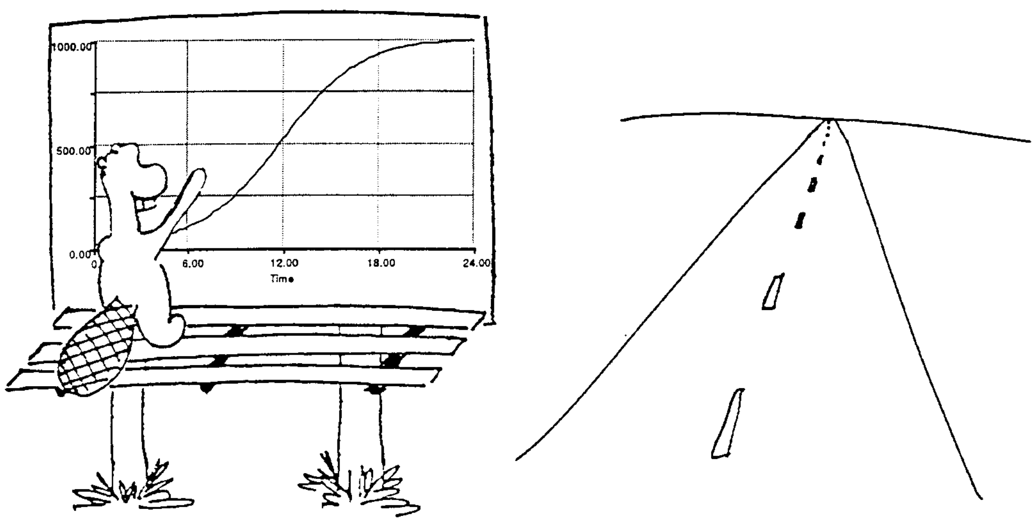
Road Maps 7

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 7

System Dynamics in Education Project
System Dynamics Group
Sloan School of Management
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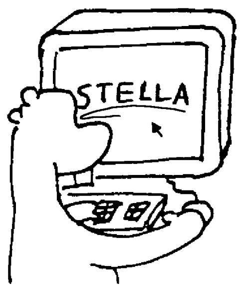
Welcome to Road Maps Seven!



Road Maps is a self-study guide to learning the principles and practice of system dynamics. This chapter is the seventh in the Road Maps series. Road Maps One through Three gives 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 introduces generic (or transferable) structures, and gives a taste of policy analysis using the Fish Banks model. Road Maps Five introduces the use of delays in computer models, explains the transferable structures that cause S-shaped growth, looks at the spread of an epidemic, and starts exploring model validity. Exercises in Road Maps Six model economic supply and demand, explore the generic structure producing oscillations and S-shaped growth, and for the first time let you create your own system dynamics models.

Road Maps Seven presents some unexpected behaviors that can occur in higher-order positive feedback loops and includes the first in a series of papers that address common mistakes and misunderstandings in modeling. To increase modeling proficiency, you will build more models through *Modeling Exercises: Section 2*. We also return to the topic of graphical integration by showing the process of “reverse” graphical integration. The chapter concludes with a paper by Jay Forrester on the relationship of systems thinking and soft operations research to system dynamics.

Topics Covered in Road Maps Seven

Structure and Behavior in System Dynamics

- *Unexpected Behaviors in Higher-Order Positive Feedback Loops*
  (D-4455-1) by Aaron Ashford

Improving Modeling Skills

- *Mistakes and Misunderstandings: Examining Dimensional Inconsistency*
  (D-4452-1) by Michael Shayne Gary

- *Modeling Exercises: Section 2* (D-4451-1)
  by Joseph Whelan

Graphical Integration Exercises

- *Graphical Integration Exercises Part 4: Reverse Graphical Integration* (D-4603) by Laughton Stanley

The Methodology of System Dynamics

- *System dynamics, systems thinking, and soft OR* (D-4405-1)
  by Jay W. Forrester

Things You'll Need for Road Maps Seven

Modeling Software

In order to complete Road Maps Seven 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.

How to Use Road Maps Seven

Road Maps Seven 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 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 revised 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.

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!

Structure and Behavior in System Dynamics

Positive feedback loops are usually associated with their characteristic behavior of exponential growth. However, when a positive feedback loop is of a higher order (contains more than 1 level), it can exhibit a variety of other behaviors.

- Unexpected Behaviors in Higher-Order Positive Feedback Loops[1]

by Aaron Ashford

This paper discusses possible types of behavior in first to fifth-order positive feedback loops. Only the first-order loop always shows exponential growth (unless the initial value of the stock is equal to zero). Depending on the order of the loop as well as on the initial values of all the levels, a positive feedback loop can exhibit not only exponential growth, but also asymptotic growth, and damped, sustained, or expanding oscillations. The paper offers several independent explorations and provides solutions to them.[2]

Please read *Unexpected Behaviors in Higher-Order Positive Feedback Loops* now.

[1] Aaron Ashford, 1995. *Unexpected Behaviors in Higher-Order Positive Feedback Loops* (D-4455-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 8, 21 pp.

[2] Please note that if you want to simulate the positive feedback loops with STELLA, you should make sure that all the flows in your model are biflows and that all the stocks can become negative.

After reading *Unexpected Behaviors*...

A positive feedback loop is able to show a surprising variety of behaviors. The initial values of the levels determine what behavior the loop will exhibit. However, the behavior modes created by such specific initial values are very unstable—even a slight change in one of the initial values will cause the loop to destabilize to exponential growth. Exponential growth is the most common behavior of positive feedback loops. We now review this idea as a new system principle.

<u>System Principle #17:</u>

Higher-order, positive-feedback loops usually show exponential behavior.

Positive feedback loops of nth order usually exhibit simple exponential growth (ignoring possible initial transients).

Look back to Figure 4 on page 8 of *Unexpected Behaviors in Higher-Order Positive Feedback Loops*. The figure shows the most common behavior of positive feedback loops. Exponential growth is the only stable behavior of positive loops. All other behaviors are unstable—a very slight perturbation of the initial values of the levels will cause the behavior to destabilize to exponential growth. Figures 6, 9, and 12 show examples of such destabilization.

In most real-world systems, the initial values are such that the positive feedback loops will generate exponential growth.

Improving Modeling Skills

While modeling, you may find yourself consistently making the same mistakes, or misunderstanding certain concepts. However, you should not be discouraged. Making a mistake and then examining it can be a very good way to learn system principles and thus good modeling practices.

- *Mistakes and Misunderstandings: Examining Dimensional Inconsistency*[3]

by Michael Shayne Gary

This is the first in a series of papers to be included in Road Maps that will examine common mistakes and misunderstandings in system dynamics modeling. Using a simple thermostat model, this first paper analyzes the common mistake of dimensional inconsistency in modeling. It looks at where and why a dimensional inconsistency mistake could be made, as well as ways to avoid mistakes in the future.

Please read *Mistakes and Misunderstandings* now.

After reading *Mistakes and Misunderstandings*...

The paper addressed common mistakes such as designating stocks and flows with inconsistent dimensions or creating stocks that cannot accumulate. You should keep a note of common mistakes you make and ask yourself why it happened. Did you not understand the concept? Or was it a mistake in applying the concept to the structure of the model? There will be more mistakes and misunderstandings in future Road Maps.

Dimensional equality is one of the most basic and powerful ways to check against incorrect formulations of models. To underscore the importance of checking for dimensional consistency, we now review dimensional equality as a system principle that we introduced in Road Maps Four.

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[3] Michael Shayne Gary, 1992. *Mistakes and Misunderstandings: Examining Dimensional Inconsistency* (D-4452-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, January 1992, revised September 1995, 6 pp.

System Principle #9:

Every equation must have dimensional equality.

In any equation, every term must be measured in the same dimensions. "One cannot add apples and oranges." This is true within converters, and it is true within level and rate equations—as is seen *in Mistakes and Misunderstandings: Examining Dimensional Inconsistency*.

House_Temperature(t+dt) = House_Temperature(t) + Heat_Production(t)*dt.

Dimensionally this equation becomes:

[Degrees Celsius] = [Degrees Celsius] + [BTUs/min]*[min]
= [Degrees Celsius] + [BTUs],

which is clearly "apples and oranges." Dimensional inequality between terms indicates a faulty equation formulation.

We now introduce a new system principle about conversion coefficients.

System Principle #18:

Conversion coefficients are identifiable within real systems.

Conversion coefficients should always have a clear, real meaning. They are not inserted just to balance equations.

The model shown in Figure 2 on page 6 of *Mistakes and Misunderstandings: Examining Dimensional Inconsistency* contains a "Conversion Factor." The conversion factor, or coefficient, specifies how much heat must be generated by the furnace to increase the temperature in the house by one degree. This way, it transforms the units of "Heat," calories, into the units of "Temperature," degrees Celsius or degrees Fahrenheit, and provides dimensional equality. The conversion factor thus has a real physical meaning and balances the equations dimensionally.

Taking a given system and modeling it from scratch is not an easy thing to do, and all of us are bound to make mistakes. Now that you have some good modeling experience under your belt, it might be helpful to go back and analyze your mistakes. See if you consistently make the same types of mistakes and ask yourself how you can fix them. Mistakes can be great things if we are willing to learn from them!

The next exercises test your model-building and mental simulation skills. This is your chance to apply the skills and knowledge you have acquired so far in Road Maps to build your own model from scratch.

- *Modeling Exercises: Section 2*[4]

by Joseph Whelan

This is the second in a continuing series of papers in Road Maps to provide you with exercises to develop your modeling skills. The first exercise in this paper presents an urban growth and stagnation scenario. Exploration questions lead you through the modeling process, but the model will be largely your creation. The second exercise presents a simple model for practicing mental simulation. You should think about and attempt each exercise before looking at the answers.

Please read and do the exercises in *Modeling Exercises: Section 2* now.

After reading and doing the exercises in *Modeling Exercises: Section 2...*

Using the modeling process outlined by the author as a guideline for modeling often helps to avoid confusion and mistakes. Also, mentally simulating a model before running it on the computer will help you to catch your mistakes. More importantly, mental simulation will help you to better understand the relationship between the structure and behavior of systems.

Modeling Exercises: Section 2 also explained the use of multipliers and time constants in system dynamics models. These concepts are very important and will be useful in your future modeling.

Please read the following system principles to review some of the important ideas introduced in the paper you just read.

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[4] Joseph Whelan, 1994. *Modeling Exercises: Section 2* (D-4451-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, August 1994, 35 pp. Revised by Lucia Breierova, January 1997.

<u>System Principle #11:</u>

Levels completely describe the system condition.

There must be a level for each quantity needed to describe the condition of the system, and the value of each level must be specified at the start of a simulation.

The solution to the Urban Dynamics Exercise in *Modeling Exercises: Section 2* contains two levels**, Business Structures** and **Population**. Both levels are necessary to describe the system condition.

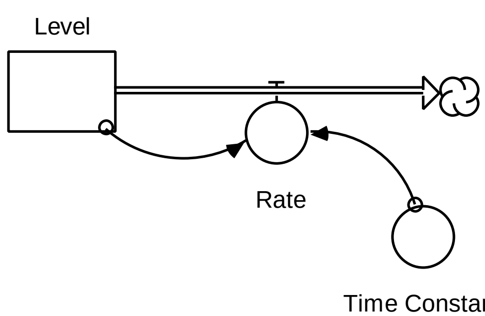
Because the system condition is computed at every step of the simulation and depends on the previous values, it must be known at the start of simulation. Thus the initial values of both Business Structures and Population must be determined.

<u>System Principle #19:</u>

Time constant of a first-order loop relates a level to a rate.

Starting on page 26 of *Modeling Exercises: Section 2*, there is a thorough discussion of the effects of time constants on first-order loops. Here is a brief summary:

The exponential time constant of a first-order loop is the reciprocal of the multiplier that defines the rate in terms of the level. It relates a level to the rate that affects it.



$$\text{Rate} = \frac{\text{Level}}{\text{Time Constant}}$$

The Rate is equal to the Level divided by the Time Constant, or to the Level multiplied by the reciprocal of the Time Constant (the fraction 1/Time Constant).

Graphical Integration Exercises

Previous chapters of Road Maps introduced the Graphical Integration Exercises series. So far, the papers in the series have focused on the process of integration—how to determine the value of the stock if you know the behavior of the flow. However, the reverse process is often useful in dealing with real world systems. Most information usually comes in terms of stocks, but the behavior of their flows can also be important. Therefore, the following paper explains the method of reverse graphical information—estimating the behavior of the stock's net flow from the graph of the stock.

- *Graphical Integration Exercises Part 4: Reverse Graphical Integration*[5] by Laughton Stanley

This paper covers three methods for drawing the graph of a net flow based on the graph of the stock. It explains how to use intervals to estimate the net flow, and how to quantify the net flow behavior by drawing tangent lines on the stock graph. The exercises included at the end of the paper give you some experience with the technique of reverse graphical integration. Solutions to the exercises are also provided.

Please read and do *Graphical Integration...* now.

After reading *Graphical Integration...*

The paper examined several ways for determining the behavior of a stock's net flow from the graph of the stock. It also clarified the general relationship between the behavior of a stock and its net flow: if the stock is increasing, the net flow is positive; if the stock is decreasing, the net flow is negative. We hope that you can now use the knowledge and techniques you have acquired so far in the graphical integration series to estimate the value of the stock if you know the behavior of the flow, or to do the reverse process. Such insights are often helpful in understanding the dynamic behavior of the system.

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[5] Laughton Stanley, 1996. *Graphical Integration Exercises Part 4: Reverse Graphical Integration* (D-4603), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, August 20, 24 pp.

The following system principle reviews an important concept introduced in the paper you just read.

System Principle #20:
Rates are not instantaneously measurable.

No rate of flow can be measured instantaneously. A rate is a change over time. Without an observation over a time interval, a rate cannot be measured.

Look back to page 6 of *Graphical Integration Exercises Part 4: Reverse Graphical Integration*. The Introduction describes several examples in which the rate is determined from the accumulation of the level over a period of time. The rate is determined as the change in the value of the level over time. There is no way to measure the instantaneous value of a rate.

The Methodology of System Dynamics

System dynamics, systems thinking, and soft operations research (soft OR) are all methods for studying complex systems. The relation and differences between them can often be unclear to someone who has not had much experience in the field. In the following article that appeared in the *System Dynamics Review*, Prof. Forrester offers his point of view.

- System dynamics, systems thinking, and soft OR[6]

by Jay W. Forrester

The following article describes the relation of systems thinking and soft operations research to system dynamics. Unlike system dynamics that uses explicit models and simulations of dynamic behavior, systems thinking and soft OR lack such a rigorous foundation. However, they can still contribute useful insights from the real-world system and help in the conceptualization phase of building a system dynamics model.

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[6] Jay W. Forrester, 1994. "System dynamics, systems thinking, and soft OR" (D-4405-1), *System Dynamics Review* Vol. 10, nos. 2-3 (Summer-Fall 1994), pp. 245-256.

Please read *System dynamics, systems thinking, and soft OR* now.

After reading *System dynamics, systems thinking, and soft OR*...

Professor Forrester outlined six steps through which system dynamics moves from a problem in a system to an improvement. He suggested that in some of them soft OR and systems thinking are closely related to system dynamics. His critical opinion of systems thinking and soft OR comes from the fact that they are not based on a quantitative structure such as the stock and flow diagrams in system dynamics.

Finishing off Road Maps Seven

Road Maps Seven presented some surprising behaviors that may occur in higher-order positive feedback loops. We introduced a new series of papers in Road Maps, Mistakes and Misunderstandings. Its first paper looked at dimensional inconsistency. The second paper in the Modeling Exercises series gave you a chance to create a model on urban growth and stagnation as well as to improve your mental simulation skills. We also explained the method of “reverse” graphical integration, or graphical differentiation. The final reading in Road Maps Seven discussed how system dynamics relates to systems thinking and soft OR.

In Road Maps Seven, you learned about four more system principles:
a) that higher-order positive feedback loops usually show exponential growth;
b) that conversion coefficients are identifiable within real world systems;
c) that the time constant of a first-order loop relates the level to the rate; and
d) that rates are not instantaneously measurable.

Key Terms and Concepts:

closed boundary
conversion coefficient
dimensional inconsistency
higher-order positive feedback loops
multiplier
reverse graphical integration
soft operations research
time constant