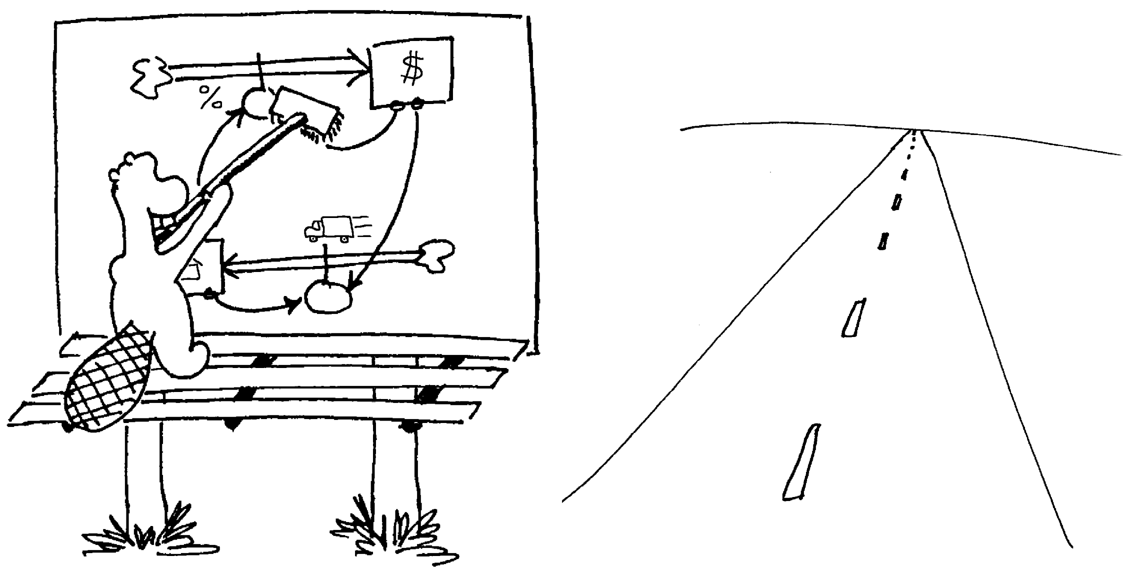
Road Maps 5

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 5

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

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Compiled under the direction of Professor Jay W. Forrester

Welcome to Road Maps Five!

Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Five is the fifth in the series of chapters in Road Maps. Road Maps One through Three gave you a broad introduction to system dynamics and focused on the building blocks of models: positive and negative feedback loops. Road Maps Four continued to broaden your understanding by introducing generic structures, policy analysis, computer simulation games, and tragedy of the commons.

In Road Maps Five you will explore and challenge the understanding of system dynamics that you have built in Road Maps One through Four. Specifically, Road Maps Five introduces the modeling of delays, mental simulation of S-shaped growth, generic structures producing S-shaped growth, the dynamics of the spread of an epidemic, and the concept of model validity. You will also practice and improve your graphical integration skills. At the end of Road Maps Five, we recommend that you read *Beyond the Limits*, an insightful book about the need for a transition to a sustainable world.

Topics Covered in Road Maps Five

An Introduction to Delays in Computer Modeling

- *Answers to Exercises for Chapter 17: Introduction To Delays* from *Introduction to Computer Simulation: A System Dynamics Modeling Approach* (D-4415)

by Kamil Msefer and Mark Choudhari

Beginner Modeling Exercises

- *Beginner Modeling Exercises Section 5: Mental Simulation of Combining Feedbacks in First Order Systems* (D-4593-1)

by Laughton Stanley and Helen Zhu

Transferability of Structures

- *Generic Structures: S-Shaped Growth I* (D-4432)

by Terri Duhon and Mark Glick

Model Validity

- *Dynamic Simulation Models: How Valid Are They?* (D-4463)
  by Ray C. Shreckengost

The Spread of an Epidemic: S-Shaped Growth

- *Teaching System Dynamics: Looking at Epidemics* (D-4243)
  by Will Glass

Graphical Integration Exercises

- *Graphical Integration Exercises Part 3: Combining Flows* (D-4596)
  by Kevin Agatstein and Lucia Breierova

Limits to Growth

- *Beyond the Limits*
  by Donella Meadows, Dennis Meadows, J?rgen Randers

Things You'll Need for Road Maps Five

Modeling Software

In order to complete Road Maps Five 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 books for Road Maps Five. *Introduction to Computer Simulation*, by Nancy Roberts et al, was previously required. Please note that selected chapters from this book are available for download on the SDEP server in electronic format.

Roberts, Nancy, 1983. *Introduction to Computer Simulation.*
Portland, Oregon: Productivity Press, 562 pp.

Meadows, Donella H., Dennis Meadows, J?rgen Randers, 1992.
Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future.
Post Mills, VT: Chelsea Green Publishing Co., 300 pp.

To order a copy of this book, contact Chelsea Green Publishing Co. (see Appendix).

How to Use Road Maps Five

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!

Introduction to Delays

- Answers to Exercises for Chapter 17: Introduction To Delays[1] from ***Introduction to Computer Simulation: A System Dynamics Modeling Approach*** by Nancy Roberts, et al.

by Kamil Msefer and Mark Choudhari

In Chapter 17 of *Introduction to Computer Modeling*, two different types of delays, material delays and information delays, are discussed. However, the chapter in the book has its models built in using the DYNAMO simulation language, and as you are probably using STELLA or iTHINK, we have translated the models for your convenience. In addition, the paper describes the use of STELLA delay functions such as SMTH1. The paper works through six modeling exercises and provides their solutions. If you understand equations written in DYNAMO, you do not have to refer to the paper when you do the exercises, unless you want to check your answers to the exercises.

The importance of delays is well presented by the following poem credited to W.L. Everitt:

There was a dachsund once so long
He hadn't any notion
How long it took to notify
His tail of an emotion.

And so it was that though his eyes
Were filled with woe and sadness
His little tail went wagging on
Because of previous gladness.

Please read and do *Chapter 17...* now.

After reading *Chapter 17...*

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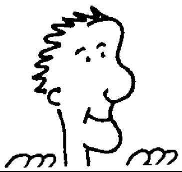
1 Kamil Msefer and Mark Choudhari, 1994. *Answers to Exercises for Chapter 17: Introduction to Delays* (D-4415) from Roberts, Nancy, David Andersen, Ralph Deal, Michael Garet, and William Shaffer, 1983. *Introduction to Computer Simulation: A System Dynamics Approach*, Portland, Oregon: Productivity Press. (800) 394-6868. 562 pp. The models in Chapter 17 are translated from DYNAMO into STELLA and answers to the exercises are provided. This translation was done for the System Dynamics in Education Project, System Dynamics Group with approval from the authors, August 5, 26 pp.

Chapter 17 explained why delay functions are used in computer modeling and gave you more experience with computer modeling. The answers to exercises also described the usage of some STELLA commands, such as SMTH1. What is the difference between a material and an information delay? When would you use them? Where would you include them in your model? Why is a delay important?

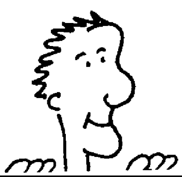
We now introduce two new system principles with examples from the chapter you've just read in *Introduction to Computer Simulation.*



<u>System Principle #10:</u>
First-order loops exhibit exponential behavior.

The first-order feedback loop always exhibits an exponential time shape. Take for example the solution given to Exercise 1 in *Answers to Exercises for Chapter 17* from *Introduction to Computer Simulation* (or look at your own solution). The system here is a first-order feedback loop—there is one level with feedback. Its solutions show an exponential approach to an upper value.

The solution to Exercise 5 is also a first-order feedback loop, and it also shows exponential behavior. All the first-order feedback solutions in this chapter—or anywhere—exhibit exponential growth or decay.



<u>System Principle #11:</u>
Levels completely describe the system condition.

Look at the solution to Exercise 7 on pp. 24-25 *of Answers to Exercises for Chapter 17: Introduction To Delays* from *Introduction to Computer Simulation*. There are two levels: **Apartments in Construction**, and **Total # of Apartments**. There are initially zero **Apartments in Construction**, and 10000 **Total # of Apartments**. This completely describes the state of system. The values of all other variables (the rate variables) can be computed from these values and the system equations alone.

Beginner Modeling Exercises

The next reading in Road Maps Five is the fifth in the series of Beginner Modeling Exercises. You have already learned how to mentally simulate positive and negative feedback systems, as well as systems with constant flows. We will now look at mental simulations of first-order systems with combined feedbacks.

- Beginner Modeling Exercises Section 5: Mental Simulation of Combining Feedbacks in First-Order Systems[2]

by Laughton Stanley and Helen Zhu

The fifth paper in the Beginner Modeling Exercises series explains mental simulation of systems with both a positive and a negative feedback loop. It describes four different examples of such systems, and discusses how to mentally simulate the behavior they produce. Exercises and their solutions are provided at the end of the paper.

Please read *Beginner Modeling Exercises Section 5* now.

After reading *Beginner Modeling Exercises Section 5...*

This paper explained that systems with combined positive and negative feedback can produce four different kinds of behavior: equilibrium, exponential growth, asymptotic growth, and S-shaped growth, and described how to use mental simulation to estimate the behavior of these systems. It is necessary to understand the concepts introduced in this paper before moving on to the next reading.

Transferability of Structures

In Road Maps Four, you learned about the generic structures in first-order positive and negative feedback systems. Generic structures are structures that are common to several systems. You will now see which generic structures produce S-shaped growth.

- Generic Structures: S-Shaped Growth I[3]

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[2] Laughton Stanley and Helen Zhu, 1996. *Beginner Modeling Exercises Section 5: Mental Simulation of Combining Feedbacks in First Order Systems* (D-4593-1), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May 28, 28pp.

by Terri Duhon and Marc Glick

This paper develops the concept of generic structures and presents two different systems that produce S-shaped growth. STELLA II models are used to describe the fact that generic structures are common to many systems. Causal loop diagrams are also used to explain why these specific generic structures produce S-shaped growth behavior. This paper emphasizes the transferability of these two structures to explain S-shaped growth in models of different systems.

Please read *Generic Structures: S-Shaped Growth I* now.

After reading *Generic Structures: S-Shaped Growth I*...

This paper again emphasized that in many cases different systems share the same underlying structure. Can you think of any other systems that have similar structures producing S-shaped growth? Transferability of structure is important in system dynamics 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 be familiar. It is important to understand the two structures introduced in this paper before moving to the next paper in the generic structures series.

The following system principle about levels has been introduced earlier in Road Maps. Now we discuss it again to emphasize its importance through an example in the *Generic Structures* paper that you just read.

System Principle #5:

Levels are changed only by the Rates.

Look at the model depicted in Figure 5a (and similarly in 5b) of *Generic Structures: S-Shaped Growth I*. Note that **Rabbit Population** is changed only by the rates **Births** and **Deaths**. **Rabbit Population** is increased by **Births** decreased by **Deaths**. But no other variables alter the levels. Only rates can change levels. Even the levels do not alter each other or themselves.

A level variable's current value is computed using only its previous value and the change due to the rates acting on the level. The earlier value of the level is

[3] Marc Glick and Terri Duhon, 1994. *Generic Structures: S-Shaped Growth I* (D-4432), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, June 22, 25 pp.

carried forward from the previous period. It is altered by rates that flow in and out of the level over the intervening time period. The present value of a level is not directly dependent on the present or previous values of any other levels.

We now introduce a new system principle.

System Principle #12:
Variables have the same units within conservative subsystems.

Recall from System Principle #6 that levels exist in conservative subsystems—the contents of stocks are neither created nor destroyed, just moved between levels via flows. Levels connected within a conservative subsystem have the same units of measure.

For example, look at the models on p.10 of *Generic Structures: S-Shaped Growth I*. The units of measure for both levels in the Epidemic model is People (both sick and healthy). The units of measure for both levels in the New Product Life Cycle model is Customers. Levels have the same units within conservative subsystems.

Model Validity

Have you ever looked at a model and wondered whether or not it was valid? How does one know whether or not the structure, components, or assumptions made while creating a model are valid? Is there any way to test a model for validity?

- Dynamic Simulation Models: How valid are they?[4]

by Ray C. Shreckengost

In this paper, the author outlines several structural, behavioral and policy implication tests that can be applied to a model to test its validity. He continues on to explain why these tests are different from the more traditional statistical tests.

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4 Raymond C. Shreckengost, 1984. Self-Report Methods of Estimating Drug Use: Meeting Current Challenges to Validity, *Dynamic Simulation Models: How valid are they?* (D-4463), NIDA Research Monograph 57, DHHS Publication No. (ADM)85-1402, May, 13 pp. Also available upon request from the System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology.

This paper also emphasizes certain good modeling practices, such as the emphasis on judgment and intuition rather than data in determining a model's structure.

Please read *Dynamic Simulation Models* now.

After reading *Dynamic Simulation Models...*

The paper offered some excellent tools to check the validity of models which you may create in the future. These tests are also good for critiquing other people's models. However, remember that there is no one right way to model a situation; as mentioned in the paper, there are as many valid models as there are different fingerprints. The only thing that will determine in the end whether or not a model is valid is the usefulness of the model to the user. While modeling, it is important to think of what you are trying to demonstrate with your model, and how you can show this through your model.

The Spread of an Epidemic: S-Shaped Growth

In Road Maps Three, you saw a model that showed S-shaped growth. In Road Maps Five, you have mentally simulated a system producing this type of behavior, and you just explored the generic structures that generate it. In this section, we will model the spread of an epidemic. Such a system also shows S-shaped growth, but with a different structure than the one shown earlier.

***- Teaching System Dynamics: Looking at Epidemics*[5]**

by William Glass-Husain

This paper is a complete set of information and suggestions for teachers who want to begin system dynamics curricula in their classrooms. The paper includes notes, transparencies, worksheets, and handouts. We only ask that you read certain parts of the paper but if you are interested in the rest of the information, feel free to review the entire paper.

The paper describes The Epidemic Game, a game where a "disease" is spread by shaking hands. By playing the game, the students gain an understanding of the

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[5] William Glass-Husain, 1991. *Teaching System Dynamics: Looking at Epidemics* (D-4243), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, October 3, 54 pp.

dynamics of an epidemic. Afterwards, the students can model the game in STELLA and learn about the structure of the system.

Read pages 18 and 19 to learn about the game and the model. Then skip ahead to page 33 and complete all the exercises. The exercises may seem simple at first, but they are an important review of feedback loops.

This paper uses the terms "balancing loop" and "reinforcing loop" in place of "negative feedback loop" and "positive feedback loop." The different terms do not imply a different meaning; they were invented to move away from the connotations of "positive" and "negative" movement that most beginning modelers confuse with the true meanings of "positive" and "negative" feedback.

Now please read *Teaching System Dynamics: Looking at Epidemics.*

After you have read *Teaching System Dynamics...*

This paper described that the spread of an epidemic (or a rumor, joke, etc.) has a characteristic S-shape. Notice that S-shaped behavior can be caused by two different structures. This behavior is common to all systems where something spreads until it approaches some kind of limit. This limit could simply be the number of people in a room or the area of a plot of land. The paper explained why the system starts off with exponential growth and then switches to goal-seeking behavior. What is happening in the system to create this behavior?

The following System Principle is one that you have seen before. We are revisiting the principle in order to emphasize its importance.

<u>System Principle #5:</u>

Levels are changed only by the Rates.

Look at the model depicted on page 20 in *Appendix III* of *Looking at Epidemics*. Note that **Healthy People** and **Sick People** are changed only by the rate **New Infections**. **Healthy People** are decreased by this rate and **Sick People** are increased. No other variables alter the levels. Even the levels do not alter each other or themselves.

A level variable is computed by the change, due to rate variables, that alters the previous value of the level. The earlier value of the level is carried forward from the previous period and is altered by rates that flow in and out of the level over the intervening time period.

Graphical Integration Exercises

Road Maps Two and Three introduced you to graphical integration of constant, step function, and linearly increasing and decreasing flows. However, in the previous two papers in the Graphical Integration Exercises series, we have only looked at systems with a net flow. We will now turn to consider systems with a separate inflow and outflow.

- Graphical Integration Exercises Part 3: Combining Flows[6]

by Kevin Agatstein and Lucia Breierova

The third paper in the Graphical Integration Exercises series explains the methods of graphical integration to estimate the behavior of systems with an inflow and an outflow. It shows how to calculate the net flow, and then expands your knowledge from the first two papers to find out the value of the stock. You can then test your understanding of these concepts by doing the exercises; their solutions are again provided at the end of the paper.

Please read *Graphical Integration Exercises Part 3* now.

After reading *Graphical Integration Exercises Part 3...*

This paper developed your skills of using graphical integration as a method to estimate the behavior of the stock. It also reviewed how to find the stock ís value at a certain point in time. Doing all the exercises and understanding the concepts presented in the paper completely is necessary before moving on to the next paper in this series.

Limits to Growth

- Beyond the Limits[7]

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[6] Kevin Agatstein and Lucia Breierova, 1996. *Graphical Integration Exercises Part 3: Combining Flows* (D-4596), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, March 14, 32 pp.

[7]Meadows, Donella H., Dennis L. Meadows, J?rgen Randers, 1992. *Beyond the Limits: Confronting Global Collapse Envisioning a Sustainable Future*, Post Mills, VT: Chelsea Green Publ. Co., 300 pp.

by Donella Meadows et al.

Beyond the Limits is the sequel to the bestseller, *The Limits to Growth*[8], which was written twenty years ago by the same authors. We feel that this book is important enough to encourage you to read it. The following is a review of *Beyond the Limits* by which we hope to inspire you to read the book.

REVIEW: *Beyond the Limits*

In *Beyond the Limits* , a system dynamics model, WORLD3, was used to analyze the Earth's limits to population growth, nonrenewable resources, pollution, food production and industrial output. The original book that used a system dynamics model of the world was *World Dynamics*[9] by Forrester, which, along with *Limits to Growth*, sparked much controversy and public debate. This sequel provides an update of the model and its implications based on the 20 years that have passed since the publication of *Limits to Growth*.

By using the WORLD3 model, one is able to see into the future with the ability to vary global policy assumptions. The model allows one to try different things and test different scenarios. The policies that the authors test result in outcomes that range from collapse to the ability to sustain the human race. The authors discuss the importance of balancing long and short term goals in an effort to make a transition to a sustainable society. Specifically the book discusses possible changes in the situation of our society which could help bring about sustainability.

The book stresses that the driving force pushing us into a potential overshoot situation is exponential growth. As you have discovered thus far, exponential growth behavior results from a positive feedback situation.

In this sequel, the information that was included in the *Limits to Growth* is updated and a number of new insights are discussed. The depletion of the ozone layer is given as an example of an overshoot situation. The authors look at this story in some detail, and express a certain degree of hope based on human reactions to this global problem.

The entire model is also displayed in the book. It is separated into its different subsystems, and displayed in STELLA. (The original model was in

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[8] Meadows, Donella H., Dennis L. Meadows, J?rgen Randers, William W. Behrens III, 1992. *The Limits to Growth*, New York, New York: Universe Books, 205 pp.

[9] Forrester, Jay W., 1971. World Dynamics, (1973 second ed.). Portland, Oregon: Productivity Press. 144 pp. Second ed. has an added chapter on physical vs. social limits.

DYNAMO.) This book is intriguing, and is a good example of the power of using a system dynamics modeling approach for real world issues and problems.

In order to provide some background of the books that address the world model (and its revisions), we will include here a few of the numerous criticisms and review comments that surrounded the initial publication of *World Dynamics* and *Limits to Growth*. The issues were in the press and publications ranging from *Technology Review* to *Playboy*.

The books sparked controversy, inspired public debate, and encouraged others to pursue global models to study this issue. *The Henoit Book Review* said that "This book will open eyes, stimulate studies, start fights, and affect public policies."[10] William Bowen of *Fortune* stated in 1971 that "This year will not see the publication of a more important book than Forrester's *World Dynamics*, or a book more certain to arouse dislike."[11]

Some have centered their criticisms around the structure and assumptions of the model, while others have looked at conclusions and policy recommendations in the books. As Robert Gillette stated in *Science*, "There are too many assumptions that are not founded, and there is too high a level of aggregation in the model."[12] Robert Solow, an MIT economist, and other economists assert that the model is not valid without a pricing system. The books have been labeled "doomsday" predictions and some have claimed that the authors started with a conclusion and worked their way backwards to the structure without valid data.[13] Other criticisms are in a different light. Henry Wallich, a Yale economist, said: "This is a piece of irresponsible nonsense, a publicity stunt."[14] Wallich is also a proponent of the theory that physical (economic) growth equals progress. Martin Shubik of Yale was also quite skeptical: "This is extremely simplistic, given the current state of knowledge in the social sciences."[15]

On the other side, there are an equal number of rave reviews. Anthony Lewis of the New York Times said that "This is likely to be one of the most important documents of our age..."[16] Eliot Richardson, Secretary, HEW, said "Too thoughtful,

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[10] *Henoit Book Review*, 1972, Vol. 126 America, p. 636.

[11] William Bowen, *Fortune*, Sept. 1971, Vol. LXXXIV, No. 3, p. 131.

[12] Robert Gillette, *Science*, 10 Mar 1972, Vol. 175, No. 4026, p. 1088.

[13] Robert Solow, Proceedings of the National Academy of Sciences, "Notes on Doomsday Models", Dec. 1972, Vol. 69, No. 12, 3833.

[14] Henry Wallich, *Connecticut Review*, 1972, Vol. 6, No. 1, 7.

[15] Martin Shubnik, *Science*, 3 Dec. 1971, Vol. 174, No. 4013, p. 1014.

[16] Anthony Lewis, *The New York Times*, 4 Oct. 1973.

too thorough, too significant to ignore even if it is not entirely correct."[17] E.J. Mishan of Great Britain studied the global situation in an entirely different way and came to a similar conclusion.[18] Robert S. Saunders in the *Stanford Journal of International Studies* stated that "The book makes a number of philosophical contentions in the most dramatic and convincing way," and that "this was not a very technical or academic paper, but it is a crucial philosophical treatise about man's role on the planet."[19]

There were also a number of responses to these criticisms by the authors. These responses were often backed by a number of people who reviewed the books favorably. In response to the exclusion of prices, the authors pointed out that prices are inherent in the system because of the structure. The authors admitted that this was not a perfect model, but they asked: "Is there a better one? Produce better data." They insisted that people should awaken from the dream that growth has no limits, and anticipated people would simply not like this idea. The authors insisted that physical growth must inevitably come to an end.

Obviously, the models and books have led to much controversy and debate. We encourage you to read *Beyond the Limits*, draw your own conclusions, and join the public debate that will surround issues related to the present day version of the model.

Finishing Off Road Maps Five

Road Maps Five covered a broad spectrum of intermediate concepts in system dynamics through readings and exercises. Delays in computer models were introduced through Chapter 17 of *Introduction to Computer Simulation.* Delays are an important concept to understand in system dynamics. You continued to develop your mental simulation skills on first-order systems with combined feedbacks. Generic, or transferable, structures were developed through the explanation of S-shaped growth and two different structures that cause this common behavior. Model validity was explored in *Dynamic Simulation Models: How Valid Are They?* through various tests which can be applied to existing and future models. We also

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[17]Elliot Richardson, *Industrial Engineering*, Sep. 1972, Vol. 4, No. 9.

[18] E.J. Mishan, *Connecticut Review*, 1972, Vol. 6, No. 1.

[19]Robert S. Saunders, *Stanford Journal of International Studies*.

explained the dynamics of the spread of an epidemic. What other types of systems can be represented this way? You have also practiced your graphical integration skills in estimating the behavior of systems with independent inflows and outflows. Road Maps Five also introduced three new system principles: a) that first-order loops exhibit exponential behavior; b) that levels completely describe the system condition; and c) that variables have the same units within conservative subsystems.

Finally, you've now had some insight into a real-world controversy related to system dynamics used for policy analysis. The authors of *Beyond the Limits* have repeatedly claimed that the increasing rate of growth of world systems cannot continue as it has in the past. How do they justify that statement? Can you find evidence that supports or casts doubts on their predictions? Try looking in the newspaper for examples.

Road Maps Six describes how system dynamics can be used in economics, and introduces more generic structures. It also gives you a first experience with completely independent computer modeling.

Key Terms and Concepts:

Balancing Loop
Delays
Generic structure
Limit to Growth
Model validity
Reinforcing Loop
S-shaped growth
Transferability of structure

Appendix: Names and Numbers

- To obtain additional copies of Road Maps, please visit our System Dynamics in Education home page on the World Wide Web at:

http://sysdyn.mit.edu/

If you do not have access to the World Wide Web, you can buy paper or disk copies of Road Maps through:

Lees Stuntz
Creative Learning Exchange
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Acton, MA 01720, USA
Phone: (508) 287-0070
Fax: (508) 287-0080
Email: stuntzln@tiac.net

- For information on the System Dynamics in Education Project, please visit our home page, or contact:

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System Dynamics in Education Project
System Dynamics Group
E60-383
Massachusetts Institute of Technology
30 Memorial Dr.
Cambridge, MA 02139, USA
Phone: (617) 253-1574
Fax: (617) 258-9405
Email: nlux@mit.edu

- To inquire about educational prices for STELLA II software, please contact:

High Performance Systems
45 Lyme Road
Hanover, NH 03755, USA
Phone: 1-800-332-1202 (product inquiries)
(603) 643-9636 (customer support)
Fax: (603) 643-9636
Email (for customer service, tech support and product questions): support@hps-inc.com
WWW Site: http://www.hps-inc.com/

- Although Road Maps is written specifically around the STELLA II software, two other software applications are suitable for use with Road Maps, assuming the user is willing to make some interpretations and translations:

Powersim for PC:

Powersim Corporation
12030 Sunrise Valley Drive, Suite 300
Reston, VA 22091, USA
Phone: (703) 391-2779
Fax: (703) 391-2768
Email: powersim@powersim.com

Vensim for PC or Macintosh:
Ventana Systems, Inc.
149 Waverley Street
Belmont, MA 02178, USA
Phone: (617) 489-5249
Fax: (617) 489-5316
Email: vensim@world.std.com
A free "Personal Learning Edition" of Vensim can be downloaded from:
http://www.vensim.com/

- If you have any questions about obtaining books required for Road Maps, please contact their respective publishers:

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WWW Site: http://www.pegasuscom.com/

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Portland, OR 97213
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- Road Maps HELP line: If you are having any problems with the material in Road Maps, or if you have any helpful comments or suggestions, please email:

rm-help@sysdyn.mit.edu

outlining your problem. We will respond as soon as possible.

- To join the K-12 Discussion Group for educators interested in using System Dynamics to teach, email Nan Lux, discussion group administrator, at **nlux@mit.edu**