Maps guides and most papers included in Road Maps were written with the use of STELLA II for the Macintosh. STELLA II is currently available for both the Macintosh and the Windows platforms. If you have any questions about STELLA, contact High Performance Systems (see Appendix). Ask about prices for educational use.

Vensim, Powersim, and DYNAMO are other software programs designed for building system dynamics models. Vensim is produced by Ventana Systems, which offers a free introductory version of its software, Vensim PLE, that can be downloaded off the World Wide Web. See the Appendix for more information about obtaining Vensim and Powersim.

Notice written June, 2000:

We have written a guide on how to use Vensim modeling software for each section of the Road Maps series that involves computer modeling. Each guide is located in the back of the exercise document. When Chapters 1-9 of the Road Maps series were written, STELLA software was the most common beginner modeling program available. Now you may choose from a number of system dynamics modeling software packages. If you would like more information on Vensim, please go to <http://www.vensim.com>. A free version called Vensim PLE is located there.

For more detailed information on using Vensim software in the Road Maps series, please refer to the paper titled: "Vensim Guide (D-4856)" in the Appendix section at the end of Road Maps.

From now on as additional papers for the Road Maps series are written, the Vensim software will be used exclusively for modeling exercises.

A Computer

To run the latest version of STELLA, STELLA 5.0, on a Macintosh, you will need an Apple Macintosh computer (68020 processor or higher) with at least 8 MB of RAM, a 12 MB hard disk and System 7.1 or higher. To run STELLA 5.0 for Windows you will need an IBM PC-compatible computer with a 486-class

processor running Windows 3.1 or greater. You will need at least 8 MB RAM, a hard disk with a least 16 MB of free space. Previous versions of STELLA have similar requirements.

In either case, if you plan on continuing to model, it may be a good idea to have access to a computer with more memory, hard disk space and a faster processor.

Books

You will need chapters from the following book for Road Maps Two. Selected material from this book will also be used in later Road Maps, and is available for download in electronic format from the SDEP server.

Roberts, Nancy, 1983. *Introduction to Computer Simulation*.
Portland, Oregon: Pegasus Communications, 562 pp.

How to Use Road Maps Two

Road Maps Two explores several topics in system dynamics through selected readings and exercises. Before each reading or exercise is a short description of the reading and its most important ideas. After each reading or exercise, we highlight the main ideas before moving on.

Each chapter in Road Maps contains readings that introduce and strengthen some of the basic concepts of system dynamics. Other readings focus on practicing the acquired skills through various exercises or simulation games. Most of the chapters conclude with a prominent paper from the literature in the system dynamics field.

We present the fundamental concepts of system dynamics as *System Principles* in Road Maps. These principles are enclosed in boxes that highlight them from the rest of the text to emphasize their importance. The progression of system principles in Road Maps allows you to revisit each principle several times. Each time a principle is revisited in Road Maps, you will build upon your previous understanding of the principle by learning something new about the principle. The system principles are the core of Road Maps around which the readings, exercises, and papers are built.

As part of the spiral learning approach that we use in Road Maps, many concepts will be briefly introduced early on and then explained later in greater detail. Road Maps contains a number of series of papers that are spread out over successive chapters. Each of these series focuses on a specific topic in system dynamics or the developing of a particular skill. The series start out with a simple paper, and progress to further develop the idea in subsequent chapters.

Now let's get started!

Introduction To Computer Modeling

The first two readings in Road Maps Two will get you started with the basics of modeling in STELLA. You don't need any experience using STELLA or a computer before. We'll help you one step at a time, from turning on the computer to actually creating a working model in STELLA.

If you would like to use another modeling software as you study Road Maps, please take some time now to get acquainted with your software. A beginner's tutorial for Vensim PLE¹ is included at the end of Road Maps Two. You are also encouraged to read through the Vensim PLE documentation that is available on the Ventana website. The documentation guides the reader through a series of interesting tutorials, providing an overview of system dynamics and a thorough introduction to the Vensim software. After you have worked through the tutorials or experimented with your software, please proceed with Road Maps by reading *The First Step*, converting between STELLA and your modeling software as you go along.

- *The First Step*²

by Leslie A. Martin

The First Step goes over the basics of system dynamics and introduces key terms and concepts. The tutorial will guide you through creating your first models in STELLA and will help you with using the software itself.

Please read *The First Step* now.

After reading *The First Step*...

The First Step covered a great deal of important material. It helped you to construct, analyze, and test two one-level multiple-rate systems. It also explained the concepts of stocks and flows and the fundamental role they play in building models of systems.

Before you continue, it is important to note that while *The First Step* uses the terms **stocks** and **flows**, the terms **levels** and **rates** can also be used. 'Stocks' and 'levels' are used interchangeably in system dynamics, as are 'flows' and 'rates'. Also, the two pairs of terms are always used in conjunction with each other. In other words, you should use 'stock' and 'flow' together, or use 'level' and 'rate' together, and not mix the terms, as in 'stock' and 'rate'. Speaking of levels and rates...

¹ Nelson Repenning, 1997. *Formulating Models of Simple Systems using VENSIM PLE* (D-4697), System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, August, 20 pp.

² Leslie A. Martin, 1997. *The First Step* (D-4694), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, July 24, 59 pp. Based on *The First Three Hours* (D-4230-4) by Matthew C. Halbower.

**System Principle #2:****Levels and Rates are fundamental to loop substructure.**

Look at the final population model in Figures 34 on pages 51 in *The First Step*. Note that the level (“**Population**”) and rates (“**births**” and “**deaths**”) are the primary components of structure. Levels and rates are fundamental to system structure.

System Principle #2 is important to understand because all system dynamics models use levels and rates as loop substructure. The distinction must be made between this principle and System Principle #1, which states that feedback loops are the building blocks of systems. Just as feedback loops are the building blocks of systems, levels and rates are the building blocks of feedback loops.

In order to develop more familiarity with the STELLA software, please take some time now to look over the STELLA tutorial that came included with the software: *Getting Started with STELLA II: A Hands-On Experience*.

The reading uses a predator-prey system to incorporate instructions for building a one-level model, entering the equations, and running the model.³ The process of building and running the model should be quite similar to what you have just done in *The First Step*. *Getting Started with STELLA II*, however, will also

³ The iThink tutorial, on the other hand, will guide you through a management flight simulator. The iThink software is the corporate version of the STELLA software.

introduce several unique features of the software, such as using and creating high-level maps and sub-models.

In addition to the tutorial, High Performance Systems also provides several folders of systems modeled with the STELLA II software. A wide range of models are also included with Vensim PLE. We encourage you to look at the models to see some of the many applications of system dynamics.

The next paper will help you develop your modeling skills.

- *Beginner Modeling Exercises* ⁴

by Leslie A. Martin

Beginner Modeling Exercises will give you a chance to test yourself on what you've learned so far in Road Maps One and Two. The modeling exercises ask you to identify stocks and flows, distinguish between inflows and outflows, set up stock-and-flow diagrams, and translate short scenarios into equations for the stocks and flows.

Please read and complete *Beginner Modeling Exercises* now.

After completing *Beginner Modeling Exercises*...

The modeling exercises are a good review of what was introduced in Road Maps One and Two to this point. It is important to be able to do all these exercises and, if necessary, to review some of the material before continuing to work through Road Maps.

⁴ Leslie A. Martin, 1997. *Beginner Modeling Exercises* (D-4347-6), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, September 5, 42 pp.

**System Principle #3:****Levels and Rates are not distinguished by units of measure.**

Units do not determine whether a variable is a level or a rate. In the *Beginner Modeling Exercises*, “velocity” appears in two different systems. In the example in which Randy trains for the Boston marathon, “velocity” is a rate that increases the distance he travels. In the example of a Ferrari accelerating at a green light, “velocity” is a level, the accumulation of the sports car’s acceleration. In both cases, “velocity” is in units of distance per time.

System Principle #3 is important in modeling because it tells us not to assume that a particular component of a system is a level or a rate just from looking at its units of measure. Can you identify any other real-life components that can be classified as either a level or a rate?

The next paper will use simple system dynamics models to develop your understanding of feedback processes.

- *Introduction to Feedback*⁵

by Leslie A. Martin

⁵ Leslie A. Martin, 1997. *Beginner Modeling Exercises* (D-4347-6), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, September 5, 42 pp.

Introduction to Feedback will teach you how to trace causal connections. You will learn how to differentiate between positive and negative feedback loops.

Please read and complete *Introduction to Feedback* now.

After completing *Introduction to Feedback*...

You should now be able to distinguish between positive and negative feedback loops. You have seen several simple feedback structures that you should start to recognize in other people's models and later incorporate into your own models.

Graphical Integration Exercises

Computer programs such as STELLA II are a very powerful tool in simulating systems. However, we must also be able to estimate the system behavior without using a computer. The next reading introduces the method of graphical integration.

- *Graphical Integration Exercises Part 1: Exogenous Rates*⁶

by Alice Oh

This is the first in a series of papers on graphical integration. It explains the methods of graphical integration for systems with constant and step function rates. You will be asked to do several exercises; you can check your answers in the appendix.

Please read *Graphical Integration Exercises Part 1* now.

After completing *Graphical Integration Exercises Part 1*...

The method of graphical integration is very useful in estimating the behavior of many systems. This paper covered systems with constant positive and negative rates as well as step function rates. It is necessary to understand this method fully before moving to the next paper in this series.

⁶ Alice Oh, 1995. *Graphical Integration Exercises Part 1: Exogenous Rates* (D-4547-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, December 1, 19 pp.

Levels and Rates

- *Introduction to Computer Simulation*,⁷ Chapter 13 Levels and Rates
by Nancy Roberts et al.

Chapter 13 of *Introduction to Computer Simulation*, “Levels and Rates,” explains stock-and-flow diagrams as a progression from causal-loop diagrams. The equations that correspond to the variables in stock-and-flow diagrams will also be explained. The equations in Chapter 13 are written in the DYNAMO simulation language. DYNAMO is the equation-based computer simulation language that was used in system dynamics between 1963 and 1986, so we will provide help with understanding DYNAMO equations and converting DYNAMO equations to STELLA.

Please begin Chapter 13 of *Introduction to Computer Simulation* now.

The following tips may help you:

Read Chapter 13 from page 223 up to and including the top of page 229. Do all of the exercises and read through all of the examples.

Modeling Figure 13.11 on STELLA

Read “Simulation, Structure, and Behavior” from page 229 up to and including the first paragraph on page 231.

- Open a new STELLA file.
- Place a stock (□) in the middle of your screen and rename it “Population.”
- Place a flow (⌘) to the left of the “Population” stock and have it flowing into it. Rename the flow “births.” Your model on the screen should now look like Figure 13.11.


Defining Figure 13.11 in STELLA


Read from the second full paragraph on page 231 up to Exercise 5 on page 234. Example 2 calls for simulation of the model you are building. The book

⁷ Roberts, Nancy, David Andersen, Ralph Deal, Michael Garett, and William Shaffer, 1983. *Introduction to Computer Simulation: A System Dynamics Approach*. Portland, Oregon: Productivity Press. 562 pp.

derives and uses DYNAMO equations to do this. Follow the directions below to convert the DYNAMO equations to STELLA.

Look at the DYNAMO equations in the middle of page 233.

- To convert “births” = 100 into a STELLA equation, toggle the globe in the upper-left-hand corner () so that it becomes \times^2 . Question marks should appear in the stock and flow.
- Double-click on “births” and the dialog box will appear on your screen. Type “100” as the equation for “births”. (Units of “births” are in people per year.)
- Click on the *Document* button. In the document box, type “100 babies are born every year in the kingdom of Xanadu.” Click OK.
- Double-click on the “Population” stock and type “5510” (the initial population of Xanadu).
- Click on *Document*. Type “The initial population of Xanadu is 5510 people.” Click OK.

To view the equations for the model you’ve just created, click on the arrow () above the \times^2 icon. Then select *Equation Prefs* under the Edit menu. Once the *Equation Prefs* dialog box appears on your screen, click on *Show Documentation*. Click OK. The following equations will appear:

Population(t) = Population(t - dt) + births * dt

INIT Population = 5510 {people}

DOCUMENT: The initial population of the kingdom of Xanadu is 5510 people.

births = 100 {people/year}

DOCUMENT: 100 babies are born every year in the kingdom of Xanadu.

You will notice that you typed in the information for everything except the first equation for “Population”. This is because every stock equation is automatically formulated by STELLA. Notice the similarities between the equation that STELLA uses and the DYNAMO equation for this stock.



- Click on the arrow () to get the model back.

Read and do Exercise 5 on page 234 as it is written in the book.


Simulating Figure 13.11 in STELLA

Read and do Example III on pages 234-238 as it is written in the book,

including Exercises 6 and 7. The hand calculation that Example III requires can be done much more easily by using the STELLA model you've just created. The directions for creating and running a table in STELLA are given below:


- Create a table by clicking on the table icon () and placing it on the workspace. Double-click on the table to make the table dialog box appear. Rename the table "Xanadu Table."
- The table now needs to be defined. Double-click on "Population" and on "births" in the Allowable list (or click on each variable, then click the ) icon). "Population" and "births" should now be in the Selected list.
- Click on *Every Dt* to de-select it. "1" should now be highlighted as the Report Interval. Click OK.
- Select *Time Specs* in the Run menu. When the dialog box appears, select "Years." Set the Range values from 2020 to 2040. Click OK.
- To run the table, select *Run* from the Run menu.
- Once the run is complete, note that the numbers in the table agree with Table 13.1 in the book.
- To close the table, click on the box in the upper-left-hand corner.

Exercise 6 asks you to graph the population of Xanadu through the year 2040. Because you have already constructed the model, generating a graph with STELLA is very easy. The time specs you entered for the table are also valid for the graph of the model.

- Create a graph by clicking the graph icon () and placing it onto the workspace. Double-click on the icon.
- Double-click on the graph pad itself to open it. When the dialog box opens, name the graph "Xanadu Graph." Double-click on "Population" and on "births" from the Allowable list to select them to be graphed. Click OK.

When STELLA graphs the variables in a model, each variable has a different scale. Also, the scales do not begin with zero unless the variable itself begins with a zero value.




- To see this, select *Run* from the Run menu.
- When the graphing is complete, double-click on the graph to open the dialog box again. Click on "Population" under the Selected list and click on the double-headed

arrow to the right of “Population” (). Set “4000” as the min. and “8000” as the max. for the range of “Population”.

- Repeat this process for “births”. Use the numbers “0” to “200.” Now click Set, then click OK. The graph should now be re-scaled.
- Close the graph.

Modeling and Defining Figure 13.13 in STELLA

Read through Example IV. In this example, a model is created to simulate world population growth. You can build this model in STELLA the same way you built the model for the population of Xanadu. The only difference in the two models is that in the world population model, the birth rate is not constant, but dependent on the population.

- Model the flow diagram in Figure 13.13 on page 238. Use the connector () to connect “Population” to “net births”. (The position of the connector can be changed by clicking on and moving the circle at the beginning of the arrow).
- Now you need to enter the equations for your model. Toggle the globe () to \times^2 and enter the initial world population into the model. Do not forget to document “Population”.
- To complete the world population model, study the DYNAMO equations on page 239. Notice that a new variable, “GROWTH FRACTION” (GF), is introduced. Good modeling practice is to give every variable in a system a name and an icon (i.e., stock, flow, converter). Click once on the converter icon () and name it “GROWTH FRACTION”. Connect “GROWTH FRACTION” to “net births”. Define “GROWTH FRACTION” as “0.02.” Do not forget to document “GROWTH FRACTION”.
- The only variable left to define is “net births”. Double-click on “net births” to open up the dialog box. If the document window is open, click on *Hide Document*. Enter “Population * GROWTH FRACTION” as the equation. Document “net births”.
- Compare the STELLA equations to the DYNAMO equations as you did previously.

Simulating Figure 13.13 in STELLA

- Create and define a table () and a graph () for this model as done before. Do not forget to:

Type in a title for each.

Select variables for each.

Change the report interval for the table.

Change the scales for the graph.

Enter the correct time specs for both simulations.

- Compare the table you created to Table 13.2 on page 241.

After reading Chapter 13 of *Introduction to Computer Simulation...*

Chapter 13 gave you more experience with using and creating stock and flow diagrams on STELLA, and explained how to enter the corresponding equations for models in STELLA. It also showed how to recognize and understand the equations for the stocks and flows in DYNAMO. Chapter 13 also illustrates System Principle #4:



System Principle #4:

Levels are accumulations (integrations).

In Example I on pages 227-228 of *Introduction to Computer Simulation*, levels are emphasized as quantities that accumulate over time. Note that the levels **children** and **adults** are accumulations of the rates **births** and **maturing**. Levels accumulate the results of rates (actions) in the system.

Finishing Off Road Maps Two

Road Maps Two explained how to use STELLA to create some simple models of systems on the computer. The ability to use a computer to model a real-world system is a skill that will become vital as you learn more about systems and system behavior. Graphical integration has been introduced as a method to estimate system behavior. Road Maps Two continued to explain how to identify feedback loops and classify the loops in terms of positive or negative feedback. Road Maps

Two also introduced three more principles of systems: a) that levels and rates are fundamental to loop substructure; b) that levels and rates are not distinguished by units of measure; and c) that levels are accumulations.

Road Maps Three will continue to have you practice modeling on the computer and creating stock-and-flow diagrams. You will also begin to explore common behaviors of systems in greater detail.

Key Terms and Concepts:

Causal Loop

Connector

Converter

Exogenous Variable

Endogenous Variable

Feedback Loop

Graphical Integration

Level/Stock

Negative Feedback

Positive Feedback

Rate/Flow

