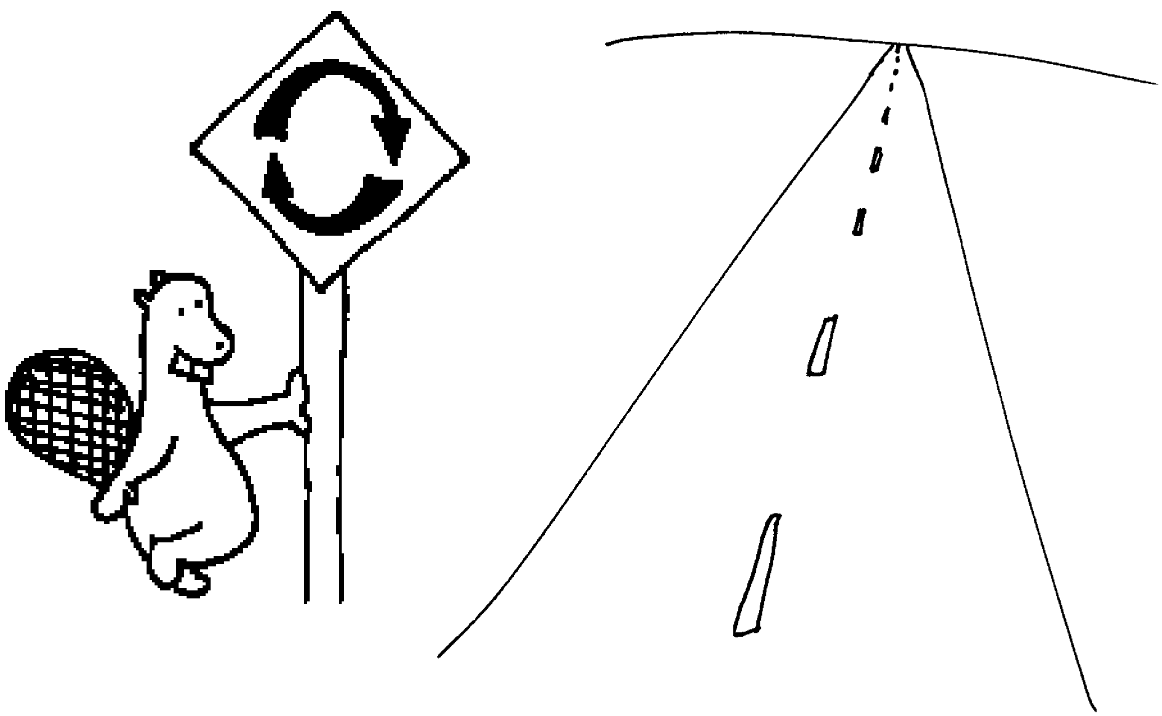
Road Maps 2

A Guide to Learning System Dynamics



System Dynamics in Education Project

Road Maps 2

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

Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Two is the second in the series of chapters in Road Maps. In Road Maps Two, you will begin to model simple systems using STELLA II™ (Systems Thinking Educational Learning Laboratory with Animation) software. STELLA is an easy-to-use software package which allows the user to create and run models on the computer.

Road Maps Two continues to expand on the concept of feedback loops introduced in Road Maps One through causal loop exercises. It also introduces graphical integration and the concepts of levels and rates, as well as the relationship between feedback loops and levels and rates.

Topics Covered in Road Maps Two

Introduction to Computer Modeling

- *The First Three Hours* (D-4230-3)
  by Matthew Halbower
- *Getting Started with STELLA II: A Hands-On Experience* (STELLA tutorial)

Causal Loop Exercises

- *Study Notes in System Dynamics,* Exercise 1
  by Michael R. Goodman
- *Beginner Modeling Exercises* (D-4347-5) and *Answers to Beginner Modeling Exercises* (D-4356-3)
  by Shayne M. Gary and William Glass-Husain

Graphical Integration Exercises

- *Graphical Integration Exercises Part 1: Exogenous Rates* (D-4547)
  by Alice Oh

From Causal Loops to Levels and Rates

- *Introduction to Computer Simulation,* Chapter 13 Levels and Rates
  by Nancy Roberts et al.

Things You'll Need for Road Maps Two

STELLA II Software

In order to complete Road Maps Two and subsequent Road Maps, you will need to have access to STELLA II. STELLA II is currently available for both the Macintosh and the Windows platforms. The Road Maps guides and several papers included in Road Maps were written with the use of STELLA II for the Macintosh. If you have any questions about STELLA, contact High Performance Systems (see Appendix). Ask about prices for educational use.

A Computer

To run STELLA on a Macintosh, you will need an Apple Macintosh computer (Macintosh Plus or higher) with at least 2 MB of RAM, a hard disk and System 6.0.4 or higher. If using System 7, you will need at least 4 MB of RAM.

To run STELLA for Windows you will need an IBM PC-compatible computer with a 486-class processor or 386 Enhanced mode running Windows 3.1 or greater. You'll need at least 4 MB RAM, a hard disk with a least 5 MB free space, and a 3.5-inch high-density floppy drive.

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 Two. These books will also be used in later Road Maps.

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

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

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

How to Use Road Maps Two

Road Maps Two 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 Computer Modeling

The first two readings in Road Maps Two will get you started with the basics of modeling in STELLA. You don’t need any experience using STELLA or a computer before. We'll help you one step at a time, from turning on the computer to actually creating a working model in STELLA.

· ***The First Three Hours***[1]

by Matthew Halbower

The First Three Hours goes over the basics of system dynamics and introduces basic terms and concepts. It will guide you through creating your first models in STELLA, and will help you with using the software itself.

Please read *The First Three Hours* now.

After reading *The First Three Hours*...

The First Three Hours covered a great deal of important material. It helped you to construct, analyze and test a two-level multiple-rate system. It also explained the concepts of stocks and flows and the fundamental role they play in building models of systems.

Before you continue, it is important to note that while *The First Three Hours* uses the terms **stocks** and **flows**, the terms **levels** and **rates** can also be used. 'Stocks' and 'levels' are used interchangeably in system dynamics, as are 'flows' and 'rates'. Also, the two pairs of terms are always used in conjunction with each other. In other words, you should use 'stock' and 'flow' together, or use 'level' and 'rate' together, and not mix the terms as in 'stock' and 'rate'. Speaking of levels and rates...

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

Look at the model in Figures 4b and 4c on pages 15-16 in *The First Three Hours*. Note that the level (**Water in Bathtub**) and rates (**Water Inflow Rate** and **Water Outflow Rate**) are the primary components of structure. Levels and rates are fundamental to system structure.

System Principle #2 is important to understand, since all system dynamics models use levels and rates as loop substructure. The distinction must be made

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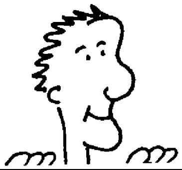
[1] Halbower, Matt C., 1991. *The First Three Hours* (D-4230-3), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, May, 50 pp. This paper is accompanied by a Macintosh® computer disk.

between this principle and System Principle #1, which states that feedback loops are the building blocks of systems. Just as feedback loops are the building blocks of systems, levels and rates are the building blocks of feedback loops.



<u>System Principle #3:</u>
Levels and Rates are not distinguished by units of measure.

Look at the model in Figure 26 on page 38 of *The First Three Hours*. Note that **Jay's Velocity** is a level and that **Velocity of Jay** is a rate, yet they both have the same units, meters per second. Units do not determine whether a variable is a level or a rate.

System Principle #3 is important to in modeling, because it tells us not to assume that a particular component of a system is a level or a rate just from looking at its units of measure. Can you identify any other real-life components that can be classified as either a level or a rate?

The next exercise provides more experience with modeling in STELLA.

- ***Getting Started with STELLA II: A Hands-On Experience***
  (included with STELLA II software)

This booklet is part of the STELLA II software package. For versions of STELLA II before version 2.2.1, the equivalent exercise is in Chapter 2 of *An Academic User's Guide to STELLA II*, titled <u>An Extended Example</u>. *Getting Started with STELLA II* not only introduces the software that is most widely used in teaching system dynamics today, but also introduces some basic modeling concepts that will be explored further.

The reading uses a predator-prey system to incorporate instructions for building a one-level model, entering the equations, and running the model. This should be quite similar to what you have just done in *The First Three Hours*. However, *Getting Started with STELLA II* will also introduce several unique features of the software, such as using and creating high-level maps and sub-models.

Please read *Getting Started with STELLA II* now.

After reading *Getting Started with STELLA II*...

This exercise provided more practice for understanding the software and for working with the various tools in it. The reading also briefly mentioned "overshoot and collapse" which is one of several common patterns of behavior which will be discussed in future Road Maps. There are also other common behaviors, and they will be explained in greater detail later in Road Maps. However, you can now begin to watch for these types of behaviors as you investigate more models.

Causal Loop Exercises

The next two readings are designed to give you practice with developing and understanding causal loop diagrams. Causal loop diagrams are a good way to understand feedback loops and causal relationships among constituents of a system, but as we will show later, they are only one of many tools for understanding systems.

· ***Study Notes in System Dynamics*,**[2] Exercise 1

by Michael R. Goodman

Exercise 1 of *Study Notes in System Dynamics* provides hands-on practice in developing your causal loop diagramming abilities. It gives several scenarios and asks you to draw causal loop diagrams for each. We’ve included some tips and questions to help you in completing this exercise.

Please begin Exercise 1 of *Study Notes in System Dynamics* now.
Use the following guide to help you through the material:

Read through Exercise 1.1 (E1.1) on pages 137-138. Then read through the solution S1.1 on pages 141-145. The problem given in E1.1 illustrates how system dynamics can be used to organize a narrative description into a more explicit form. The problem is not well defined, so many assumptions must be

[2] Goodman, Michael R., 1974. Study Notes in System Dynamics, Portland, Oregon: Productivity Press. 800/394-6868. 388 pp.

made about the system. S1.1 is an excellent example of how to approach this type of problem.

Read through E1.2, "Ecology—Population Growth and Regulation" given on the bottom of page 138. To tackle this problem, follow the outline given below to create a causal loop diagram for the system. The outline is in the same format as S1.1, the solution to Exercise 1.1, but the links are not given. (The key variables are highlighted in **bold**.)

- The **population** is increased by the number of **births**.
- The number of **births** is increased by the size of the **population**.
- The **population** is reduced by the number of **deaths**.
- As the **population** increases, the number of **deaths** increases.
- As the **population** increases, the population **density** of the **area** also increases.
- As the given **area** increases, the **density** decreases. (Since the **area** is not affected by any other variables, i.e. it does not change with the values of other variables in the system, it is called an exogenous variable. A variable that is affected by other factors within the system is known as an endogenous variable.)
- As the **density** increases, the **fertility** is decreased; therefore, the number of **births** decreases. (This is not intuitive; what assumptions are being made?)
- The population **density** affects the **average lifetime** of individuals which in turn affects the **deaths**. (This is not intuitive either; what assumptions are being made?)

Now compare your causal loop diagram to the answer given on page 145.

Read through "Economics—Economic Development" on page 139. For each of the variables listed below, ask yourself: What does this variable affect? and What affects this variable? As you do this, draw the causal loop diagram. Then compare your answer to the diagram on page 146.

- **human labor**
- **consumable goods**
- **capital goods**
- **capital stock**
- **aids to labor**
- **production**

Read "Sociology–General Group Processes" on pages 139-140. Again, for each of the variables listed below ask: What does this variable affect? and What affects this variable? As you do this, draw the causal loop diagram. Then compare your answer to the diagram on page 146.

- **intensity of interaction among group members**
- **level of friendliness among group members**
- **total amount of activity carried on by members of group**
- **amount of activity imposed to justify group's continued existence** (exogenous)

Read "Psychology–Managerial Goal Setting" on page 140. Then use the variables given below to diagram this system. Once again remember to ask: What does this variable affect? and What affects this variable? Then compare your answer to the diagram on page 147.

- **operational goal**
- **absolute goal** (exogenous)
- **traditional performance**
- **weighting factor**
- **management projection of goal** (exogenous)
- **effective size** (measured by the delays and conflicting pressures of the organization)
- **observed conditions**
- **difference** (between observed conditions and the operational goal)
- **actions**
- **delays and conflicting pressures**
- **actual performance**

After reading Exercise 1 of *Study Notes in System Dynamics*...

Two different ways to represent a system have been introduced so far. The first is a stock-and-flow diagram used in both *The First Three Hours* and *Getting Started With STELLA II*. The second is the causal loop diagram you just explored in Exercise 1.

Because a causal loop diagram is a very general representation of a system, as opposed to the more explicit stock-and-flow diagram, causal loop diagrams can cause many misunderstandings that you may have already encountered. These problems will be explored later in Road Maps. The stock-and flow diagrams are more explicit.

- ***Beginner Modeling Exercises*** and ***Answers to Beginner Modeling Exercises*** [3]

by Michael Shayne Gary and William Glass

Beginner Modeling Exercises will give you a chance to test yourself on what you've learned so far in Road Maps One and Two. In these exercises, you are asked to identify stocks and flows, draw causal loop diagrams, assign positive or negative signs to links, and convert causal loop diagrams to stock-and-flow diagrams. Use the *Answers to Beginner Modeling Exercises* to check your answers.

Please read and complete *Beginner Modeling Exercises* now.

After completing *Beginner Modeling Exercises*...

These exercises are a good review of what was introduced in Road Maps One and Two to this point. It is important to be able to do all these exercises and, if necessary, to review some of the material before continuing to work through Road Maps.

Graphical Integration Exercises

Computer programs such as STELLA II are a very powerful tool in simulating systems. However, we must also be able to estimate the system behavior without using a computer. The next reading introduces the method of graphical integration.

- ***Graphical Integration Exercises Part 1: Exogenous Rates*** [4]

by Alice Oh

This is the first in a series of papers on graphical integration. It explains the methods of graphical integration for systems with constant and step function

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[3] Gary, M. Shayne, William Glass, 1992. *Beginner Modeling Exercises* (D-4307) and *Answers to Beginner Modeling Exercises* (D-4356-3), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, July 22, 6 pp.

[4] Alice Oh, 1995. *Graphical Integration Exercises Part 1: Exogenous Rates* (D-4547), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, Dec. 1, 19 pp.

rates. You will be asked to do several exercises; you can check your answers in the appendix.

Please read *Graphical Integration Exercises Part 1* now.

After completing *Graphical Integration Exercises Part 1*...

The method of graphical integration is very useful in estimating the behavior of many systems. This paper covered systems with constant positive and negative rates as well as step function rates. It is necessary to understand this method fully before moving to the next paper in this series.

From Causal Loops To Levels And Rates

So far, we have mostly used a causal loop diagram to understand the relationships between the different variables in a system. However, a more explicit way of representing the system, a stock-and-flow diagram, is often needed.

· ***Introduction to Computer Simulation*,**[5] Chapter 13 Levels and Rates
by Nancy Roberts et al.

Chapter 13 of *Introduction to Computer Simulation,* "Levels and Rates," explains stock-and-flow diagrams as a progression from causal loop diagrams. The equations that correspond to the variables in stock-and-flow diagrams will also be explained. The equations in Chapter 13 are written in the DYNAMO simulation language. DYNAMO is the computer simulation language that was used in system dynamics between 1963 and 1986, so we will provide help with understanding DYNAMO equations, and with converting DYNAMO equations to STELLA.

Please begin Chapter 13 of *Introduction to Computer Simulation* now.
The following tips may help you:

Read Chapter 13 from page 223 up to and including the top of page 229. Do all of the exercises asked for, and read through all of the examples.

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[5] 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.

Modeling Figure 13.11 on STELLA

Read “Simulation, Structure, and Behavior” from page 229 up to and including the first paragraph on page 231. Until now, all of the exercises and examples in Chapter 13 have only asked for hand drawings of flow diagrams. For this example, we will model the flow diagram in Figure 13.11 on STELLA.

- Open a new STELLA file.
- Place a stock ( ) in the middle of your screen and rename it “POPULATION.”
- Place a flow ( ) to the left of the POPULATION stock and have it flowing into it. Rename the flow “BIRTHS.” Your model on the screen should now look like Figure 13.11.

Defining Figure 13.11 in STELLA

Read from the second full paragraph on page 231 up to Exercise 5 on page 234. Example 2 calls for simulation of the model you are building. The book derives and uses DYNAMO equations to do this. Follow the directions below to convert the DYNAMO equations to STELLA.

Look at the DYNAMO equations in the middle of page 233.

- To convert "BIRTHS = 100" into a STELLA equation, toggle the globe in the upper-left-hand corner ( ) so that it becomes X^2. Question marks should appear in the stock and flow.
- Double-click on BIRTHS and the dialog box will appear on your screen. Type "100" as the equation for BIRTHS. (Units of BIRTHS are in people per year.)
- Click on the Document button. In the document box, type "100 babies are born every year in the kingdom of Xanadu." Click OK.
- Double-click on the POPULATION stock and type "5510" (the initial population of Xanadu).
- Click on Document. Type "The initial population of Xanadu is 5510 people." Click OK.

To view the equations for the model you’ve just created, click on the arrow ( ) above the X^2 icon. Then select Equation Prefs under the Edit menu.

Once the Equation Prefs dialog box appears on your screen, click on Show Documentation. Click OK. The following equations will appear:

POPULATION(t) = POPULATION(t - dt) + (BIRTHS) * dt
INIT POPULATION = 5510 {people}
DOCUMENT: The initial population of the kingdom of Xanadu is 5510 people.
BIRTHS = 100 {people/year}
DOCUMENT: 100 babies are born every year in the kingdom of Xanadu.

You will notice that you typed in the information for everything except the first equation for POPULATION. This is because every stock equation is automatically formulated by STELLA. Notice the similarities between the equation that STELLA uses and the DYNAMO equation for this stock.

· Click on the arrow (△) to get the model back.

Read and do Exercise 5 on page 234 as it is written in the book.

Simulating Figure 13.11 in STELLA

Read and do Example III on pages 234-238 as it is written in the book, including Exercises 6 and 7. The hand calculation that Example III requires can be done much more easily by using the STELLA model you've just created. The directions for creating and running a table in STELLA are given below:

· Create a table by clicking on the table icon () and placing it on the workspace. Double-click on the table to make the table dialog box appear. Rename the table "Xanadu Table."
· The table now needs to be defined. Double-click on POPULATION and on BIRTHS in the Allowable list (or click on each variable, then click the >> icon). POPULATION and BIRTHS should now be in the Selected list.
· Click on Every Dt to de-select it. "1" should now be highlighted as the Report Interval. Click OK.
· Select Time Specs in the Run menu. When the dialog box appears, select "Years." Set the Range values from 2020 to 2040. Click OK.
· To run the table, select Run from the Run menu.
· Once the run is complete, note that the numbers in the table agree with Table 13.1 in the book.
· To close the table, click on the box in the upper-left-hand corner.

Exercise 6 asks you to graph the population of Xanadu through the year 2040. Since you have already constructed the model, generating a graph with STELLA is very easy. The time specs you entered for the table are also valid for the graph of the model.

- Create a graph by clicking the graph icon () and placing it onto the workspace. Double-click on the icon.
- Double-click on the graph pad itself to open it. When the dialog box opens, name the graph "Xanadu Graph." Double-click on POPULATION and on BIRTHS from the Allowable list to select them to be graphed. Click OK.

When STELLA graphs the variables in a model, each variable has a different scale. Also, the scales do not begin with zero unless the variable itself begins with a zero value.

- To see this, select Run from the Run menu.
- When the graphing is complete, double-click on the graph to open the dialog box again. Click on POPULATION under the Selected list and click on the double-headed arrow to the right of POPULATION (⇕). Set “4000” as the min and “8000” as the max for the range of POPULATION.
- Repeat this process for BIRTHS. Use the numbers "0" to "200." Now click Set, then click OK. The graph should now be rescaled.
- Close the graph.

Modeling and Defining Figure 13.13 in STELLA

Read through Example IV. In this example, a model is created to simulate world population growth. You can build this model on STELLA the same way you built the model for the population of Xanadu. The only difference in the two models is that in the world population model, the birth rate is not constant, but dependent on the population.

- Model the flow diagram in Figure 13.13 on page 238. Use the connector ( ) to connect POPULATION to NET BIRTHS. (The position of the connector can be changed by clicking on and moving the circle at the beginning of the arrow).

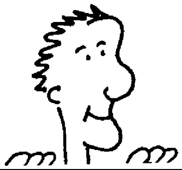
- Now you need to enter the equations for your model. Toggle the globe ( ) to x^2 and enter the initial world population into the model. Do not forget to document POPULATION.
- To complete the world population model, study the DYNAMO equations on page 239. Notice that a new variable, GROWTH FRACTION (GF), is introduced. Good modeling practice is to give every variable in a system a name and an icon (i.e., stock, flow, converter). Click once on the converter icon ( ) and name it GROWTH FRACTION. Connect GROWTH FRACTION to NET BIRTHS. Define GROWTH FRACTION as "0.02." Do not forget to document GROWTH FRACTION.
- The only variable left to define is NET BIRTHS. Double-click on NET BIRTHS to open up the dialog box. If the document window is open, click on Hide Document. Enter "POPULATION * GROWTH FRACTION" as the equation. Document BIRTHS.
- Compare the STELLA equations to the DYNAMO equations as you did previously.

Simulating Figure 13.13 in STELLA

- Create and define a table ( ) and a graph ( ) for this model as done before. Don't forget to:
  - Type in a title for each.
  - Select variables for each.
  - Change the report interval for the table.
  - Change the scales for the graph.
  - Enter the correct time specs for both simulations.
- Compare the table you created to Table 13.2 on page 241.

After reading Chapter 13 of *Introduction to Computer Simulation...*

Chapter 13 gave you more experience with using and creating stock and flow diagrams on STELLA, and explained how to enter the corresponding equations for models in STELLA. It also showed how to recognize and understand the equations for the stocks and flows in DYNAMO. Chapter 13 also illustrates System Principle #4:



<u>System Principle #4:</u>
Levels are accumulations (integrations).

In Example I on pages 227-228 of Introduction to Computer Simulation, levels are emphasized as quantities that accumulate over time. Note that the levels **children** and **adults** are accumulations of the rates **births** and **maturing**. Levels accumulate the results of rates (actions) in the system.

Try to think about some possible connections between causal loop diagrams and stock and flow diagrams. How are they alike? How do you think each would be most useful?

Finishing Off Road Maps Two

Road Maps Two explained how to use STELLA to create some simple models of systems on the computer. This is a skill which will become vital as you learn more about systems and system behavior. Graphical integration has been introduced as a method to estimate system behavior. Road Maps Two continued to explain how to create and use feedback loops through causal loop diagramming exercises, and examined the relationship between causal loops and levels and rates. Road Maps Two also introduced three more principles of systems: a) that levels and rates are fundamental to loop substructure; b) that levels and rates are not distinguished by units of measure; and c) that levels are accumulations.

Road Maps Three will continue to have you practice modeling on the computer and converting causal loop diagrams to stock-and-flow diagrams. You will also begin to explore common behaviors of systems in greater detail.

Key Terms and Concepts:

Causal Loop
Connector
Converter
Exogenous Variable
Endogenous Variable
Feedback Loop
Graphical Integration
Level/Stock
Negative Feedback
Positive Feedback
Rate/Flow

Appendix: Names and Numbers

To order additional copies of Road Maps, please contact:
Lees Stuntz
Creative Learning Exchange
1 Keefe Road
Acton, MA 01720
Email: stuntzln@tiac.net
Phone: (508) 287-0070
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For information on the System Dynamics in Education Project, please contact:
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E60-383
30 Memorial Dr.
Cambridge, MA 02139
Phone: (617) 253-1574
Fax: (617) 252-1998
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To inquire about educational prices for STELLA II software, please contact:
High Performance Systems
45 Lyme Road
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Phone: 1-800-332-1202 (product inquiries), (603) 643-9636 (customer support)
Fax: (603) 643-9636
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WWW Site: http://www.hps-inc.com/

If you have any questions about obtaining books required for Road Maps, contact:
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Order Dept.
P.O. Box 120 Kendall Square
Cambridge, MA 02142-0001
Phone: (617) 576-1231

Productivity Press
P.O. Box 13390
Portland, OR 97213
Phone: 1-800-394-6868, (503) 235-0600
Fax: 1-800-394-6286

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**

The address for our System Dynamics home page on World Wide Web is:
http://sysdyn.mit.edu/