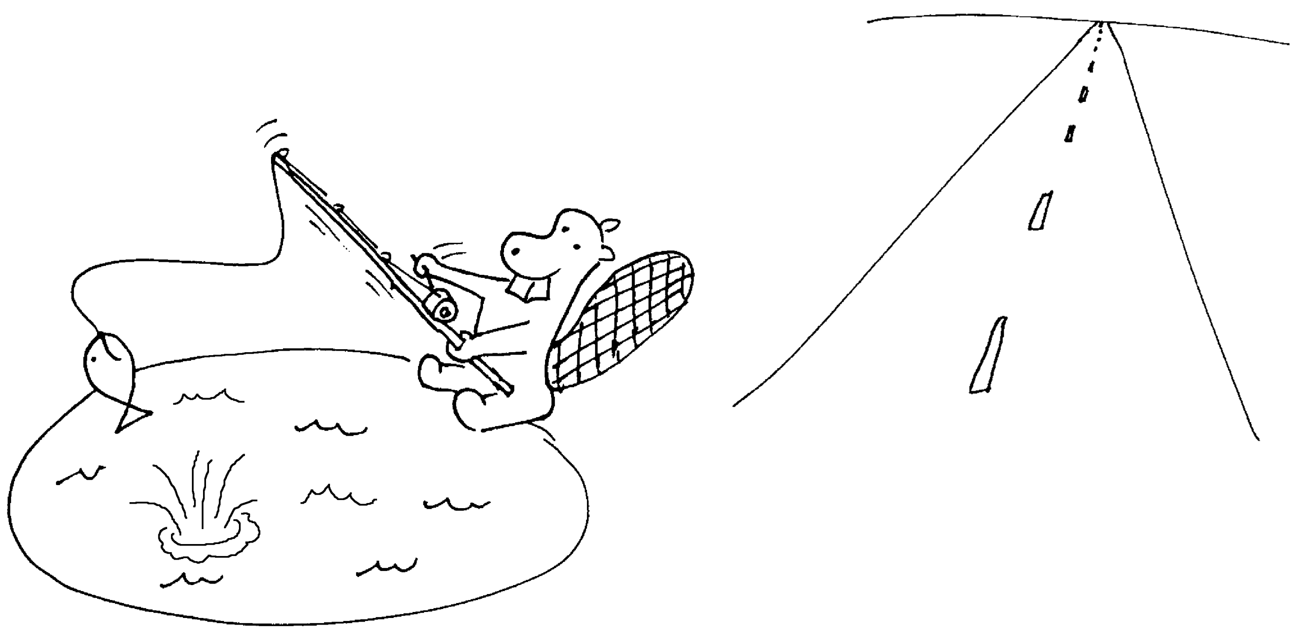
Road Maps 4

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 4

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 Four!

Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Four is the fourth in the series of chapters in Road Maps. The first three chapters of Road Maps gave you a broad introduction to the field of system dynamics and a focus on the building blocks of modeling: positive and negative feedback loops. Road Maps Four will explore and challenge your system dynamics knowledge and understanding.

The first two papers in Road Maps Four introduce the concept of generic structures. You will then do some more beginner modeling exercises. The next paper, *Building the Fish Banks Model and Renewable Resource Depletion*, includes a computer simulation game of a fishing industry based on a system dynamics model. After playing the game, you will create your own model of the fishing industry and try out different policies on the system. At the end of Road Maps Four, we will talk about some of the shortcomings of causal loop diagrams.

Topics Covered in Road Maps Four

Transferability of Structures

- *Generic Structures: First-Order Positive Feedback* (D-4474-1) by Stephanie Albin and Mark Choudhari
- *Generic Structures: First-Order Negative Feedback* (D-4475-1) by Stephanie Albin

Beginner Modeling Exercises

- *Beginner Modeling Exercises Section 4: Mental Simulation: Adding Constant Flows* (D-4546) by Alan Coronado

The Tragedy of the Commons

- *Building the Fish Banks Model and Renewable Resource Depletion* (D-4543) by Joseph G. Whelan and Matthew C. Halbower

Shortcomings of Causal Loop Diagrams

- *Problems with Causal Loop Diagrams* (D-3312)
  by George P. Richardson

Things You'll Need for Road Maps Four

Modeling Software

In order to complete Road Maps Four 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 Four

Road Maps Four 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!

Transferability of Structures

After going through three sections of Road Maps you might have noticed that some of the models seem to look similar. For example, the model that would be used to describe the filling of a bathtub looks very much like a simple population model. This phenomenon occurs all the time in system dynamics, and is known as the **transferability of structures**. These structures that are common to several systems are called **generic structures**.

- Generic Structures: First-Order Positive Feedback [1]

by Stephanie Albin and Mark Choudhari

The first paper in the series of generic structures introduces the concept of generic structures in systems with first-order positive feedback. After offering and explaining some examples, the paper studies the generic structure and discusses the various types of behavior it can produce. You will then be asked to do several exercises. The solutions are provided at the end of the paper.

Please read *Generic Structures: First-Order Positive Feedback* now.

After reading *Generic Structures: First-Order Positive Feedback...*

This paper described the generic structure of first-order positive feedback systems. In many cases different systems share the same underlying structure. What other systems can you think of that have the same positive feedback loop structure? Transferability of structures is important because it allows you to estimate the behavior of new systems with the same underlying generic structures, based on your knowledge of other systems with which you may already be familiar. It is important to understand all the concepts and to be able to do the exercises before moving to the next paper.

- Generic Structures: First-Order Negative Feedback [2]

by Stephanie Albin

This paper will develop your understanding of generic structures and will present this concept in systems with first-order negative feedback. As in the previous paper, several examples are offered at the beginning, and the paper then explains the generic structure as well as the goal-seeking behaviors it produces. You will again do some exercises; solutions are included at the end of the paper.

Please read *Generic Structures: First-Order Negative Feedback* now.

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[1] Stephanie Albin and Mark Choudhari, 1996. *Generic Structures: First-Order Positive Feedback* (D-4474-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, March 8, 19 pp.

[2] Stephanie Albin, 1996. *Generic Structures: First-Order Negative Feedback* (D-4475-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 28, 22pp.

After reading *Generic Structures: First-Order Negative Feedback...*

This paper discussed the generic structure in first-order negative feedback systems. Again, it explained that different systems often have the same underlying structure. Can you think of any other systems that have the same negative feedback loop structure? The paper emphasized the importance of transferability of structures.

By enabling an efficient transfer of knowledge from one discipline to another, system dynamics serves as the only effective framework for integrating and organizing knowledge from diverse fields. We will return several times in Road Maps to identify and explore generic structures.

Beginner Modeling Exercises

The next reading is the fourth paper in the series of Beginner Modeling Exercises. In Road Maps Three, you learned how to mentally simulate the behavior of simple systems containing either a positive or a negative feedback loop. We will now have a look at how the introduction of a constant flow affects this behavior.

- *Beginner Modeling Exercises Section 4: Mental Simulation: Adding Constant Flows*[3]

by Alan Coronado

This paper will continue to develop your mental simulation skills, and will apply them to estimate the behavior of systems that also contain a constant flow. Both positive and negative feedback with a constant flow will be explored, and after each section you will be asked to complete some exercises. You can compare your answers to the ones provided at the end of the paper.

Please read *Beginner Modeling Exercises Section 4* now.

After reading *Beginner Modeling Exercises Section 4...*

The addition of a constant flow to a system containing a positive or a negative feedback loop does not change the general pattern of behavior, but changes the

[3] Alan Coronado, 1996. *Beginner Modeling Exercises Section 4: Mental Simulation: Adding Constant Flows* (D-4546), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 28, 27 pp.

system goals. This paper explained how to determine the equilibrium stock, the net flow, and the time constant of a system. It is necessary to be able to solve all the exercises before moving to the next paper in the Beginner Modeling Exercises series.

The Tragedy of the Commons

The disappearing tropical rain forests, the dwindling Scandinavian fish supply, and the depletion of fish from the Grand Banks: what do these three have in common? In each case, a shared resource has diminished as a result of individual overuse. In system dynamics this is known as "The Tragedy of the Commons." The next paper examines the system structure that causes this behavior.

- *Building the Fish Banks Model and Renewable Resource Depletion*[4]

by Joseph G. Whelan and Matthew C. Halbower

This paper leads you through The Fishing Game, a one player computer simulation game about a fishing industry. The game allows you to role-play, making decisions similar to those made by people in the real system. As you will see, situations of this sort can produce unexpected behavior. This game and the model you will create after you finish the game illustrate a common system behavior called "The Tragedy of the Commons."

Computer simulation games allow you to experiment with different policies without taking “risks” in real life. Computer simulation also helps to clear up any uncertainty that you might have about the results of a policy. You simply try the policy in the game and see the results.

Now please read *Building the Fish Banks Model...*

After reading *Building the Fish Banks Model...*

The behavior known as "The Tragedy of the Commons" occurs because of the system's structure. Individuals within the system (in this case fishermen) do not

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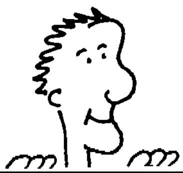
[4] Joseph G. Whelan and Matthew C. Halbower, 1994. *Building the Fish Banks Model and Renewable Resource Depletion* (D-4448), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, July, 55 pp. This paper is accompanied by a Macintosh® computer disk.

see that their goal to maximize their own profits undermines the very source of their livelihood. Do you see any other situations that might have a tragedy of the commons structure?

As discouraging as this situation seems, the model also points out that some policies can prevent the overuse of the resource. Policy analysis is one of the most powerful applications of system dynamics. How do system dynamics models help decision makers (government agencies, regulatory commissions, etc.) in their policy making? This issue will be explored in later chapters of Road Maps.

Note each of the following System Principles that were illustrated in *Building the Fish Banks Model*.



<u>System Principle #7:</u>
Rates depend only on Levels and Constants.

Look at Figure 7 on page 15 in *Building the Fish Banks Model*. Note that the only inputs to the rates **Fish Hatch Rate** and **Fish Death Rate** are the level **FISH** and constants. The two rates do not directly influence each other. Rates depend only on levels and constants.

We now introduce a new principle about decisions within feedback loops.

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

Look now at Figure 9 on page 19 of *Building the Fish Banks Model*. The decision made to determine the **Ship Building Rate** is part of two feedback loops (one positive, the other negative). Look again at Figure 7 on page 15. The "decisions" for Fish Hatch Rate and Fish Death Rate also occur within feedback loops.

No matter what the nature of the decision process—human, subconscious, biological, chemical, mechanical, electrical, etc.—it is always imbedded within at least one feedback loop.

It may be difficult to think of a machine or a chemical reaction as making decisions. In System Principle #8 we consider a “decision process” to be any case where a change is made based on information gathered in a system.

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.” Look in *Renewable Resource Depletion* at Figure 11 on p. 16 and the model equations on p. 37. **Yearly Profits** is defined as the difference between **Revenues** and **Costs**. Both **Revenues** and **Costs** must have the same units of measure, in this case $/year. Dimensional inequality between terms indicates a faulty equation formulation.

The following system principle is one that you have seen before. We are revisiting it in our spiral approach to emphasize its importance.

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

As you become familiar with the Fish Banks Model, trace through the feedback loops abundant within it. Notice that both the levels and the rates are fundamental substructure of the feedback loops. The loop dynamics cannot be represented without their inclusion. Further, the dynamics can be completely modeled with **only** the level and rate variables. These two variables are both necessary and sufficient to structure in representing a feedback system.

Since causal loop diagrams do not show the substructure described in System Principle #2, they lack much of the clarity of stock-and-flow diagrams. This leads to problems as described in the next section.

Shortcomings of Causal Loop Diagrams

In many previous readings and exercises in Road Maps, we have made use of causal loop diagrams. These diagrams are widely used to illustrate systems and their structure to people who are not familiar with system dynamics. However, as we will soon show you, these diagrams have problems of their own.

- *Problems with Causal Loop Diagrams*[5]

by George P. Richardson

This paper discusses some of the problems that arise when causal loop diagrams are used to model systems. The basic cause of these problems is that causal loop diagrams are not clear enough to convey structure or behavior, which are the defining characteristics of a system. Although the author redefines positive and negative loops to try to decrease confusion, the best way to avoid confusion is to use stock-and-flow diagrams to model the system directly without needing causal loop diagrams.

Now please read *Problems with Causal Loop Diagrams.*

After you have read *Problems with Causal Loop Diagrams*...

This paper explained why causal loop diagrams are used with caution by system dynamicists. Their structure does not show the difference between a stock and a flow, whereas the stock-and-flow diagram is much less ambiguous. The best way to avoid the confusion is to simply avoid using causal loop diagrams whenever possible. Causal loop diagrams can be used to explain behavior after the model is built, but using these diagrams to build models can be dangerous.

Finishing Off Road Maps Four

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[5] George P. Richardson, 1981. *Problems with Causal Loop Diagrams* (D-3312), System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, April, 23 pp. Current Address (as of 9/94): The Rockefeller College, SUNY-Albany, 135 Western Avenue, Albany, NY 12222.

Road Maps Four introduced the idea of transferability of structures, and explained that many different systems often exhibit similar types of behavior because of their same underlying structure. This chapter also showed how to mentally simulate the behavior of systems that contain a constant flow in addition to a positive or negative feedback loop. We described the "Tragedy of the Commons," and we explained why it occurs so frequently. Where does this type of behavior occur? Why is it an important phenomenon?

We also explained policy analysis, and the role of computer simulation games in teaching people about systems. What use are games in education? Why should people play these games? Why is policy analysis such a big topic in system dynamics?

In Road Maps Four we also described the limitations of causal loop diagrams, and explained how to avoid future misunderstandings caused by these limitations. Why do these tools break down when explaining systems?

Road Maps Four also presented three new systems principles: a) that rates depend only on levels and constants; b) that decisions are always made within feedback loops; and c) that every equation must have dimensional equality.

In Road Maps Five you will further develop your understanding of S-shaped growth through mental simulation and through studying the generic structures that produce it, and by exploring the spread of an epidemic. More theory about systems and their structure will be introduced as well.

Key Terms and Concepts:

Conserved Flow
Generic Structure
Information Link
Net Rate
Parameter
Policy Analysis
Tragedy of the Commons
Transferability of Structure