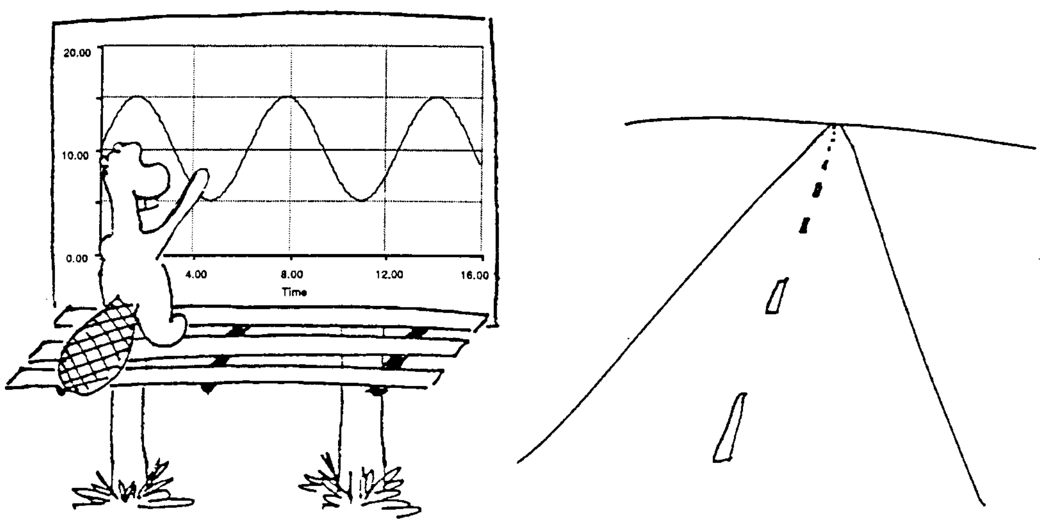
Road Maps 8

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 8

System Dynamics in Education Project
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Welcome to Road Maps Eight!

Road Maps is a self-study guide to learning the principles and practice of system dynamics. This chapter is the eighth in the Road Maps series. Road Maps One through Three give a broad introduction to the field of system dynamics, focusing on understanding the structure and behavior of systems through positive and negative feedback loops. Road Maps Four through Six introduce several generic structures, give a taste of policy analysis and model validity, and provide opportunities for independent modeling.

Road Maps Seven presents some unexpected behaviors that can occur in higher-order positive feedback loops. Also, Road Maps Seven contains the first paper explaining common mistakes and misunderstandings in system dynamics modeling. The chapter offers more independent modeling exercises, and explains "reverse" graphical integration. Road Maps Seven concludes with a paper on the relationship of systems thinking and soft operations research to system dynamics.

In Road Maps Eight we begin a series of papers on the model-building process with an analysis of the conceptualization stage of building a system dynamics model. The second mistakes and misunderstandings paper warns against an incorrect use of generic structures and emphasizes the real nature of stocks and flows. Road Maps Eight continues with a detailed explanation of the structural causes of sustained oscillation, and presents the first in a series of papers on sensitivity analysis. The chapter ends with a transcription of a speech by Prof. Jay Forrester given at the Systems Thinking and Dynamics Modeling Conference for K-12 Education in June 1994.

Topics Covered in Road Maps Eight

Improving Modeling Skills

- *Building a System Dynamics Model Part 1: Conceptualization* (D-4597)
by Stephanie Albin

- *Mistakes and Misunderstandings: Use of Generic Structures and Reality of Stocks and Flows* (D-4646)

by Lucia Breierova

Oscillation

- *Oscillating Systems II: Sustained Oscillation* (D-4602)

by Kevin Agatstein

Sensitivity Analysis

- *An Introduction to Sensitivity Analysis* (D-4526)

by Lucia Breierova and Mark Choudhari

System Dynamics in Education

- *Learning through System Dynamics as Preparation for the 21st Century* (D-4434-1)

by Jay W. Forrester

Things You'll Need for Road Maps Eight

Modeling Software

In order to complete Road Maps Eight 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 the following book for Road Maps Eight. The book was previously required in Road Maps.

Goodman, Michael R., 1974. Study Notes in System Dynamics. Portland, Oregon: Productivity Press, 388 p.

If you have any problems in getting this book, contact Productivity Press (see Appendix).

How to Use Road Maps Eight

Road Maps Eight 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. Many of the chapters conclude with a prominent paper from the literature in the field of system dynamics.

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

Road Maps present the fundamental concepts of system dynamics as *System Principles*. 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 it. The system principles are the core of Road Maps around which the readings, exercises, and papers are built.

Now let's get started!

Improving Modeling Skills

Building a system dynamics model is not an easy task. Most modelers follow a similar set of rules and steps when building a model. The four stages of the model-building process are *conceptualization, formulation, testing,* and *implementation,* which will be examined one by one in individual papers. The following paper examines the first stage, conceptualization.

- *Building a System Dynamics Model Part 1: Conceptualization*[1]

by Stephanie Albin

This paper provides an in-depth explanation of the conceptualization stage of building a system dynamics model. The paper provides a written description of a Heroin-Crime system and then uses the system to demonstrate the four steps used in conceptualization: determining the model purpose, model boundary, shape of the reference modes, and basic mechanisms. The paper then offers an exercise in conceptualization and suggests a solution. You will need Study Notes in System Dynamics by Michael R. Goodman to complete the exercise.[2]

Please read *Building a System Dynamics Model Part 1* now.

After reading *Building a System Dynamics Model Part 1...*

Conceptualization is a crucial stage in building a system dynamics model. During this stage, the modeler must define the purpose of the model, set its boundary, and determine the reference modes and the basic mechanisms. Without completing such a rigorous set of steps, the model-building process may be more difficult because crucial pieces of information may be overlooked. Later chapters of Road Maps will describe the remaining three stages of the model-building process.

The previous paper introduces an important system principle on the concept of closed boundary. Later chapters of Road Maps will return to this system principle.

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[1] Stephanie Albin, 1997. *Building a System Dynamics Model: Conceptualization* (D-4597), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology June 30, 36 pp.

[2] Michael R. Goodman, 1974. Study Notes in System Dynamics, Portland, Oregon: Productivity Press, 388 pp.

System Principle #21:

Every system has a closed boundary.

In creating a model of a real system, any interaction which is essential to the behavior mode being investigated must be included inside the system boundary. If our model is to generate the same behavior as the real system, then the system structure that is responsible for that behavior must be included inside the model. The behavior and its generator are endogenous to the closed system.

Reread section 4.2 of *Building a System Dynamics Model Part I: Conceptualization.* The section explains the concept of model boundary and shows how a modeler sets it during the conceptualization stage. In defining the model boundary, a modeler selects all the components necessary to create the behavior mode under investigation.

- Mistakes and Misunderstandings: Use of Generic Structures and Reality of Stocks and Flows[3]

by Lucia Breierova

This is the second in a series of papers in Road Maps that examine common mistakes and misunderstandings in system dynamics modeling. This paper explains a mistake made by using an unsuitable generic structure to model a system. It also reminds the reader that stocks represent real-world accumulations and flows change the stocks over time.

Please read *Mistakes and Misunderstandings* now.

After reading *Mistakes and Misunderstandings...*

When building a model, keep in mind that stocks in a model must represent accumulations within the system, and that flows represent changes in the stocks. In addition, remember that many structures can produce similar behaviors. Thus, generic structures should not be used blindly without first thinking about the

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[3] Lucia Breierova, 1996. *Mistakes and Misunderstandings: Use of Generic Structures and Reality of Stocks and Flows* (D-4646), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, December 18, 10 pp.

structure of the specific system being modeled. Future chapters of Road Maps will point out other mistakes and misunderstandings.

Oscillation

Road Maps Six introduced the behavior of oscillation through *Generic Structures in Oscillating Systems I.*[4] This paper discussed the generic structure that produces oscillation and showed how the same structure can be applied to a variety of systems. The following paper provides an in-depth explanation of the causes of sustained oscillation.

- *Oscillating Systems 2: Sustained Oscillation*[5]

by Kevin Agatstein

This paper offers a detailed analysis of the structural causes of oscillation. It starts with description of a first-order system and shows why such a system cannot oscillate. Two second-order systems, an Academic Performance Model, and a Cleanliness of a College Dorm Room Model, are then discussed. For each system, the discussion starts with a stock-and-flow model of the system and follows with a brief explanation of the feedback relationships. A step-by-step explanation of one cycle of the model behavior is then offered, focusing on structural reasons of the oscillation.

Please read *Oscillating Systems 2: Sustained Oscillation* now.

After reading *Oscillating Systems 2...*

A system must meet several conditions in order to oscillate. It must be a second or higher-order feedback loop. The system also must have a momentum associated with it that causes it to undershoot and overshoot the goal value, thus producing oscillation. Oscillation is a complex behavior mode and later chapters of Road Maps will return to it.

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[4] Celeste V. Chung, 1994. *Generic Structures in Oscillating Systems I* (D-4426-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, June 17, 24 pp.

[5] Kevin Agatstein, 1997. *Oscillating Systems 2: Sustained Oscillation* (D-4602), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 15, 31 pp.

The paper you just read emphasizes an important system principle that was already presented in previous chapters of Road Maps.

System Principle #11:

Levels completely describe the system condition.

Before the start of a simulation, a set of initial conditions must be specified for all the levels.

Look at the Academic Performance Model in Figure 6 on page 13 of *Oscillating Systems II: Sustained Oscillation*. The system contains two levels: "Current Grades" and "Hours of Weekly Studying." Before running a simulation, the initial values of both levels must be specified. For example, the initial value of "Current Grades" is 3.0 GPA units, and the initial value of "Hours of Weekly Studying" is 21 hours in a week. Without knowing the initial values, the simulation cannot be run. The simulation must begin from a specified condition of the system, reflecting the state of the system at the initial point in time.

Oscillating Systems 2: Sustained Oscillation also presents a new system principle on information links. Please read it carefully. Later chapters of Road Maps will review the system principle several times.

System Principle #22:

Information links connect levels to rates.

Information links, or connectors, link levels to the control of rates. Through information links, values of level variables go to the rate equations, determining the rates of flow.

In the Cleanliness of a College Dorm Room Model, shown in Figure 8 on page 19 of *Oscillating Systems II: Sustained Oscillation,* the level "Daily Complaints of my Roommate" controls the rate of "picking up laundry." The connector between the two variables is an information link. Through the information link, the value of "Daily Complaints of my Roommate" goes to the rate equation determining the value of the "picking up laundry" rate.

Sensitivity Analysis

When building system dynamics models, you may have wondered how to choose specific values of some parameters in a model. How would the behavior demonstrated by a model change if you decided to increase or decrease a parameter? What if the simulation started with a different initial value of a stock? What value should you choose for a parameter if you are not completely sure about its value from the real world system? The next section introduces the concept of sensitivity analysis that aims to answer these and many other questions.

- An Introduction to Sensitivity Analysis[6]

by Lucia Breierova and Mark Choudhari

The following paper introduces sensitivity analysis, a powerful tool in model building and evaluation. The paper presents two models, a lemonade stand model and an epidemics model, and then conducts sensitivity analysis on model parameters to see how behavior is affected when parameter values change. You are then encouraged to experiment on your own with another suggested model. It is

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[6] Lucia Breierova and Mark Choudhari, 1996. *An Introduction to Sensitivity Analysis* (D-4526), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, September 6, 40 pp.

recommended that you build all the presented models and that you run the tests along with the paper to increase your understanding of the model's dynamic behavior as well as of sensitivity analysis.

Please read *An Introduction to Sensitivity Analysis* now and do the suggested exercises on your computer.

After reading *An Introduction to Sensitivity Analysis...*

Sensitivity analysis is very important in building a valid system dynamics model. This paper shows that system dynamics models are usually insensitive to many parameter changes: even though the detailed behavior seems to be affected, the fundamental behavior mode stays the same. Sensitivity analysis, however, can help to identify high leverage points by finding parameters whose specific values can greatly influence the mode of behavior. Sensitivity analysis can also increase confidence in a model and reduce the uncertainties of some parameter values. It is often the structure of a system, more than the parameter values, that primarily determines the system behavior.

Please read the following system principle on conversion coefficients that was first introduced in Road Maps Seven.

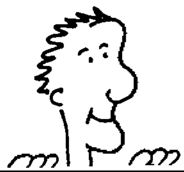
<u>System Principle #18:</u>

Conversion coefficients should be identifiable within real systems.

Conversion coefficients should have numerical values that can be logically deduced from observation. They are not the result of only statistical analysis.

Look back to Figure 13 of *An Introduction to Sensitivity Analysis*. The parameter called "Productivity" is a conversion factor connecting the stock of "Workers" to the flow of "Making Coffee." The value of "Productivity" can be obtained from observing the real world system, the Coffeehouse. For example, if each Coffeehouse worker has time to prepare a ten-cup pot of coffee in half an hour, then the workers' productivity is 20 cups per worker per hour.

The sensitivity analysis paper you just read also introduces a new system principle on decisions in systems. Later chapters of Road Maps will present other aspects of this system principle.



<u>System Principle #23:</u>
Decisions (rates) are based only on available information.

Decisions are made based on the policy statements in the rate equations.

The rate equations in a system dynamics model are policy statements that determine how "decisions" are made. For example, in the Lemonade stand model shown in Figure 1 of *An Introduction to Sensitivity Analysis*, the rate of "Making lemonade" determines how much lemonade should be made. Howard's decision rule on how much lemonade to prepare is captured in the rate equation:

Making lemonade = MAX (Expected lemonade buying + Correction in amount of lemonade, 0)

System Dynamics in Education

The next paper is Prof. Forrester's keynote address for the Systems Thinking and Dynamic Modeling Conference for K-12 Education in June 1994 at the Concord Academy in Concord, Massachusetts. In his speech, Prof. Forrester proposes three objectives that should be achieved through a system dynamics education: developing personal skills; shaping an outlook and personality to fit the 21st century; and understanding the nature of complex systems in which we work and live.

- Learning through System Dynamics as Preparation for the 21st Century [7]

by Jay W. Forrester

Of the three objectives outlined above, it is a continuing goal of Road Maps to help its readers understand the nature of complex systems that surround us. Complex systems differ from simple systems in many ways. The same decisions that can improve simple systems are often counterproductive when applied to

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[7] Jay W. Forrester, 1994. *Learning through System Dynamics as Preparation for the 21st Century* (D-4434-1), Sloan School of Management, Massachusetts Institute of Technology.

complex systems. Prof. Forrester's speech presents six characteristics of complex systems; please read about them carefully, and try to think of other situations in which you have experienced similar behavior of complex systems.

Please read *Learning through System Dynamics...* now.

After reading *Learning through System Dynamics...*

Apart from developing students' personal skills and building their outlook and personality, a systems education should lead students to understand the nature of complex systems. According to Prof. Forrester, in complex systems, cause and effect are not closely related in time or space. In addition, most policies that try to improve a complex system's behavior have little leverage. If a high-leverage policy is found, it is often used incorrectly, thus worsening the initial problem. Moreover, in complex systems, problems are caused by decisions of people within that system. As our low performance causes a failure to reach our goals, we keep lowering the goals to make them more achievable. Finally, a conflict often exists between short-term and long-term goals of a complex system.

After reading Prof. Forrester's speech, you should try to look for examples of these characteristics of complex systems in your own experiences. As you read through the following chapters of Road Maps, you will often be reminded of the characteristics of complex systems in the models that you build and study.

Finishing off Road Maps Eight

Road Maps Eight presented several papers through which you can significantly improve your modeling skills. The chapter covered the conceptualization stage of the model-building process and warned you against more mistakes and misunderstandings in modeling. It then continued to explain the structural causes of sustained oscillation. In addition, Road Maps Eight introduced sensitivity analysis, a useful tool in building and evaluating a model, as well as in understanding its dynamic behavior. Finally, the chapter discussed the goals of a systems education and presented some basic characteristics of complex systems.

In Road Maps Eight, you learned three new system principles:

a) that every system should be formulated with a closed boundary that contains the forces causing the behavior being studied;

b) that information links connect levels to rates; and
c) that decisions (rates) are based only on available information.

Key Terms and Concepts:

basic mechanisms
complex systems
conceptualization
dynamic hypothesis
model boundary
parameter
period of oscillation
reference mode
sensitivity analysis
sustained oscillation
time horizon