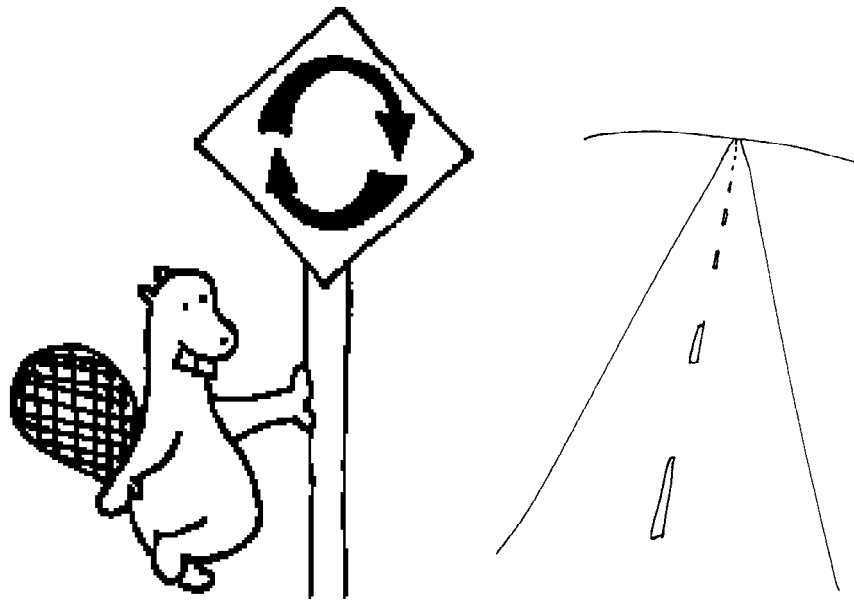# Road Maps 3

A Guide to Learning System Dynamics

System Dynamics in Education Project

Road Maps 3

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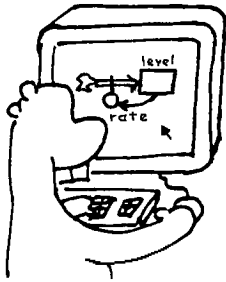Sloan School of Management
Massachusetts Institute of Technology

August 21, 1992
Latest Revision March 18, 2001

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Compiled under the direction of Professor Jay W. Forrester

Welcome to Road Maps Three!

Road Maps is a self-study guide to learning the principles and practice of system dynamics. Road Maps Three is the third in the series of chapters in Road Maps. In Road Maps Three you will reinforce the material you learned earlier in Road Maps One and Two while continuing to develop your modeling skills. Specifically, you will learn how to convert causal loop diagrams into flow diagrams and DYNAMO equations into their corresponding STELLA models and equations. Road Maps Three will expand your graphical integration as well as mental simulation skills. The modeling in Road Maps Three begins with positive and negative feedback loops and goes on to combining them to form an S-shaped growth structure. The final section of Road Maps Three is Professor Jay Forrester's book, *Urban Dynamics*. The book describes a system dynamics model used to study urban problems.

Topics Covered in Road Maps Three

Graphical Integration Exercises

- *Graphical Integration Exercises Part 2: Ramp Functions* (D-4571)
  by Kevin Agatstein and Lucia Breierova

Beginner Modeling Exercises

- *Beginner Modeling Exercises Section 2: Mental Simulation of Simple Positive Feedback* (D-4487)
  by Joseph G. Whelan
- *Beginner Modeling Exercises Section 3: Mental Simulation of Simple Negative Feedback* (D-4536)
  by Helen Zhu

Positive and Negative Feedback Loops

- *Study Notes in System Dynamics,* Exercises 4, 5
  by Michael R. Goodman

- Introduction to Computer Simulation, Chapter 15: Using Simulation to
Analyze Simple Positive and Negative Loops
by Nancy Roberts et al.

Practice with More Extensive Computer Modeling
- Study Notes in System Dynamics, Section 3.10-3.12
by Michael R. Goodman

Development and Modeling of S-Shaped Growth
- Study Notes in System Dynamics, Chapter 4: S-Shaped Growth Structure
and Chapter 5: Review of Simple Structures
by Michael R. Goodman

Real-Life Applications of System Dynamics
- Urban Dynamics
by Jay W. Forrester

Things You'll Need for Road Maps Three

Modeling Software
In order to complete Road Maps Three 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.

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.

See the Appendix for more information about obtaining Vensim and Powersim.

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 three books for Road Maps Three. *Study Notes in System Dynamics,* by Michael R. Goodman, and *Introduction to Computer Simulation,* by Nancy Roberts et al, were previously required for Road Maps Two. These books will also be used in later Road Maps. Please note that required chapters for the Roberts text can be downloaded from the SDEP server in electronic format.

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.

Forrester, Jay W., 1969. *Urban Dynamics*.

Portland, Oregon: Productivity Press, 285 pp.

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

How to Use Road Maps Three

Road Maps Three 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!

Graphical Integration Exercises

The first reading in Road Maps Three develops your understanding and skills of graphical integration. Road Maps Two introduced the use of graphical integration to estimate the behavior of systems with constant positive and negative flows, as well as step functions flows. The following paper explores ramp function flows.

- Graphical Integration Exercises Part 2: Ramp Functions [1]

by Kevin Agatstein and Lucia Breierova

A "ramp function" in a flow is a linearly increasing or decreasing flow. The paper describes the behaviors caused by such flows: parabolic growth or ìdownwardsî parabolic growth. To practice the methods of graphical integration, you will be asked to do some exercises. Solutions are provided at the end of the paper.

Please read *Graphical Integration Exercises Part 2* now.

After completing *Graphical Integration Exercises Part 2...*

This paper explained how to use graphical integration to estimate the behavior of systems with linearly increasing and decreasing flows. It showed how to calculate the level of a stock by calculating the area under the flow graph, and how to calculate the slope of the stock from the value of the flow. It is very important to understand these methods before moving on to the next paper in the Graphical Integration series.

Beginner Modeling Exercises

The next two readings continue the series of Beginner Modeling Exercises which was first introduced in Road Maps Two. In Road Maps One, feedback loops were described as the basic structural elements of systems. Positive and negative feedback cause almost all dynamic behavior of systems.

- Beginner Modeling Exercises Section 2: Mental Simulation of Simple Positive Feedback [2]

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[1] Kevin Agatstein and Lucia Breierova, 1996. *Graphical Integration Exercises Part 2: Ramp Functions* (D-4571), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, Feb. 7, 25 pp.

by Joseph G. Whelan

The second paper in the Beginner Modeling Exercises series discusses the effects of positive feedback on dynamic systems. It first describes how to recognize a positive feedback loop in a system, and how to use mental simulation to explore such a system. You will then be asked to do several exercises to improve your understanding of systems with simple positive feedback. Solutions to the exercises are provided.

Please read *Beginner Modeling Exercises Section 2* **now.**

After reading *Beginner Modeling Exercises Section 2...*

This paper explained how to identify a positive feedback loop in a system. A positive feedback loop generates exponential growth. It also showed how to find the doubling time of a stock. It is important to be able to do all the exercises before moving to the next reading.

- Beginner Modeling Exercises Section 3: Mental Simulation of Simple Negative Feedback [3]

by Helen Zhu

The third paper in the Beginner Modeling Exercises series explains how negative feedback affects the behavior of systems. As the previous paper, it first describes how to recognize negative feedback and how to mentally simulate the behavior of systems containing negative feedback loops. To make sure that you understand what you have just learned, you will be asked to complete several exercises. Solutions are again provided.

Please read *Beginner Modeling Exercises Section 3* **now.**

After reading *Beginner Modeling Exercises Section 3...*

The paper explained why negative feedback creates asymptotic growth, as well as described its goal-gap structure. It showed a method to calculate the half-

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[2] Joseph G. Whelan, 1995. *Beginner Modeling Exercises Section 2: Mental Simulation of Simple Positive Feedback* (D-4487), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, July 27, 15 pp.

[3] Helen Zhu, 1996. *Beginner Modeling Exercises Section 3: Mental Simulation of Simple Negative Feedback* (D-4536), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, January 28, 23 pp.

time of the stock, and explained how to use this information to estimate the behavior of the system. Understanding the concepts and exercises is very important before starting the next section of Road Maps Three.

Positive and Negative Feedback Loops

The next three sections of Road Maps Three also deal with positive and negative feedback loops. Road Maps One provided the basics of positive and negative feedback loops, Road Maps Two offered beginner modeling exercises which involved positive and negative feedback loops, and we have just explained how to use mental simulation to understand the behavior of systems with simple positive or negative feedback. Now we will go one step further by modeling positive and negative feedback loops on a computer using STELLA.

- *Study Notes in System Dynamics*,[4] Exercise 4
                                                                by Michael R. Goodman

The next section of Road Maps Three is Exercise 4 of *Study Notes in System Dynamics*, by Michael R. Goodman. Exercise 4 uses a DYNAMO model which you will need to convert to STELLA. If you have any problems with the conversion, please refer to Road Maps Two which worked with a similar model and provided supplemental information to help with the conversion.

The exercise provides you with a causal loop diagram and the equations for the DYNAMO system to be modeled. Before you are asked to model it on STELLA, you are asked to answer questions intuitively about the system. It is extremely important to think about the questions and write them down before modeling it and finding out the correct answers.

Please read and do Exercise 4 now. The following tips may help you.

Some tips on STELLA: *Multiple Graphs*
There are two different methods for creating multiple graphs in STELLA:
1. Open up the dialog box of the first graph, and click once on the upward pointing arrow next to *new*. Define the graph that you want. When you close the graph

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

dialog box, you can turn the pages of the graph by clicking on the small triangle in the lower left-hand corner of the graph.
2. Open a new graph by clicking on the graph icon and by placing it on the screen.

A few notes on DYNAMO: *Converting to STELLA*

The DYNAMO equations given in the solution on page 171 contain DYNAMO commands not previously mentioned in Road Maps. The new commands define the DYNAMO graph for a DYNAMO simulation. The resulting graph in DYNAMO, S4.9, is shown on page 172. For further information on the DYNAMO equations see pages 88-94 "The SPEC statement" in *Introduction to System Dynamics Modeling with DYNAMO* by Richardson and Pugh.

Some DYNAMO terms are clarified below in terms of STELLA software. If you have any further questions consult the STELLA manual.

[**DT = .1**] The model will be simulated every 0.1 year.
The equivalent in STELLA is to enter ".1" in the *dt* box in the *Time Specs* dialog box. Then click once on the time units desired for simulation.
[**Pltper = 1**] A point will appear on the graph every year, and a line will be drawn between all the points to see a curve on the graph.
There is no equivalent for this in STELLA. The closest is the *Report Interval* box in the table dialog box.
[**Length = 50**] The graph will show 50 years of output.
The equivalent to this in STELLA is to enter "0" in the *From* box and "50" in the *To* box in the *Time Specs* dialog box.
[**Plot Pop = P(0,320)/BR=B(0,24)**] This command assigns scales and variables for the graph. The equivalent in STELLA is to change the scales in the *Graph* dialog box for each variable.

After finishing Exercise 4...

This exercises provided more experience with converting DYNAMO equations to STELLA. It also explained the basic characteristics of positive feedback loops. Positive feedback loops are a fundamental building block of system dynamics and of computer modeling. They will be explored again in Road Maps Three, and they will be used throughout the rest of Road Maps.

The model that you just built also illustrates a systems principle:

Systems Principle #5:

Levels are changed only by the Rates.

　　Look at the model just created in STELLA (same as the model on p. 171 of *Study Notes in System Dynamics*). Note that the level, **population** is influenced only by the rate, **birth rate**. Only rates can change levels.

　　System Principle #5 is important in modeling because it helps clarify the interactions between the different levels and rates.

- *Study Notes in System Dynamics*, Exercise 5

　　　　　　　　　　　　　　　　　　by Michael R. Goodman

　　The next reading in Road Maps Three is Exercise 5 of *Study Notes in System Dynamics*. This exercise has the same pattern as Exercise 4; however, Exercise 5 deals with negative feedback loops. The exercise asks for intuitive answers to questions before you simulate your model. Answering these questions before you run the model is extremely important for learning about the feedback loops. Once again, if you need help with the conversion from DYNAMO to STELLA there is some supplemental information included in Road Maps Two that can assist you.

Please read and do Exercise 5 now. The following tip may help you.

A tip for modeling

　　To model an outflow, begin with the flow *inside* of the stock and drag the flow two inches *out* of the stock. Then release the mouse.

After finishing Exercise 5...

Exercise 5 gave you even more experience with converting equations and models from DYNAMO to STELLA. It also explained the basic characteristics of a negative feedback loop. Negative feedback loops are another fundamental building block of system dynamics and computer modeling. They will be explored again in Road Maps Three, and they will be used throughout the rest of Road Maps.

- *Introduction to Computer Simulation*,[5] Chapter 15: Using Simulation to Analyze Simple Positive and Negative Loops

by Nancy Roberts et al.

Chapter 15 discusses the fact that both positive and negative feedback loops are the only two types of loops in a system. Everything else is built from positive and negative feedback loops. This fact was mentioned in System Principle #1 which stated that feedback loops are the basic building blocks of systems. Chapter 15 is the last section of Road Maps Three dealing specifically with positive and negative feedback loops. After this chapter, we will move on to more complex structures.

Chapter 15 also uses DYNAMO equations. However, Chapter 15 includes some DYNAMO equations that will be new to you. To help you, we have included some supplemental information.

Please read Chapter 15 and do all of the exercises as the book asks. Refer to the following supplement as necessary.

Tips for "Using Simulation to Analyze Simple Positive and Negative Loops"

Read Chapter 15 from page 261 up to and including Exercise 3 on page 262. Do all of the examples and exercises as the book asks. Example I refers to equations from the same book in Chapter 14, which is not used in Road Maps. The equations, converted to STELLA, follow:

YEAST_CELLS(t) = YEAST_CELLS(t-dt) + (BUDDING) * dt

INIT YEAST_CELLS = 10 {CELLS}

INFLOWS:

BUDDING = YEAST_CELLS * BUDDING_FRACTION {CELLS/HOUR}

BUDDING_FRACTION = 0.1 {1/HOUR}

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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.

dt = 1

simulation length = 30 hours

A tip on STELLA: *Sensi Specs*

STELLA provides an easy way to view the effects of several different values for the same variable on one graph. The three values that you are experimenting with in Exercise 3 are 0.2, 0.1, and 0.05 for BUDDING_FRACTION. To see all of these values on the same graph, the graph needs to be created under *Sensi Specs*.

- First, close all graphs and dialog boxes on the screen if any are open.
- Pull down the *Run* menu, and release the mouse on *Sensi Specs*. A *Sensi Specs* dialog box will open up on the screen.
- Double click on BUDDING_FRACTION in the *Allowable* list.
- Then click once on BUDDING_FRACTION in the *Selected(value)* list.
- Click once on the button next to *ad hoc*. Type "0.2." Click once on *Set* and type "0.1" Click once on *Set*, and type "0.05." Click once on *Set*.
- Click once on *Define: Graph* button in the lower left-hand corner. The cursor will be a graph icon. Click once on an empty space to place the graph. The graph and graph dialog box will open up with a new graph ready to be defined, and *Comparative* selected.
- Define the graph with only one variable. Double click on YEAST_CELLS.
- Then title the graph and click once on OK.
- Choose S-Run from the Run menu.

Please read and do Exercise 4 on the bottom of page 262 through the top of page 264. Then read through Exercise 5 on page 263. In Exercise 5 you will modify the model from Exercise 4 by adding an outflow from the stock of BANK BALANCE. The addition of an outflow will make the model a two-flow model. It will be the first two-flow model that you model by yourself in Road Maps.
- To add the new outflow, WITHDRAWALS, place the flow inside the stock of BANK BALANCE. Then drag outward away from the inflow of INTEREST. Putting the flows on opposite sides of the stock makes the model easier to read.
- Define and document the outflow, WITHDRAWALS.
- View the equations for the STELLA model, and notice the change to the BANK BALANCE equation.

Finish part b of Exercise 5.

If you want to see WITHDRAWAL graphed remember to add WITHDRAWAL
to the *Selected* list in the graph dialog box. Part c and d of Exercise 5 can be
easily done using *Sensi Specs* in STELLA as done above. (See A tip on
STELLA: *Sensi Specs*)

Please read "Starting a Model in Equilibrium," and do Exercise 6 on page 263.
If you have difficulty with Exercise 6 try running the model for various balances,
interest rates and withdrawal rates.

Read the section "Examining a System's Response to Disturbances—Part I" on
page 264. Then read through Exercise 7 on page 265.

A tip on STELLA: *Step Functions*
        This section describes how to include instantaneous changes which occur
during the simulation of a model by using the step function. The step function
works the same in STELLA as it does in DYNAMO.
- To change the WITHDRAWAL equation in your model open the
WITHDRAWALS dialog box. Add "+ STEP(25,5)" to your equation so that it
reads "50 + STEP(25,5)."
- Graph the results.
Please read Example II from page 265 up to and including Exercise 10 on page 266.
Do all of the examples and exercises as the book asks. Example I refers to
equations from a chapter of the same book not used in Road Maps; the equations
(converted to STELLA) follow:
    YEAST_CELLS(t) = YEAST_CELLS(t-dt) + (- YEAST_DEATHS) * dt
    INIT YEAST_CELLS = 10 {CELLS}
    OUTFLOWS:
    YEAST_DEATHS = YEAST_CELLS/AVERAGE_LIFETIME {CELLS/HOUR}
    AVERAGE-LIFETIME = 0.1 {1/HOUR}

Read through Exercise 11 on page 266. Before doing this exercise remember that
good modeling practice requires that the inflow, YEAST BUDDING, and the
outflow, YEAST DEATHS, are on opposite sides of the stock, YEAST CELLS.

Do Exercises 12 and 13 on page 266 through the top of page 267. Example III, including Exercise 14 is very important to learn first-hand the behavior of the system. Try to do the experiment.

Read "Modeling Temperature Change" up to Exercise 15 on page 269. Read through Exercise 15 on the bottom of page 269 through the top of page 270. But before modeling the system, read "Auxiliary Variables" from page 270 through 271. "Auxiliary Variables" will help you to formulate a more user-friendly model for Exercise 15. Do Exercise 15.

One more input that is not shown in the flow diagram on page 271 is COOLING CONSTANT, (T). In the STELLA model, COOLING CONSTANT should be a converter connected to DECLINE so that it is not hidden in the model.

Read from "The Goal-Gap Formulation" on page 271 up to Example IV: Pushups and Practice on page 274. Do the exercises and examples as they are written in the book.

Read through Example IV from the bottom of page 274 through the top of page 277. Example IV refers to a part of the book not used in Road Maps. The discussion referred to can be inferred from the causal loop diagram in Figure 15.9 on page 274. - Create the model on STELLA as described by Exercise 18 on page 276. Your model should be similar to Figure 15.11 on page 276. The difference will be the auxiliary variables visible on your model:

      PRACTICE TIME PER PUSHUP = 0.5 {MIN/PUSHUP}

      MAINTENANCE = 10 {MIN}

      PRACTICE EFFECTIVENESS = 0.2 {PUSHUPS/MO/MIN}

When creating the flow, IMPROVEMENT RATE, click once on the *bi-flow* button in the top left-hand corner of the flow dialog box. Jim can improve as well as worsen.

Do Exercise 18b through 18e using *Sensi Specs* on STELLA.

Read Example V on page 277 up to and including Exercise 20 on the top of page 282.

For Ex. 19 on page 278, remember to name all parameters and give them an icon.

      NUMBER OF PUSHUPS = 10 {INITIAL NUMBER OF PUSHUPS}

IMPROVEMENT RATE = (AMOUNT OF PRACTICE-BASE PRACTICE) *
                      PRACTICE EFFECTIVENESS {PUSHUPS/MO}

BASE PRACTICE = 30 {MIN}

AMOUNT OF PRACTICE = PRACTICE TIME PER PUSHUP * DIFFERENCE {MIN}

DIFFERENCE = GOAL FOR PUSHUPS - NUMBER OF PUSHUPS {PUSHUPS}

GOAL FOR PUSHUPS = 50 {PUSHUPS}

PRACTICE TIME PER PUSHUP = 0.5 {MIN/PUSHUP}

PRACTICE EFFECTIVENESS = 0.2 {PUSHUPS/MO/MIN}

For "Choosing a Value for DT" on pages 279-282, STELLA II v. 2.2.1. unfortunately does not allow a value of DT greater than one, but you should follow along with this section and run the simulations you can. All the models used here are ones you have already created. The information on DT, the solution interval, will be expanded upon in further parts of the Road Maps.

Please read and do Exercise 21 on page 282.

Exercise 21 is your chance to create your own model. You can make this as complicated as you wish. Try varying the structure and complexity to demonstrate the behavior you have seen in previous models such as S-shaped growth, exponential growth and decay.

This is the end of **Tips for "Using Simulation to Analyze Simple Positive and Negative Loops."**

After finishing Chapter 15...

Chapter15 improved your STELLA modeling skills, as well as your skills for conversion from DYNAMO to STELLA. It provided more explanation of positive and negative feedback loops. As we continue in Road Maps you will see that positive and negative feedback loops are the building blocks for all other structures. Being familiar with the characteristics of feedback loops is essential for learning about system dynamics and computer simulation.

The following System Principle is one that we have already presented in Road Maps Two. We are restating the principle, as part of our spiral approach, to emphasize its importance.

System Principle #2:

Levels and Rates are fundamental to loop substructure.

      A feedback loop consists of two distinct types of variables, the **levels** (also called stocks or states) and the **rates** (also called flows or actions). These two variables are both necessary to represent the structure in a feedback loop.

      As you are reading Chapter 15 of *Introduction to Computer Simulation*, trace through the feedback loops in Figure 15.1, 15.3, and 15.5, which belong to Examples I, II, and III, respectively. Notice that both the levels and the rates are fundamental to the substructure of the feedback loops. The loop dynamics cannot be represented without their inclusion.

Practice with More Extensive Computer Modeling

- Study Notes in System Dynamics, Section 3.10-3.12
                                                                    by Michael R. Goodman

      This section introduces more advanced models than you have seen before. It demonstrates how more complicated models are built on positive and negative feedback loops. You will not have to derive the models yourself because the flow diagrams, DYNAMO equations, and run outputs are provided with each example. You will have to convert the DYNAMO equations to STELLA and then run the model for each example.

Please read and do Section 3.10-3.12 now. The following tip may help you.
A tip for STELLA: *Table Graphs*

One new DYNAMO equation, a table equation, is introduced.
The DYNAMO equations, 5 and 5.1 from page 63 are:

      PAT.K = TABLE(PATT,POLR,0,80,10)

      PATT =.6 / 2.5 / 5 / 8 / 11.5 / 15.5 / 20 / 31 / 50

      PAT - POLLUTION ABSORPTION TIME (YEARS)

      POLR - POLLUTION RATIO (DIMENSIONLESS)

PAT.K — This is the variable in the model that will represent the table. In the STELLA model the name will be POLLUTION ABSORPTION TIME.

- Open the dialog box for POLLUTION ABSORPTION TIME.

TABLE(.....) — This defines the variable, PAT.K as a table.
In STELLA, the equivalent is to open the dialog box of POLLUTION ABSORPTION TIME and to define it as "A graph of ..." POLLUTION RATIO.

- Select POLLUTION RATIO from the *Required inputs* box.
- Click once on the *Become Graph* button on the bottom of the dialog box. A new dialog box will appear, to define the table.
- Click once on the *To Equation* button on the bottom of the dialog box to view the equation. You will see POLLUTION ABSORPTION TIME = "graph of..." POLLUTION RATIO.
- Click once on the *To Graph* button.

PATT — In STELLA, this name is the same as PAT.
DYNAMO requires two different names for a table, whereas STELLA requires only one.

POLR — This is the variable of which POLLUTION ABSORPTION TIME is a function. In STELLA this means that one value for POLLUTION ABSORPTION TIME corresponds to one value for POLLUTION RATIO.

0 — This value represents the minimum value that POLLUTION RATIO can have.

80 — This value represents the maximum value that POLLUTION RATIO can have.

- Return to the graph dialog box. Notice that the horizontal and vertical side of the graph ranges from 0 to 100 (100 is the default number in STELLA). But, POLLUTION RATIO on the horizontal axis ranges from 0 to 80, as the equation tells us.
- Notice that "100," the maximum range, is highlighted on the horizontal axis for POLLUTION RATIO. To enter the correct number for POLLUTION RATIO, type "80."

10 — This value is only necessary in DYNAMO. It is the length of incrementations on the graph between 0 and 80.

PATT = .6 / 2.5 / 5 / 8 / 11.5 / 15.5 / 20 / 31 / 50 — These nine values represent the values that the table will have. Thus the range for POLLUTION ABSORPTION TIME for the vertical axis is 0.6 to 50.

- Press *tab* on your keyboard to highlight the maximum value for POLLUTION ABSORPTION TIME and type "50." Press *tab* on your keyboard again to highlight the minimum value for POLLUTION ABSORPTION TIME and type "0.6."
- Notice that there are eleven points to be defined on the output table in STELLA, but only 9 points given in *Study Notes* for POLLUTION ABSORPTION TIME.
- Highlight the number 11 in the *Data Points* box. Type "9."
- Highlight the first number, 0.000 under *Output*, by clicking once on it. Type "0.6." Press *return* on your keyboard. Type "2.5." Press *return* on your keyboard, and type "5." Press *return*.... Continue until you have filled in all of the points under *Output*.
- The graph should resemble as much as possible the table in Figure 3-20 on page 61 in *Study Notes in System Dynamics*.
- If it does, click once on *OK*.
- See page 26 in *Getting Started with STELLA II: A Hands-on Experience* for more information on table functions in STELLA.

After finishing Section 3.10-3.12...

Working with the models in Sections 3.10-3.12 gave you more a sense of the system dynamics approach. We now introduce another important system principle.

System Principle #6:

Levels exist in conservative subsystems.

A conserved quantity has the property that it is never created or destroyed (within its system); it is only moved around. Look at Figure 3-12 on page 52 in *Study Notes in System Dynamics*, a simple inventory control system. Notice that the level **Inventory** contains goods that are moved in from the **Factory** and out to

the **Customers**. The goods are neither created nor destroyed within the level. All levels contain conserved quantities.

Development and Modeling of S-shaped Growth

The next two sections of Road Maps Three build on your knowledge of positive and negative feedback loops and guide the development of a model of an S-shaped growth system.

- *Study Notes in System Dynamics*, Chapter 5

by Michael R. Goodman

Chapter 5 helps you develop a STELLA model of a system generating S-shaped growth. When you are finished, compare the output of your STELLA model to the answer in DYNAMO. The output of your model should match the answer given.

Please read and do the exercise in Chapter 5 now.
After finishing Chapter 5...

Chapter 5 developed the concepts of positive and negative feedback loops, and introduced the basic ideas behind S-shaped growth. It also reviewed the use of table functions in STELLA.

The following principle is another recurrent principle. We are restating System Principle #3 in order to emphasize its importance.

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

The units of measure of a variable do not distinguish between a level and a rate. The modeler must recognize the difference between a variable created by integration and one that is a policy statement in the system.

Look at Figure 5-11 of *Study Notes in System Dynamics*. Here, and in all models, the units of a rate are the units of its associated level over time. A good rule of thumb for distinguishing levels from rates is to imagine what would happen if action were halted. Rates will cease when action stops, but levels will continue to exist. In this case, notice that **Industrial Structures** has units of [structures], and **Industrial Construction** has units of [structures/year]. If action were to cease, then construction would cease as well, but the structures would stay (their number simply

would not change).   Thus **Industrial Structures** is a level and **Industrial Construction** is a rate.

- *Study Notes in System Dynamics*, Chapter 4
                                             by Michael R. Goodman

    Chapter 4 focuses on the structure and behavior of the different variables in an S-shaped growth system. The chapter explores two systems which exhibit S-shaped growth. One is an epidemic and the second is a pendulum. Although the pendulum example may seem confusing without prior knowledge of the equations that govern a pendulum's movements, work through the model along with the book, and focus on understanding the system through your knowledge of system dynamics.

Please read and do Chapter 4 now.

After finishing Chapter 4...

    Chapter 4 described the key characteristics behind S-shaped growth. Because systems producing this behavior are very common, you will be modeling several more S-shaped growth systems in later Road Maps.
Some key characteristics are:
- exponential growth
- goal-seeking behavior
- loop dominance
- dynamic equilibrium

Real-life Applications of System Dynamics
                                             Revised by Lei Lei

- *Urban Dynamics* [6]

    Road Maps 3 concludes with the reading of one of Professor Jay Forrester's classic system dynamics books. It is not necessary to complete the book before continuing on to the next chapter of Road Maps. However, reading *Urban Dynamics* will aid the reader in giving real world relevance to system dynamics. *Urban Dynamics* is an introduction to complex urban systems and their

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[6] Forrester, Jay W., 1969. *Urban Dynamics,* Waltham, Massachusetts: Pegasus Communications. 285 pp.

characteristics. The reader should not be discouraged if s/he cannot fully understand the models introduced in the book. The reading is assigned as part of Road Map's spiral-learning approach, where concepts are referred to and expanded upon continually throughout the series.

Urban Dynamics provides a glimpse of the origins of the field of system dynamics before the name "system dynamics" was coined. The book presents excellent examples of using simulation models to understand and explain the counterintuitive nature of complex social systems. *Urban Dynamics* is one of Professor Jay W. Forrester's more controversial books. The publication of *Urban Dynamics* in 1969 marks a unique event in the analysis of social systems.

Although *Urban Dynamics* addresses crises that our cities faced twenty years ago, many of the same problems still exist today. The *Urban Dynamics* model refutes the conventional wisdom that urban problems are caused by such factors as rural-urban migration, dwindling fiscal resources, and suburbanization.

Instead, the book suggests that most urban problems arise from the interactions of processes that occur within the cities themselves. After showing what established policies have actually done to our cities and why, Forrester uses the model to test new policies and programs for the revival of urban cities. The policies presented in the book challenge the status quo. For example, Forrester suggests that demolishing, rather than constructing, low-cost housing will be a better long-term solution to the urban crises. By reading *Urban Dynamics*, the reader will gain a deeper understanding of how high leverage policies can be pushed in the wrong direction.

Forrester discusses how cities are nonlinear systems that contain multiple feedback loops. Thus, fully understanding and managing the complex systems defies simple human reason and intuition. Forrester suggests, however, that by examining urban problems with computer simulation, we can better understand outcomes of various policies. The book uses DYNAMO models of generic urban areas to discuss and test urban policy options presented by the author.

At the time *Urban Dynamics* was published, the book sparked a controversy that related to the nationwide debate over urban crises. The controversy is summarized as follows:

Business Week praised the book in 1969 and said, "*Urban Dynamics* is an unsettling, complex and ground-breaking new book about our cities and the decay that afflicts them."[7] On the other hand, Kain says in *Fortune*, "such models (as

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[7] "A daring look at city ills," Business Week, June 14, 1969, pp. 145-146.

used in *Urban Dynamics*) have a great deal of potential for the analysis of urban problems," but also says, "before adequate models become available, many inadequate ones will be put forward. Forrester's model is a conspicuous example."

A study by Jerome Rothenberg published in the *Journal of Urban Economics* in 1974 pointed out that, "the insistence upon treating 'the city' as a self-contained system results in grave difficulties." Jantsch, in *Futures*, best summarizes the controversy as, "*Urban Dynamics* had become the subject of heated debate even prior to publication. It has captured the imagination of politicians and managers in the public domain, and it has been furiously attacked and rejected by social scientists." In 1969 Jantsch said, "It is a safe prediction to state that it [*Urban Dynamics*] will become one of the most provocative and stimulating books of our time." "But," he also said, "*Urban Dynamics* is not the only approach to long-range planning and it is not perfect." Each article above concludes that *Urban Dynamics* is a notable piece of work, and highlights the controversy created by the book.

Urban Dynamics is one of the most important books in the history of system dynamics. The reader should not be frustrated if s/he cannot fully comprehend the book at this stage in the learning process and should focus on increasing understanding of a complex social system. *Urban Dynamics* shows how system dynamics can be applied to real-world problems.

Finishing off Road Maps Three

Road Maps Three explained positive and negative feedback loops, and described how they are the building blocks of all other models in system dynamics. This chapter improved your graphical integration, mental simulation, and STELLA modeling skills, as well as your ability to convert from DYNAMO to STELLA. We have presented two more system principles: a) that levels are changed only by the rates; and b) that levels exist in conservative subsystems.

In Road Maps Four you will find out why some of the models you have built so far look similar. You will further develop your mental simulation skills through more Beginner Modeling Exercises. Road Maps Four also contains the Fish Banks Game and introduces "The Tragedy of the Commons."

Key Terms and Concepts:

Dynamic Equilibrium
Exponential Growth
Goal-seeking Behavior
Graphical Integration
Loop Dominance
S-shaped Growth