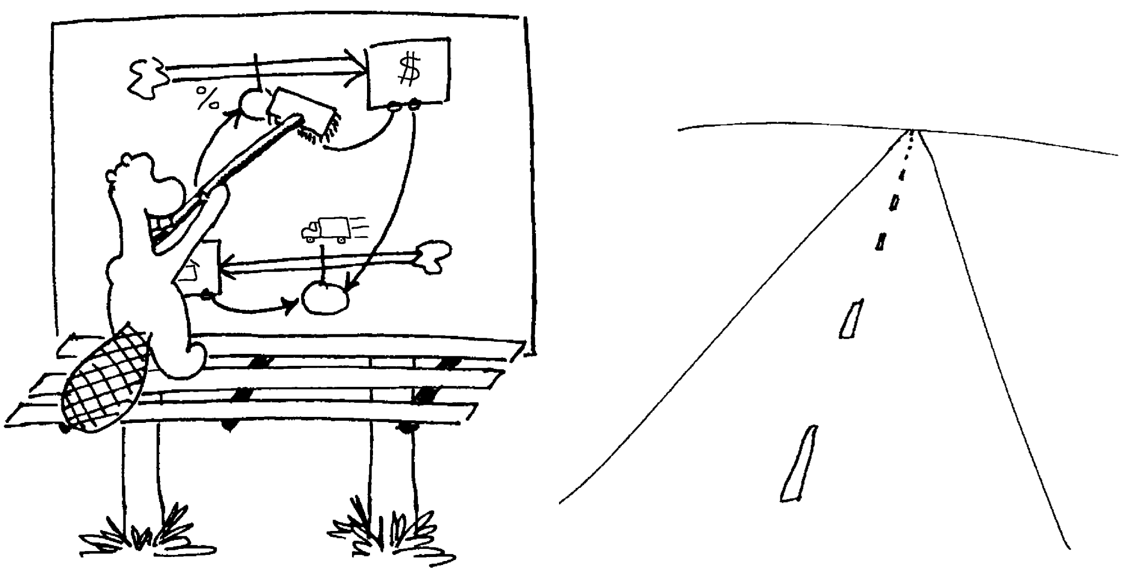
Road Maps 6

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 6

System Dynamics in Education Project
System Dynamics Group
Sloan School of Management
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July 18, 1993
Latest Revision March 18, 2001

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Welcome to Road Maps Six!

Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Six is the sixth in the series of chapters in Road Maps. Road Maps One through Three gave you 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 introduced generic (or transferable) structures, and gave you a taste of policy analysis using the Fish Banks model. Road Maps Five introduced the use of delays in computer models, explained the transferable structures causing S-shaped growth, looked at the spread of an epidemic, and started exploring model validity.

In Road Maps Six, you will be able to apply your skills to modeling economic supply and demand. We introduce a transferable structure that produces oscillation, with two real-life oscillating systems presented as examples, and we develop the study of generic structures producing S-shaped growth. Road Maps Six also provides exercises that allow you to create your own models from given information. Finally, *Systems thinking: critical thinking skills for the 1990s and beyond* focuses on addressing current global problems using critical thinking skills acquired through systems thinking.

Topics Covered in Road Maps Six

System Dynamics in Economics

- *Economics Supply and Demand* (D-4388)
  by Kamil Msefer and Joseph Whelan

Transferability of Structures

- *Generic Structures in Oscillating Systems I* (D-4426-1)
  by Celeste Chung

-*Exploring S-Shaped Growth* (D-4476)
by Leslie Martin

Modeling Exercises

- *Modeling Exercises: Section 1* (D-4421)
by Joseph Whelan

Critical Thinking Skills

- *Systems thinking: critical thinking skills for the 1990s and beyond* (D-4565)
by Barry Richmond

Things You'll Need for Road Maps Six

Modeling Software

In order to complete Road Maps Six 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 Six

Road Maps Five 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 revised 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!

System Dynamics in Economics

An important application of system dynamics is to economics. Here, we propose that a system dynamics perspective on supply and demand can describe mechanisms which most classical economics texts fail to explain.

- *Economics Supply and Demand*[1] by Kamil Msefer and Joseph Whelan

In this paper, we look at one of the fundamental tenets of economics: supply and demand theory. First, the classical economic model of supply and demand is explained. Next, a system dynamics approach is proposed as a way of better understanding the mechanism of supply and demand. With this background, you will then build a simple model and complete some exercises to improve your understanding of these concepts.

Please read *Economics Supply and Demand* now.

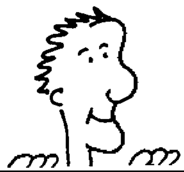
After reading *Economics Supply and Demand...*

This paper explained the basics of supply and demand as well as the distinction between classical economic theory and the premise that system dynamics makes about supply and demand. The model you built demonstrates the dynamics of supply and demand in action. We encourage you to continue to add to this model as you make observations about how a real-life economic system might behave to

[1] Kamil Msefer and Joseph Whelan, 1995. *Economic Supply and Demand* (D-4388), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, October 3, 36 pp.

certain changes. For instance, how would you account for the effect of available inventory on demand?

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



System Principle #13:
Solution interval DT is in all level equations and no others.
The DT (also called the solution interval, period of measurement, delta time, or time step) is the time period in which the level is changed by the rate. In the Supply and Demand model, measurements are made weekly; thus DT = 1 week. DT is multiplied by the current rate and added to the existing level value—determining the level value after the next DT of time. This process can be seen in the level equations included within the model equations (found in the Appendix). The DT is essential to the level equation.

Transferability of Structures

In Road Maps Chapter 5, you continued to develop the idea of generic, or transferable, structures through *Generic Structures: S-Shaped Growth I*. The idea of a transferable structure is important in system dynamics because it allows you to estimate the behavior of systems from different disciplines through understanding the behavior of its underlying generic structures.

? ***Generic Structures in Oscillating Systems I***[2]
by Celeste Chung

This paper introduces oscillation as a behavior that can be modeled using a transferable structure. A swinging pendulum and employment instability are two

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[2] Celeste 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.

real-life scenarios used to illustrate the transferability of this oscillation structure. While reading this paper, try to think of other systems which oscillate.

Please read and do the exercises in *Generic Structures in Oscillating Systems I* now. The following tips may help you.

Tips for modeling in *Generic Structures in Oscillating Systems I.*

In order to observe the sustained oscillations in your model of the system, choose the Runge-Kutta integration method instead of the usual Euler's method. To do this, open the Time Specs dialog box from the Run menu, and select the Runge-Kutta 4 integration method.

It is also necessary to make sure that both of your stocks can become negative, and that the flows are biflows. This is an important modeling rule which should be followed when building any model.

Also, to make the curves look smoother, choose a smaller solution interval, such as DT = 0.1, from the Time Specs dialog box.

After reading and doing the exercises in *Generic Structures in Oscillating Systems I...*

In addition to the first-order positive and negative feedback loops introduced in Road Maps Four, we have so far presented three different transferable structures: two that produce S-shaped growth (from Road Maps 5), and one that produces sustained oscillation. Modeling the oscillation structure on STELLA by yourself will improve your understanding of the generic structure. Experiment by changing variables like time gap or initial velocity, and see if the changes in behavior fit your mental model.

The following system principles which were introduced in the generic structures paper you just read are important concepts to remember in thinking systemically.

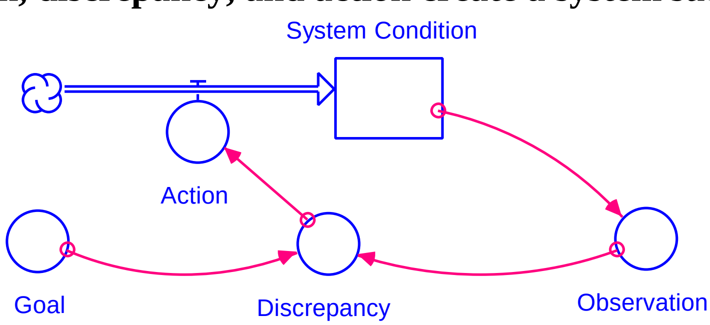
System Principle #14:

Simple, second-order negative loops exhibit sinusoidal oscillation.

All of the systems in *Generic Structures in Oscillating Systems I* are second-order negative loops, and they all oscillate. The oscillation is independent of the values of parameters; it is due to having the same qualitative structure. Any second-order, negative loop with no minor loops oscillates as a sustained sinusoid.

System Principle #15:

Goal, observation, discrepancy, and action create a system substructure.



A policy or rate equation recognizes a local goal toward which that decision point strives, compares the goal with the apparent system condition to detect a discrepancy, and uses the discrepancy to guide action.

Notice Figures 3, 5, and 7 of *Generic Structures in Oscillating Systems I*. In Figure 3, and the accompanying text, we see that the goal is **Desired Position** (namely x=0), the observation is **Position**, the discrepancy is measured in **Gap** between **Desired Position** and **Position**, and the action taken is to alter **Change in Velocity**, which changes **Velocity** and consequently **Position**. Similar processes occur within the systems seen in Figures 5 and 7. This system substructure occurs often and will be further explored later in Road Maps.

- *Exploring S-Shaped Growth*[3]

by Leslie Martin

In Road Maps Five, we introduced two generic structures that produce S-shaped growth. The following paper describes an example of the same type of behavior and provides exercises to experiment with S-shaped growth. Positive and negative loops are shown to interact with each other to generate S-shaped behavior.

Please read *Exploring S-Shaped Growth* now.

After reading *Exploring S-Shaped Growth...*

This paper discussed a generic structure producing S-shaped growth, and provided several examples of real-world systems that exhibit S-shaped growth. Can you think of any other systems with the same structure that produce S-shaped growth? It is important to remember that generic structures are useful because they let us apply our knowledge of one system to understand the behavior of other systems with the same structure.

Modeling Exercises

So far, we've guided you through the model-building process. We gave you the levels and rates, suggested links and hinted at equations. Now, in the following model exercises, you will formulate your own models using given descriptions of systems.

- *Modeling Exercises: Section 1*[4]

by Joseph Whelan

This is the first in a series of papers on modeling exercises to be included in Road Maps. Since this is your first independent modeling experience so far in Road Maps, the first part of *Modeling Exercises* addresses the process of model building and includes a some guidelines to follow. Then you are given three exercises, each with a description of a system which you are to model. You will then build a model

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[3] Leslie Martin, 1996. *Exploring S-Shaped Growth* (D-4476), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, October 3, 40 pp.
[4] Joseph Whelan, 1994. *Modeling Exercises: Section 1* (D-4421), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 19, 37 pp.

to simulate the system and use the model to help answer some exploration questions. At the end of the paper is one possible model for each of the system descriptions as well as answers to the exploration questions.

Please read *Modeling Exercises: Section 1* now.

After completing *Modeling Exercises: Section 1*...

This paper was your first opportunity in Road Maps to create a simple model yourself. It is necessary to understand all the questions and the models before moving on to *Modeling Exercises: Section 2* which will be in a later chapter of Road Maps. The modeling skills you have accumulated so far should be sufficient for you to begin exploring and creating models of your own.

Now is a good time to discuss a recurrence of the following system principle. Note the application of this principle in Model 1 of *Modeling Exercises* which you just completed.

__**System Principle #7:**__

Rates depend only on Levels and Constants.

Look at the author's solution to Model 1 in *Modeling Exercises* (the model diagram is on p. 20). Note that the **Hatch Rate** is influenced only by the level **Penguins** and a constant, **Hatch Fraction**. **Death Rate** also only depends on the level and a constant. **Death Rate** may appear to depend on **Death Fraction**, but it is only a converter. The true dependence must be traced back to **Penguins** and **Area**.

The value of a rate variable depends only on present values of level variables and constants. No rate variable depends directly on any other rate variable. The rate equations (or policy statements) of a system are of simple algebraic form; they do not involve time or the solution interval; they are not dependent on their own past values.

Another principle that we have encountered before in Road Maps is now discussed further in the context of Model 2 of *Modeling Exercises*.

<u>System Principle #8:</u>
Decisions are always made within feedback loops.

Look at the author's solution to Model 2 in *Modeling Exercises* (the model diagram is on p. 25 and the equations are on pp. 28 - 30). The house heating/cooling appliances control the **Heating** and **Cooling** in/out flows for **Heat in House**. The decision of what action to make—whether the heater or air conditioner should be on or off—is dependent upon information in the system. In this case the decision depends upon the **Measured House Temperature** and the appliance settings.

Now notice that the action made—as a result of the decision—will change **Heat in House**; the house either heats up or cools down. This change in the stock affects the **House Temperature**, which affects the **Measured House Temperature**, which in turn will affect our decision!

Every decision process is made within at least one feedback loop.

We now introduce a new system principle.

<u>System Principle #16:</u>
Level variables and Rate variables must alternate.

Look at the author's solution to Model 3 in *Modeling Exercises* (on p. 31). Trace out the loop starting with the level **Predator Population** and continuing with the rate **Prey Deaths**. Note that as you move through the loop, the level and rate variables alternate. Next comes **Prey Population**, then **Predator Deaths**, and finally **Predator Population** again, for one loop. Converters are algebraically part of the rates to which they are connected.

Any path through the structure of a system encounters alternating level and rate variables. Recall **System Principles #5** and **#7**: <u>Levels depend only on rates</u>

and <u>Rates depend only on levels (and constants)</u>, respectively. Thus for any loop in a system, if we start at a level variable, the next variable we reach cannot be another level; the next variable must be a rate.

Likewise, if we move through any loop starting from a rate variable, the next variable cannot be another rate (or even a constant, they are not influenced by any variable); the next variable must now be a level. This could be the same level, or it could be a new one. Try tracing out a loop in your own solution to the modeling exercise, and see for yourself!

Critical Thinking Skills

The world is becoming an ever-increasingly complex and interconnected place. With this growing complexity, it is imperative that we as global citizens keep pace with problems that arise as a result. How can we do this?

- Systems thinking: critical thinking skills for the 1990s and beyond[5]

by Barry Richmond

Dr. Barry Richmond is the managing director and founder of High Performance Systems, the company which produces STELLA II and *ithink* software. In his paper, he advocates the teaching of systems thinking through learner-centered learning as well as the application of systems thinking to the acquisition of various critical thinking skills (which he outlines). He argues that by their very nature, systems thinkers understand the interdependence of systems and can therefore “experience the morning after” in terms of predicting the outcome of current situations. As you read his paper, ask yourself whether you agree or disagree with what he says based on your system dynamics experience so far.

Please read *Systems thinking...* now.

After reading *Systems thinking...*

We now review a system principle which was introduced earlier in Road Maps.

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[5] Barry Richmond, 1993. *Systems thinking: critical thinking skills for the 1990s and beyond* (D-4565), System Dynamics Review Vol. 9, no. 2 (Summer 1993), pp. 113-133.

System Principle #12:

Variables have the same units within conservative subsystems.

All levels within conservative subsystems—levels connected by flows—must have the same units of measure. The rates of the flows connecting these levels have units of measure equal that of the levels divided by time.

Figures 12 and 13 in *Systems thinking: critical thinking skills for the 1990s and beyond* readily demonstrate this principle. **Empty Bottles, Bottles being Filled**, and **Inventory of Filled Bottles** all have units of [bottles]. **New empties**, **bottles on conveyer**, **and filled bottles** all have units of [bottles/time]. All together, these connected variables form a conservative subsystem. However, **Liquid in Vat** is not a part of this subsystem; it does not have the same units of measure (instead, it has units [liters]). This is why it is incorrect **for liquid into bottles** to flow into **Bottles being filled**: the flow's units are incorrectly matched.

Finishing off Road Maps Six

Road Maps Six emphasized that system dynamics has a wide variety of applications. For example, system dynamics can facilitate and improve understanding of economics.

The concept of a transferable structure is crucial in system dynamics. Oscillation is a common behavior in systems, and the transferable structure which causes it will appear time and time again. What other common behaviors are caused by a transferable structure? We will introduce more of these structures in future Road Maps. In Road Maps Six, you have also seen another structure that produces S-shaped growth. You also got your first taste of independent modeling through *Modeling Exercises: Section 1*.

In Road Maps Six, we presented four new system principles: a) that the solution interval DT is in all level equations but no others; b) that simple, second-order negative loops exhibit sinusoidal oscillation; c) that goal, observation, discrepancy, and action create a system substructure; and d) that level variables and rate variables must alternate.

Finally, Road Maps Six also explained that system dynamics can help in finding long-range solutions to global problems in the years to come.

Key Terms and Concepts:

closed-loop thinking
continuum thinking
demand
dimensional inconsistency
diminishing marginal utility
dynamic thinking
generic thinking
multiplier
operational thinking
oscillation
scientific thinking
structural thinking
supply
time constant
transferability