Building a System Dynamics Model
Part 1: Conceptualization

Prepared for the
MIT System Dynamics in Education Project
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1. ABSTRACT

Building a System Dynamics Model is a series of papers written to demystify the model building process. This paper is the first in the series and explains the first stage of the model building process called *conceptualization*. The paper examines in depth the following steps of conceptualization:

1. Define the purpose of the model.
2. Define the model boundary and identify key variables.
3. Describe the behavior or draw the reference modes of the key variables.
4. Diagram the basic mechanisms, the feedback loops, of the system.

The first step, deciding on the model purpose, means focusing on a problem and narrowing down the model's audience before concretely stating the model purpose. Defining the model boundary involves selecting components necessary to generate the behavior of interest as set by the model purpose. After defining the model boundary and identifying key variables, some of the most important variables are graphed over time as a reference mode. The major types of reference modes are the hypothesized and the historical reference modes. The final step in conceptualization is deciding on the basic mechanisms (feedback loops) of the system. The basic mechanisms are commonly diagrammed using either stock-and-flow diagrams or causal-loop diagrams.

Each step is illustrated by a general description of the step. After the general description of each step, that step will be applied to a Heroin-Crime system description. Further papers in this model-building series will also use the Heroin-Crime system. Section 5 contains a conceptualization exercise. The reader will need to refer to Study Notes in System Dynamics by Michael R. Goodman,[1] which was used previously in Road Maps. Appendix A contains a Modeling Worksheet to assist the modeler in the conceptualization process.

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

2. INTRODUCTION

In spite of a wide range of applications using system dynamics, most SD models are created in four stages. The four stages of modeling are outlined below, with the essential steps of each stage bulleted under the stage name:[2]

1. **CONCEPTUALIZATION**
    - **Define the purpose of the model**
    - **Define the model boundary and identify key variables**
    - **Describe the behavior or draw the reference modes of the key variables**
    - **Diagram the basic mechanisms, the feedback loops, of the system**
2. FORMULATION
    - Convert feedback diagrams to level and rate equations
    - Estimate and select parameter values
3. TESTING
    - Simulate the model and test the dynamic hypothesis
    - Test the model's assumptions
    - Test model behavior and sensitivity to perturbations
4. IMPLEMENTATION
    - Test the model's response to different policies
    - Translate study insights to an accessible form

This paper covers the **conceptualization stage** of modeling and provides practical advice for completing each step. Further papers in the model-building series will cover the remaining three stages of modeling. Although this paper does not cover the remaining stages, note that the four stages are recursive. After completing each stage the modeler might have to return to previous stages to incorporate new information or insights. No strict dividing lines exist between the stages.

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[2] Jorgen Randers, 1980. Elements of the System Dynamics Method. (pp.117 - 139) Portland, OR: Productivity Press, 344 pp.

The only way to become comfortable with the modeling process and improve one's modeling is through practice. Section 3 below contains a system description that will be used for practice throughout this paper.

3. HEROIN-CRIME SYSTEM DESCRIPTION

To better understand conceptualization, this paper will apply each step of the conceptualization stage to a Heroin-Crime system.[3] Read the following excerpt describing the Heroin-Crime system; refer back to the description below as needed.

> "The next time you hear of a big drug bust and the seizure of large quantities of heroin, don't go believing that your city's streets are necessarily any safer. In fact, a new study of heroin traffic in Detroit has concluded that the tighter the heroin market, the more likely you will become a victim of a robbery or a burglary by an addict in need of a fix."[4]

Most people believe that the stronger law enforcement works to get drugs off the streets, the safer those streets become. Evidence from the Drug Abuse Council, however, challenges the prevailing belief. "If the price of a bag of street heroin increased from $7 to $9 in any given month," the Drug Abuse Council said, "the number of revenue-raising crimes which occurred at the rate of about 11,000 a month...would increase to almost 12,000 a month because of heroin alone."[5]

Heroin demand does not react immediately to a shortage of supply because of heroin's addictive nature. Heroin is a "need" and not just a desire" and heroin demand can thus be taken as a constant in the short-run. When the heroin supply and heroin demand are in equilibrium, a certain price is charged. An increase in drug busts results in a decrease in the heroin supply. Basic economics states that when supply is less than demand, the price increases. An increase in price will lead to an increase in heroin importation to the area. Assuming the increase in drug busts is temporary, the heroin supply will eventually increase to the original level and bring the price of heroin back down to normal.

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[3] Further papers in this series will continue the model-building process using the Heroin-Crime system.
[4] Excerpt from Saul Friedman. "When heroin supply cut, crime rises, says report." *Boston Globe*, April 22, 1976.
[5] Taken from Friedman, "When heroin supply cut, crime rises, says report."

4. CONCEPTUALIZATION STEPS

During the conceptualization stage, a modeler must determine the purpose of the model, the model boundary, the shape of the reference modes, and the nature of the basic mechanisms. This paper will now cover each of the four steps of conceptualization in subsections 4.1 through 4.4. Each subsection is further divided into *"Discussion,"* containing a more abstract definition of the conceptualization step, and *"Heroin-Crime System,"* containing an example of an application of the conceptualization step to the Heroin-Crime system described in section 3 of this paper.

4.1 Purpose of the Model

4.1.1 Discussion

The first step of the modeling process, deciding on the model purpose, is a two-part decision. Deciding on the model purpose means focusing on a problem and narrowing down the model's audience. By deciding on the model's purpose, a modeler makes the later choices of both components and structure feasible.

A system dynamics model is built to understand a system of forces that have created a "problem" and continue to sustain it. To have a meaningful model, there must be some underlying problem in a system that creates a need for additional knowledge and understanding of the system. The goal of the conceptualization stage is to arrive at a rough conceptual model capable of addressing the relevant problem in a system. After choosing what problem area to focus on, a modeler must gather relevant data and further define the focus of the model. Relevant data for a system dynamicist consists not only of measured statistical data, but also operating knowledge from people familiar with the system being analyzed.

The modeler should also consider a model's primary audience. A model explaining causes of acid rain would be much different if built for an 8th grade biology class, than if built for the United States Environmental Protection Agency for policy decisions. If the model's structure and behavior cannot be understood by its audience, or if it does not answer questions interesting to the audience, then the model is rendered useless.

The first step in creating a meaningful model from available data is defining the purpose of a model while keeping in mind the model's audience. The model purpose should mention some type of action or behavior over time that the model will analyze. Coming to an agreement on the purpose of the model is essential. Without a clear and strictly defined purpose it is very difficult to decide which components of the system are important. Another concern of experienced modelers is whether it is worthwhile to build the model as defined. A very abstract purpose, such as “I am building this model about the environment to understand how it works,” is likely to result in a waste of time. Such a model would probably include too many components and be too complex for any practical analysis.

The purpose of a model usually falls into one of the following categories:

- to clarify knowledge and understanding of the system
- to discover policies that will improve system behavior
- to capture mental models and serve as a communication and unifying medium.

4.1.2 Heroin-Crime System

The Heroin-Crime system description presents the modeler with the problem of increased police activity in the form of drug busts having the unintended side effect of increased crime.

Given the broad problem area in the Heroin-Crime system, the model could be built for many reasons. Assume that the modeler has just read an article about the heroin-crime system in the newspaper and would like to build a model to see if the theories presented are legitimate.

- The purpose of the model is to test whether increased drug busts increase revenue-raising crime in the short-run.

The audience for this model is the average person and not a panel of experts in drug trafficking or law enforcement. Detailed statistics are not needed. The model’s audience would probably be most interested in a simple, easy-to-understand model with highly aggregated components.

4.2 Model Boundary

4.2.1 Discussion

Every feedback system has a closed boundary within which the behavior of interest is generated. When creating a system dynamics model of a feedback system, a modeler must clearly define the model boundary. The model boundary contains all components present in the final model. First, a modeler must brainstorm for all components he sees as necessary for creating a model of the system, even those of which he is unsure. The initial list shall be referred to as the initial components list.

When selecting components for the initial list, the following guidelines should help:

> *Components must be necessary*. The modeler sets the boundary such that nothing excluded from the model is necessary to generate and properly represent the behavior of interest as set by the model purpose.[6] Also, nothing included should be unnecessary.
>
> *Components should be aggregated.* Similar concepts should be aggregated if doing so does not change the nature of the problem being modeled or the model purpose. Fewer components help to avoid unnecessary complications. Do not, however, aggregate components if doing so creates a model which no longer reflects reality, for example the flows "births" and "deaths" should not usually be aggregated to "net births."
>
> *Components must be directional.* All important components must have a directional name that can grow larger or smaller, for example "anger" or "happiness" instead of "mental attitude."

Second, to further specify a model boundary, the modeler must separate the initial components list into two important groups:

- endogenous—dynamic variables involved in the feedback loops of the system
- exogenous—components whose values are not directly affected by the system

It is helpful to make two columns labeled "endogenous" and "exogenous" on a sheet of paper and fill the columns after carefully examining each component on the initial components list in the context of the model purpose. There may be some components on the initial list which, after further examination, seem unnecessary in the model. Thus it is important to save the initial components list and the subset categories of endogenous and exogenous components. The modeler should now have a better understanding of the model structure. By saving the initial components list, the modeler can always, without too much additional effort, go back and reexamine some of the initial assumptions made about the importance of variables in the system or even try an alternative model structure.

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[6] Jay W. Forrester, 1980. *Conceptualization of a Model to Study Market Growth* (D-3221), System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, 24 pp.

Finally, after dividing the initial list into two categories, it is useful for the modeler to re-examine the endogenous and exogenous components and specify which components are stocks and which are flows. (Note that exogenous components will usually be constants or time varying constants, and not stocks or flows.) The additional information gained will be of great use in the last step of conceptualization—deciding on the basic mechanisms. To make identification easier, remember that stocks are accumulations. They are usually something that can be visualized and measured, such as population, but can also be abstract, such as level of fear or reputation. Flows are changes in stocks. They are rates and are measured in units of the stock over time. Birth rate, death rate, and shipping rate are examples of flows.

4.2.2 Heroin-Crime System

A brainstorm of components for the Heroin-Crime system might lead to the following initial components list:

heroin stock
number of addicts
heroin importation
revenue-raising crime
money to support population's habit
number of arrests
drug busts
heroin demand
price of heroin
heroin use

Figure 1 defines a possible model boundary for the Heroin-Crime system. (Note that the "S" and "F" next to the component name mark it as a stock or a flow, respectively.)

ENDOGENOUS COMPONENTS	EXOGENOUS COMPONENTS
heroin stock (S)	heroin demand
revenue-raising crime	drug busts (F)
heroin importation (F)	heroin use (F)
price of heroin (S)	
money to support population's habit	

Figure 1: Components for Heroin-Crime System

Because the model purpose is to examine the theory that crime increases as drug busts increase, the number of addicts and number of arrests are not important to the dynamic behavior. The number of addicts and number of arrests components are thus left on the initial list and not placed in the endogenous or exogenous lists. A drug bust is defined as a seizure of drugs from the local stock of heroin. In the short-run, heroin demand is constant because the effect of rehabilitation and entrance of new addicts is minor. Heroin is addictive, therefore addicts require heroin regardless of price, so the need for a heroin fix in the short-run is constant. The component driving the behavior of interest is the number of drug busts per month. The model purpose focuses on the resultant behavior due to an increase in the drug bust component, and not on the reason for the increase in drug busts. The frequency of drug busts and the amount of drugs seized are therefore exogenous. The dynamic components important to the model purpose are the heroin stock, the price of heroin, and the amount of revenue-raising crime. Other important variables, such as the money to support the population's habit and the level of heroin importation, also affect and are affected by these three dynamic components. All components in such a feedback loop are endogenous to the system. Note that a modeler may interpret the system description in another way and divide up the components into columns differently.

It is important to remember that the model is not built during the conceptualization stage. The modeler does not use the computer. The modeler is simply trying to extract as much relevant information and understanding of the system as possible. The final system dynamics model of the Heroin-Crime system may have a few additions and deletions from the components listed in Figure 1. The components list is just a guideline and not a strict frame for the model.

4.3 Reference Modes

4.3.1 Discussion

Reference mode and behavior chart are simply other names for a plot of the behavior of key variables of a system over time. A reference mode graph has time on the horizontal axis and units of the variables on the vertical axis. The time plots of the key variables are often quite useful, both before and after the model is built. The reference mode captures mental models and historical data on paper, gives clues to appropriate model structure, and can check plausibility once the model is built. A modeler constructs reference modes to check for the existence of some phenomenon or behavior worth modeling. Experienced modelers often know which structures can produce which behavior modes, thus making the reference mode an invaluable resource during the formulation of the stock-and-flow structure of the model.[7] Often reference modes are not drawn due to lack of information and lack of effort. They are, however, essential both as a guide and a test throughout the model-building process.

While verbal descriptions or a set of statistics about system behavior can serve the same purpose as the graphic reference mode, preference for the graphic form exists for a number of reasons. A verbal description can be lengthy, confusing, and does not carry the same visual impression a graph does. A list of numbers is meaningless until the modeler puzzles out the patterns by creating a graph. The visual appeal of a graph is helpful in communicating the system to others and a modeler can easily hold it in memory throughout the modeling process.

Beware that reference modes are not infallible. They can change throughout the modeling process as a modeler begins to understand the system better and updates his mental model. It is also important to note that on the basis of these initial reference modes, a modeler can re-examine and restate the model purpose more precisely.

The historically observed and the hypothesized reference modes are the two types of reference modes that a modeler may create during conceptualization. Before moving to the heroin-crime system, this paper will further examine reference modes with an example of each type of reference mode.

A historically observed reference mode usually exists when a modeler is given a problem and wants to generate knowledge about possible causes or solutions. If one were presented with the question of what causes varying profitability in a specific company, research might reveal the historical reference mode shown in Figure 2. Now the modeler can focus on one lead or possible cause of varying profitability—inventory fluctuations.

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[7] Formulation is the second stage of modeling and will be addressed in a later paper.

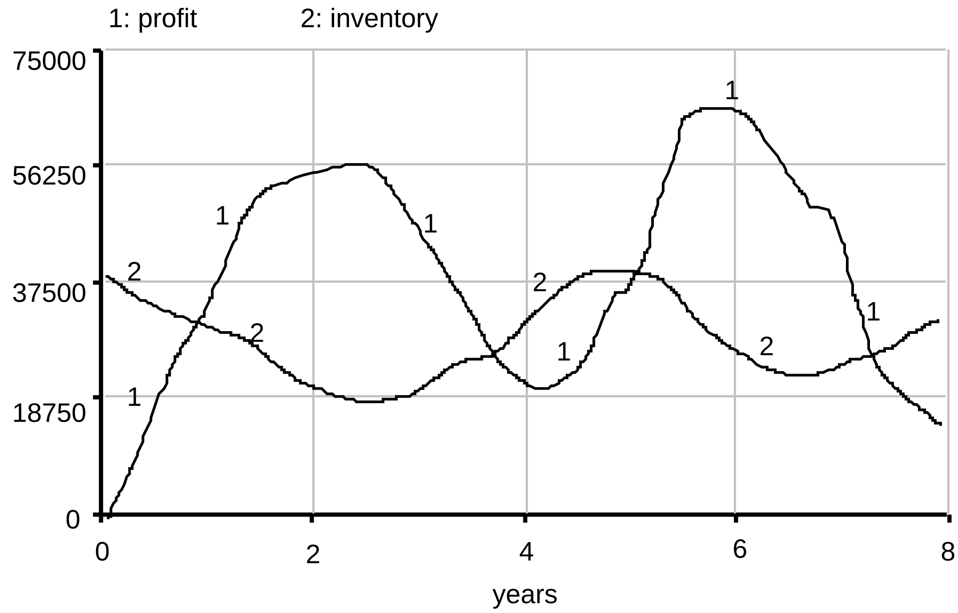

Figure 2: Historical Reference Mode for a Company Profit System

Historical reference modes use historical data. Comparing model output to the historical reference mode is particularly useful in later stages of model construction. If the model does not produce behavior similar to historical observations, it is an indication that the model might need re-work.

When no historical information is available, a modeler must create a hypothesized reference mode. The hypothesized reference mode consists of a simplified curve, typically drawn by hand, capturing the key features of the behavior pattern of the important system components. Sketching a hypothesized curve requires abstracting the interesting features of a variable from the given system details. Common hypothesized reference mode behaviors are exponential growth, exponential decay, overshoot and collapse, S-shaped growth, and damped, sustained and expanding oscillations. A hypothesized reference mode might show the future behavior once a specific policy is carried out. The reference mode in Figure 3 is an illustration of a mental model of the effects of attempting to reduce the deer population in a specific area. Half of the deer are killed over 2 months without other changes in the environment.

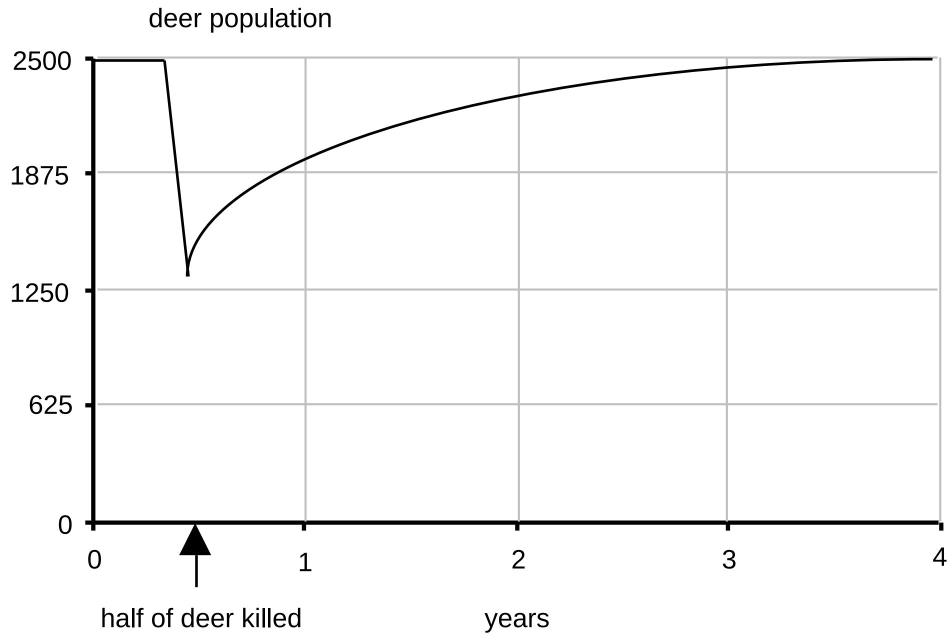

Figure 3: Hypothesized Reference Mode for Deer Population Policy System[8]

By drawing the reference modes, a modeler roughly simulates the situation in his mind. A modeler needs to think clearly about which factors influence each other. A modeler takes the most important factors, usually the stocks and flows of the system, and graphs their behavior over time. While it is not necessary to have set values for the factors, a modeler must specify the time frame and keep it constant for each reference mode component curve. One should draw reference modes on the same graph if possible, though multiple graphs may become necessary due to crowding. Start by picking one component and drawing that component's reference mode curve. Then graph the other components one at a time, relating the behavior to the curves already drawn.

The choice of time horizon is critical in drawing reference modes. If the time scale is too long or too short, it may obscure important behavior from view. Figure 4 contains an example of one component of an observed historical reference mode of an oscillating population graphed over a time horizon of 200 years. In Figure 5 the same population's reference mode is shown with a time horizon of four years. Because of the shorter time horizon, the population appears as a gently upward sloping line and not the oscillations in Figure 4. To determine which time horizon is relevant for the system being modeled, it is necessary to go back to the model purpose. A population oscillating with a period of approximately 100 years might only need a reference mode plot over 4

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[8] Reference modes, particularly hypothesized reference modes, should be drawn by hand. The reference modes included in this paper were drawn using a computer drawing program *only* for the sake of clarity.

years if the model purpose focuses on a significant change over those 4 years. Reviewing the model purpose when choosing the time horizon of the reference mode is an essential step.

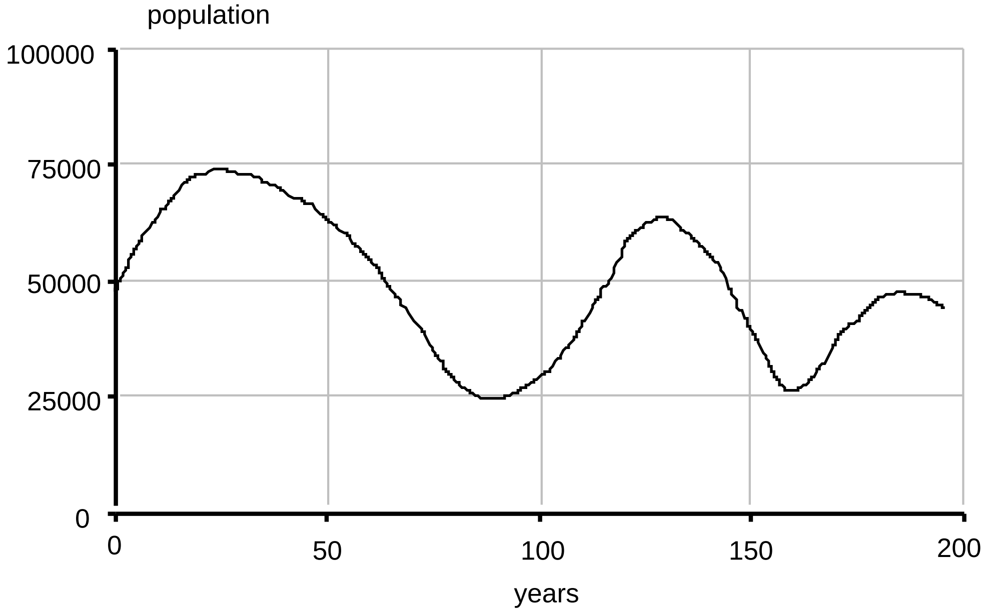

Figure 4: Historical Reference Mode of a Population over 200 Years

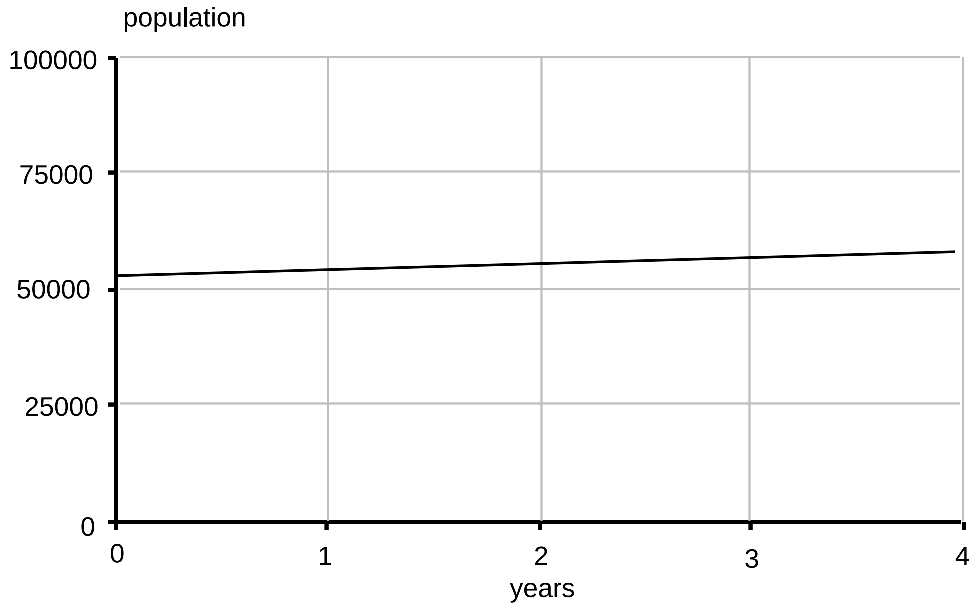

Figure 5: Historical Reference Mode of a Population over 4 Years

4.3.2 Heroin-Crime System

In the Heroin-Crime system from section 3, the reference mode could look like Figure 6. Different people will draw different reference modes because of individual mental models.

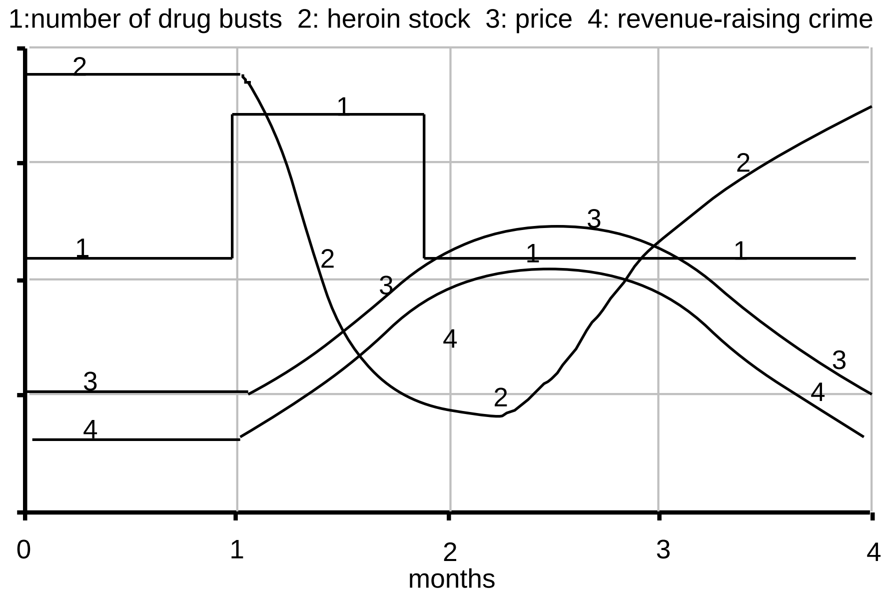

Figure 6: Reference Mode for Heroin-Crime System

To create the graph in Figure 6, the number of drug busts—the cause of the dynamics as defined by our model purpose—was graphed first. The other important variables were then graphed with respect to the drug bust curve. The number of drug busts, the component driving the important behavior isolated by our model purpose, is treated as a step input. As the number of drug busts increases, the heroin stock is depleted. With a lower heroin stock, but constant demand, the price of heroin increases. In order to pay the higher prices, many addicts commit more revenue-raising crimes, such as burglary. The higher prices (and higher profits for the sellers) will lead to a higher importation of heroin to the area. Eventually the heroin stock and price return to normal levels. The shapes of the reference mode curves are mainly hypothesized from the few historical data points given in the system description. Note that there are no numerical values on the vertical or y-axis of the graph because it is the behavior relationship among the curves that is important. Based on the quantity and quality of available data, a modeler may choose whether or not to put specific values on the vertical axis.

4.4 Basic Mechanisms

The final step in conceptualization is deciding on the basic mechanisms of the system. Specifically, the basic mechanisms are the feedback loops in the model. The basic mechanisms represent the smallest set of realistic cause-and-effect relations capable of generating the reference mode. The basic mechanisms may also be thought of as the simplest story that explains the dynamic behavior of the system.

When deciding on the basic mechanisms, a modeler must first mentally decide on a dynamic hypothesis. A dynamic hypothesis is an explanation of the reference mode behavior and should be consistent with the model purpose. A modeler uses a dynamic hypothesis to draw out and test the consequences of the feedback loops. Then a modeler creates diagrams illustrating the basic mechanisms driving the system's dynamic behavior. A model cannot be built without an understanding of the feedback loops. Having a good dynamic hypothesis and well-defined basic mechanism implies having enough information to begin formalizing the system into level and rate equations. One may then move to formulation, the next stage of the modeling process.

The field of system dynamics divides on the issue of how best to diagram the basic mechanisms. Some favor presenting the basic mechanisms in the form of causal-loop diagrams. Others prefer to begin by mapping out the stock-and-flow structure. In Road Maps we prefer the stock-and-flow representation. It is important to note that mapping out the causal-loop diagrams or the stocks and flows is not formulation. In conceptualization, both are just diagrams and the equations are not touched. Before moving on to the Heroin-Crime system, this paper will discuss both diagramming methods and give examples of each. We suggest that the reader use stock-and-flow diagrams for conceptualizing systems.

4.4.1 Discussion: Stock-and-Flow Diagrams

Modelers who choose to diagram the basic mechanisms in terms of stocks and flows often have the causal-loop relationships in the back of their minds. Stock-and-flow diagrams have a tendency to be more detailed than a causal-loop diagram representation, forcing the modeler to think more specifically about the system structure. Many simple mistakes can be avoided by diagramming the basic mechanisms with stocks and flows rather than causal loops because the relationships between components of a stock-and-flow diagram are more strictly defined than those in a causal-loop diagram. While generally more complex and more time consuming to create, stock-and-flow diagrams are more informative than causal-loop diagrams.

Figure 7 contains the basic mechanism of the company from Figure 2 in a stock-and-flow diagram. Modifications to the stock-and-flow diagram will be made when the simulation model is built and the model equations are written during the formulation stage of model building. Keep in mind that Figure 7 is just a diagram of the basic mechanisms. Certain components, such as table functions, will need to be added to create a set of equations which can be simulated. Until the model is built and simulated, the modeler will not know how reasonable the conceptualized diagram is.

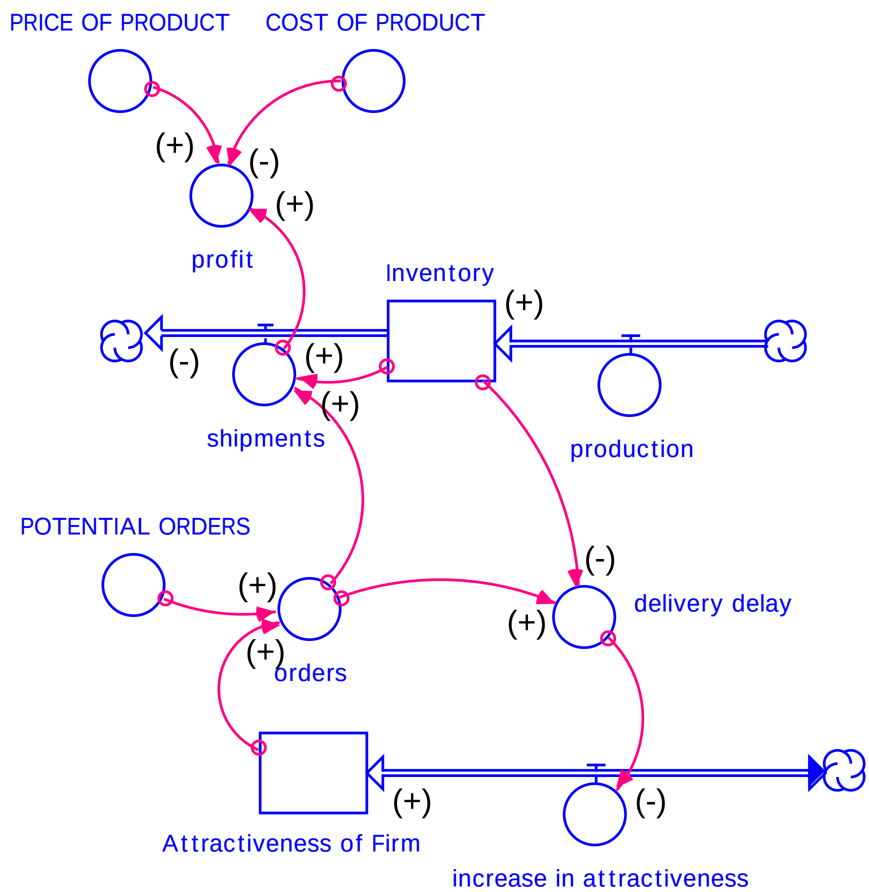

Figure 7: Stock-and-Flow Diagram of Basic Mechanism of a Company (see Fig. 2)

4.4.2 Discussion: Causal-loop Diagrams

Modelers who conceptualize the basic mechanisms of a system in terms of causal-loop diagrams usually have some idea of the stock-and-flow structure of the model in the back of their minds. It is good practice to draw boxes around the stocks in the causal loops. By definition, each causal loop must contain at least one stock. Stocks are accumulations. If a causal loop did not contain a stock, the loop dynamic would be instantaneous. No behavior over time would exist to examine.

If one ends the conceptualization stage with causal-loop diagrams, it becomes easy to overemphasize the value of causal-loop diagrams. A causal-loop diagram is not a model. One cannot conduct any type of policy analysis, locate leverage points, or tell which loop is dominant with just a causal-loop diagram. Causal-loop diagrams are, however, simple to understand and easy to use, and therefore, they are often used *after* simulation to explain to others the insights gained from the model. It is important to understand the limitations of causal loop diagrams if they are used.[9]

Look back to Figure 2, the reference mode of a company's profit and inventory levels. The cause and effect relationship between inventory and profit, leading to profit fluctuations, is captured by the basic mechanism in Figure 8.

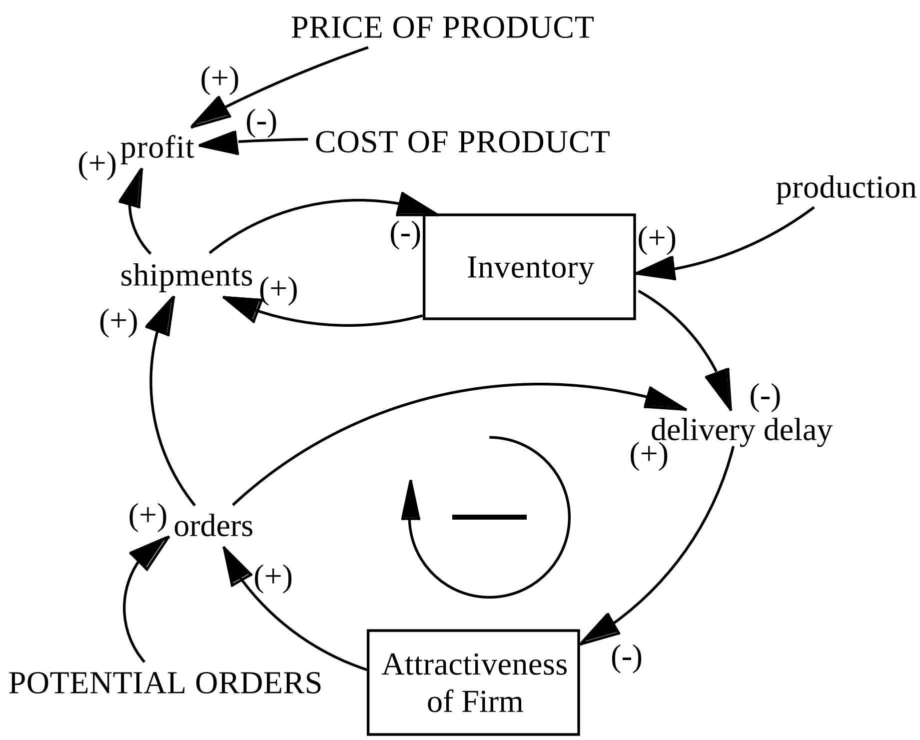

Figure 8: Causal-loop Diagram of Basic Mechanism of a Company (see Fig. 2)

Some people believe that a stock-and-flow structure is more complex than a causal-loop diagram. In some cases, however, a causal-loop diagram may seem more complex than a stock-and-flow structure. For example, Figure 9 contains the stock-and-

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[9] The limitations of causal-loop diagrams are summarized by: George P. Richardson, 1976. *Problems with causal-loop diagrams* (D-3312), Sloan School of Management, Massachusetts Institute of Technology, 13 pp. (available in Road Maps 4)

flow structure of an aging chain for a company's employees. The stock-and-flow diagram is conceptually easier to understand and less complex than the causal-loop of the aging chain shown in Figure 10. Because a stock-and-flow diagram is a more specific representation of the system being modeled, we believe that initial conceptualization should be done with stock-and-flow structures.

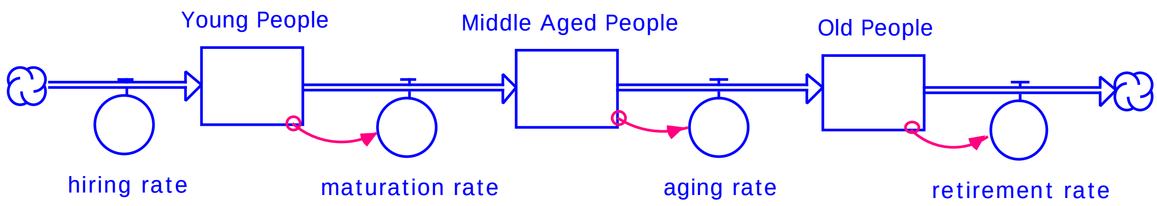

Figure 9: Stock-and-Flow Diagram of an Aging Chain

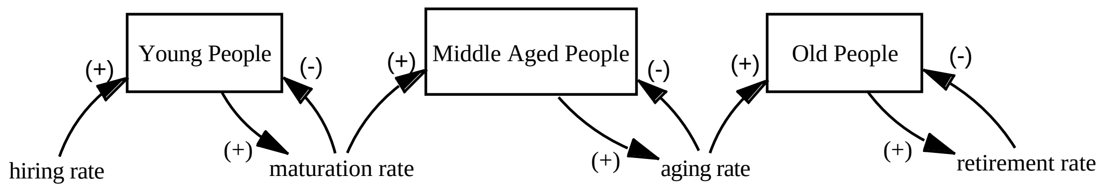

Figure 10: Causal-loop Diagram of an Aging Chain

To have a complete description of the basic mechanisms, a modeler must make certain that all feedback loops are complete and captured within the closed boundary. If not, either the basic mechanisms, the model boundary, or both must be revised. The modeling effort should be performed by choosing and linking levels and rates. Causal-loop diagrams can sometimes be useful for later communication of the model insights.

4.4.3 Heroin-Crime System

Figure 11 contains the stock-and-flow diagram representation of the basic mechanisms of the heroin-crime system. Figure 11 does not show the final model structure. It is simply a representation of the relationships between the system components that create the dynamic behavior of the reference mode. Other components, such as "demand-supply ratio" or "heroin availability factor," as well as additional information links, might be added to make the heroin-crime model plausible and more robust. Such additions will be made during the formulation stage.

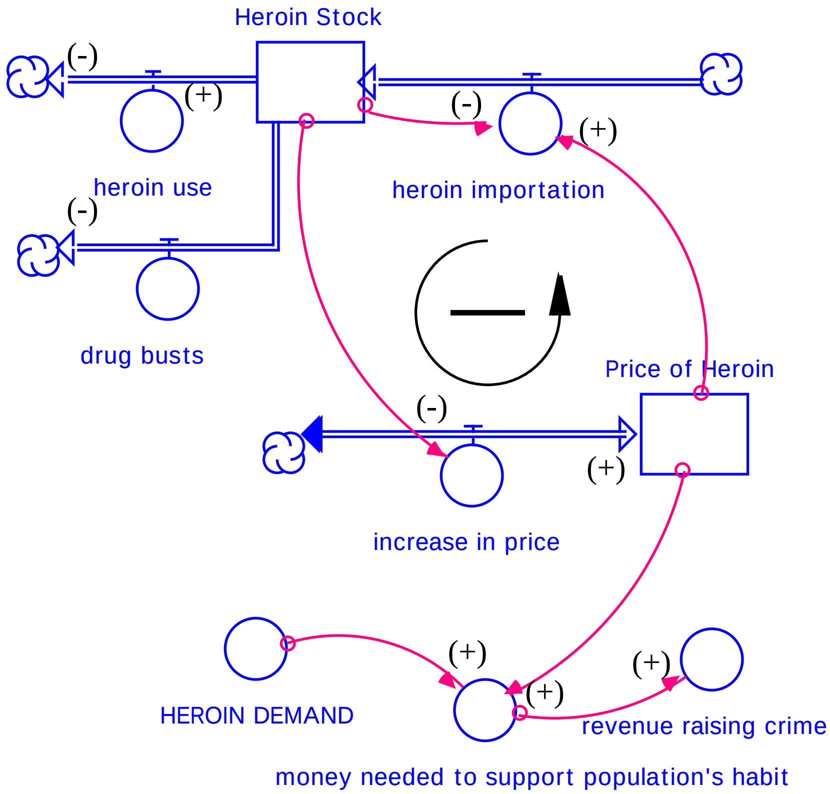

Figure 11: Stock-and-Flow Diagram of the Basic Mechanisms of the Heroin-Crime System

For the Heroin-Crime system, a causal-loop representation of the basic mechanisms might look like Figure 12.

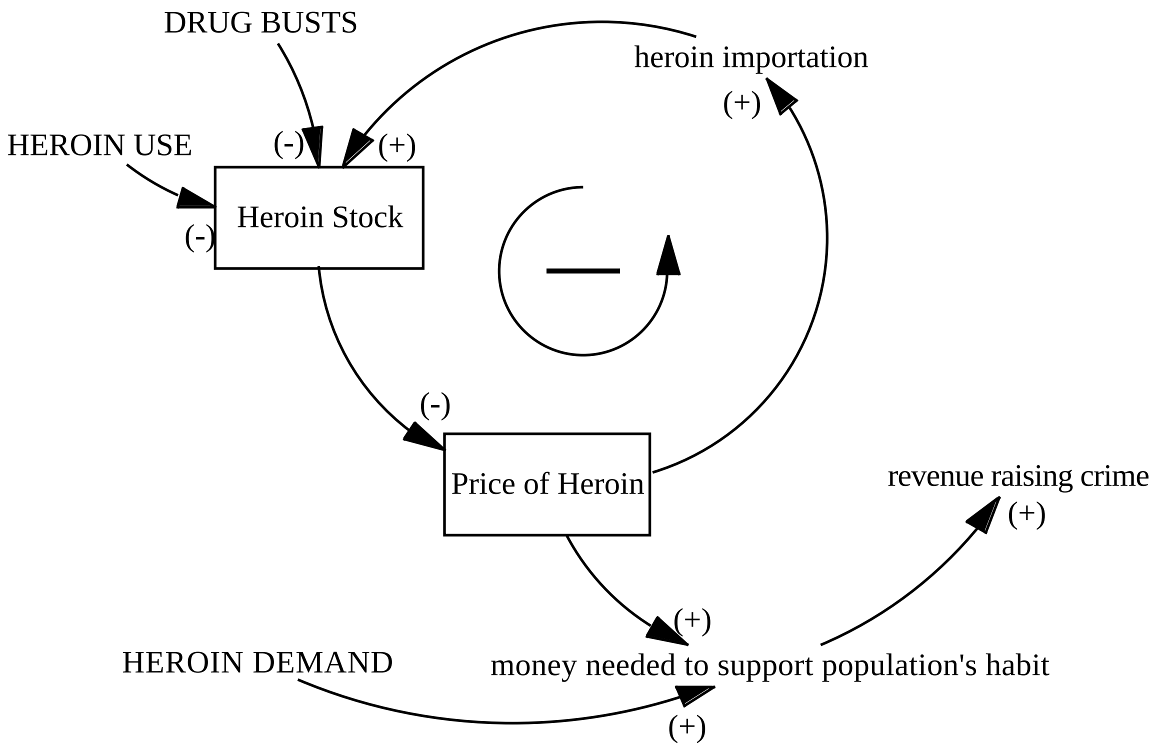

Figure 12: Causal-loop Diagram of the Basic Mechanisms of the Heroin-Crime System

In creating the diagrams of the basic mechanism, the modeler must look back to the components list for the Heroin-Crime System in Figure 1 and the reference mode in Figure 6. One can begin the diagram with the endogenous components. Heroin Stock is drawn on the paper. Depending on the level of detail the modeler would like, the modeler adds the various flows to and from the Heroin Stock that affect its level. These flows are drug busts, heroin use, and heroin importation. Because heroin importation is an endogenous component, it seems natural to analyze that component next. Heroin importation is affected in the Heroin-Crime System described primarily by the Price of Heroin. The Price of Heroin is effected by the Heroin Stock, thus completing our major negative feedback loop. The remaining endogenous and exogenous components of heroin demand, money to support population’s habit, and revenue raising crime can easily be added to the diagram now that the major loop has been diagrammed.

The modeler has now reached the end of the conceptualization stage of model-building. The remaining steps will be discussed in future Road Maps papers. The modeler should now have extracted as much information as possible from a simple system description, and have reached a new level of understanding of that system.

5. CONCEPTUALIZATION EXERCISE[10]

Turn to Exercise 14 of *Study Notes in System Dynamics*.[11] Read the description of the Yellow-Fever Epidemic on pages 365 to 367. **Do not** do the exercises in the book that follow the description. Instead, assume that you want to build a system dynamics model of the Yellow-Fever system. Begin by conceptualizing the system using the steps described in this paper. The system described in the book gives much more information than needed to conceptualize the system. It is not necessary to use all of the facts given.

Now, answer the following questions. Appendix A contains a Modeling Worksheet that may be useful as a guide to answering the exercise questions.

1. What is the purpose of the model being created? Keep the answer to this question in mind while answering the remaining questions.
2. What is the model boundary? Develop an initial components list, divide it up into two categories (endogenous and exogenous) and do a preliminary identification of stocks and flows.
3. What does the reference mode look like? Draw a graph by hand.
4. Describe the basic mechanisms. Give only those essential for the model behavior.

Answers to the above four questions create a dynamic hypothesis to explain the behavior present in the Yellow-Fever Epidemic system.

[10] The solution to the following exercise is in section 6.
[11] Michael R. Goodman, 1974. Study Notes in System Dynamics. Portland, OR: Productivity Press, 388 pp.

6. CONCEPTUALIZATION EXERCISE SOLUTION

Many different solutions are possible to the questions asked in the exercise in section 5. The following solution is only one of the possibilities.

1. The purpose of the model could be to estimate the course of yellow-fever once the virus hits a city. The information generated could be useful for city officials in developing a plan of action and immunization programs.

2. A reasonable initial components list could contain the following components:

mosquito population
death fraction for mosquitoes
birth fraction for mosquitoes
sick humans
immunized humans (by vaccine)
recovery rate for humans
death fraction for sick humans
birth fraction for humans
infections mosquitoes
incubating mosquitoes
vulnerable humans
incubating or infectious humans
immune humans
death rate for humans
human population
birth rate for humans

The initial components list is then divided up and the model boundary is defined by the table of components in Figure 13.

ENDOGENOUS COMPONENTS	EXOGENOUS COMPONENTS
infectious mosquitoes (S)	mosquito population
incubating or infectious humans (S)	birth fraction for mosquitoes
sick humans (S)	death fraction for mosquitoes
death rate for humans (F)	death fraction for sick humans
incubating mosquitoes (S)	
vulnerable humans (S)	
immune humans(S)	
recovery rate for humans (F)	

Figure 13: Model Boundary for Yellow-Fever System

Because the purpose for building the model is to trace the natural path of a yellow-fever epidemic in a city, the base model should not include immunizations. Immunizations would mask the natural course of the disease. The relevant disease in a city is urban or classical yellow-fever, not jungle yellow-fever. Both the number of immunized people and any component relating to jungle yellow-fever are thus to be excluded from the model boundary, though they exist on the initial components list.

The system description states that the mosquito population can be taken as a constant, thereby making it an exogenous component. Carrying the disease makes no difference to the mosquitoes so the death and birth fractions for all mosquitoes (normal and infectious) are constant exogenous components of the system. The death fraction for sick people is also an exogenously measured constant fraction.

The dynamic components of greatest interest when charting the course of an epidemic are the number of sick and number of vulnerable humans, and the human death and recovery rates. Other important components are the number of infectious mosquitoes, the number of infectious humans, and the number of incubating humans. All of the above dynamic variables are endogenous components of the system.

Because the model system deals with a short time horizon, the birth fraction and birth rate for people will not affect the dynamics of yellow-fever. Because all humans living in the area can be divided into one of the human population stocks (vulnerable humans, immune humans, sick humans, incubating or infectious humans), there is no need to create an additional human population stock in the model.

3. The reference mode for the most important dynamic components is shown in Figure 14. Again, note that the specific components included in the reference mode can vary depending on the model purpose. The stocks of sick humans and immune humans, the human death rate, and the stock of infectious mosquitoes were chosen for the reference mode since these four components will reflect the dynamics of both the mosquito and human population. Using the information in the system description, the first curve graphed was the number of sick people, because naturally people must be sick before they either die or become immune. Initially, before the epidemic hits, there are no sick people. After the epidemic has passed and the sick period of 7 days for humans is over, there will also be no sick people. In between these two points, the number of sick humans rises dramatically as the epidemic spreads and then reduces as people either recover or die. The reference mode for the number of sick humans was thus graphed as a bell-shaped curve. Given the fast spread of an epidemic and the data given in the reading, it seems reasonable to have a time frame of only 4 months.

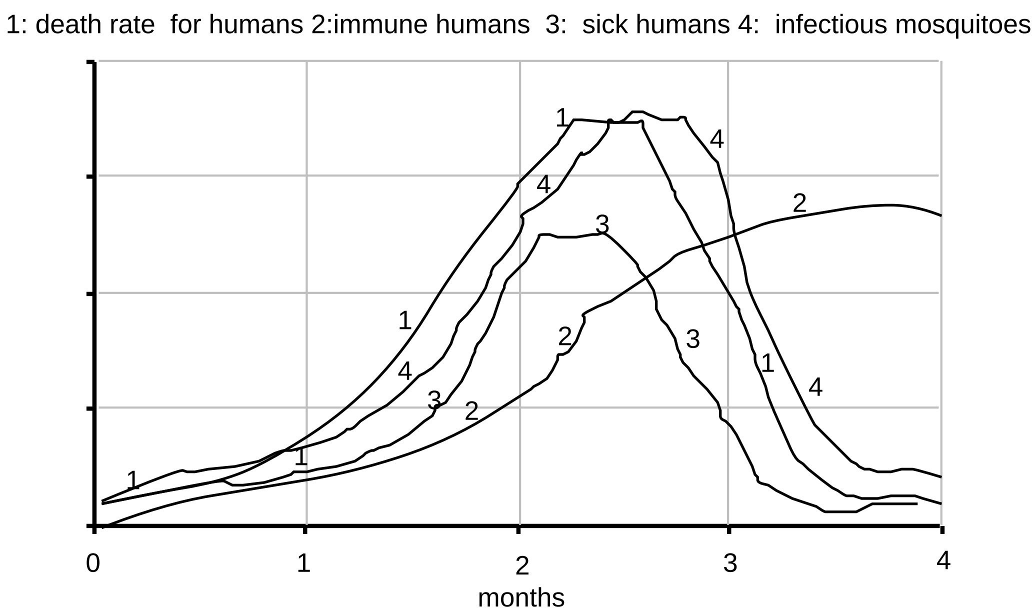

Figure 14: Reference Mode for Yellow-Fever System

The remaining important components were graphed with respect to curve of sick humans. Because the death rate is going to be some constant percentage of the number of sick humans, the reference mode for the death rate for humans is also a bell-shaped curve. The recovery rate of sick humans will also be a constant percentage of the number of sick humans, and is thus also a bell-shaped curve. In the reference mode in Figure 14, however, the modeler is graphing the stock of immune humans and not the recovery rate of humans, which is the flow into the immune humans stock. If the flow into any stock is a bell-shaped curve, the behavior of the stock will be S-shaped.[12] The reference mode for immune humans is S-shaped. Because mosquitoes pass on yellow-fever to humans, making humans sick, and humans pass on the disease to mosquitoes, making mosquitoes infectious, it seems natural that the infectious mosquito curve also mirrors the bell-shaped behavior of the sick humans curve. To double check this assumptions, the modeler should check the expected value of the number of infectious mosquitoes before and after the epidemic hits. Given the short life-span of the mosquito, the bell-shaped reference mode of infectious mosquitoes accurately captures the assumption that there will be no infectious mosquitoes before or after the epidemic. Note that the infectious mosquitoes curve peaks slightly after the sick humans curve peaks. By examining the data in the reading, it takes humans only 3 to 6 days when bitten by an infectious mosquito to become sick. Humans are then sick for about 7 days, and then humans either die or recover. After biting an infectious human, mosquitoes go through a 12 day incubation process before becoming infectious. Once infectious, mosquitoes will only live about another 4 days. From this data, it seems reasonable to assume that it takes longer for the infectious mosquitoes population to peak because mosquitoes have a longer 12 day incubation delay as compared to the 3 to 6 day human incubation delay.

4. The simplified stock-and-flow and causal-loop diagrams for the basic mechanism driving the yellow-fever reference modes are shown in Figures 15 and 16 respectively. The dynamic hypothesis that is driving the reference mode behavior consists of two main points, stressed in the Goodman reading[13]:

1. Infectious mosquitoes pass the disease on to humans. These humans are now contagious and can, in turn, make mosquitoes into carriers of the disease. Yellow-fever is thus **self-perpetuating**, creating an important **positive** or **reinforcing loop** in the model.
2. Mosquitoes which bite infected humans first go through an incubation period before becoming infectious to vulnerable humans. Incubating mosquitoes **do not** transmit yellow-fever to humans.
3. A human bitten by an infectious mosquito goes through a disease incubation period, during which the human is infectious to a mosquito. After the

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[12] For more explanation please see: Leslie Martin, 1996. *Exploring S-shaped growth* (D-4476), System Dynamics in Education Project, System Dynamics Group, Sloan School of Management, Massachusetts Institute of Technology, October 3, 40 p.

[13] Goodman, pp. 365 - 367.

incubating period, the humans become visibly sick, but cannot pass the disease on to mosquitoes. Incubating humans **do** transmit yellow-fever to mosquitoes.

4. Given that the spread of yellow-fever is a positive loop, some limiting force must exist to prevent the infection of the entire human population. One example of such a limit is a **negative feedback or balancing loop** containing the component of vulnerable humans. As the number of vulnerable humans decreases, the spread of the disease through mosquitoes and humans also decreases.

Keep in mind the model boundary defined in Figure 13 and which components were designated as stocks and which as flows. The endogenous stocks and flows are a good starting point for diagramming the basic mechanisms. Some modelers may find it easiest to start by drawing all the stocks first, and then figure out how they connect to one another, keeping in mind the positive and negative loops mentioned above.

The stock-and-flow structure in Figure 15 depicts one way of representing the basic mechanisms. Remember, the stock-and-flow diagram is not a model ready for simulation, but only a diagram of the feedback loops causing the dynamic behavior depicted in the reference modes for the system.

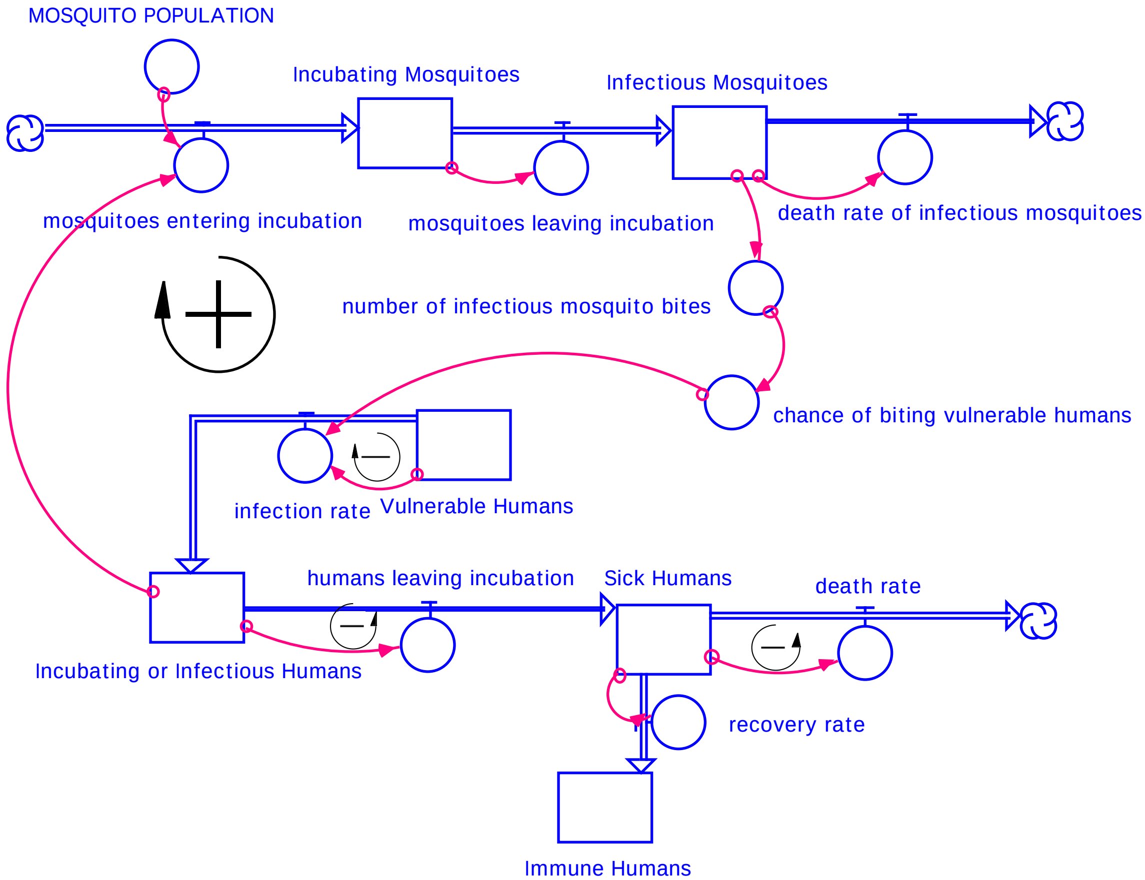

Figure 15: Stock-and-flow Diagram of the Basic Mechanisms of the Yellow-Fever System

Figure 16 contains the alternative causal-loop diagram representation of the basic mechanisms.

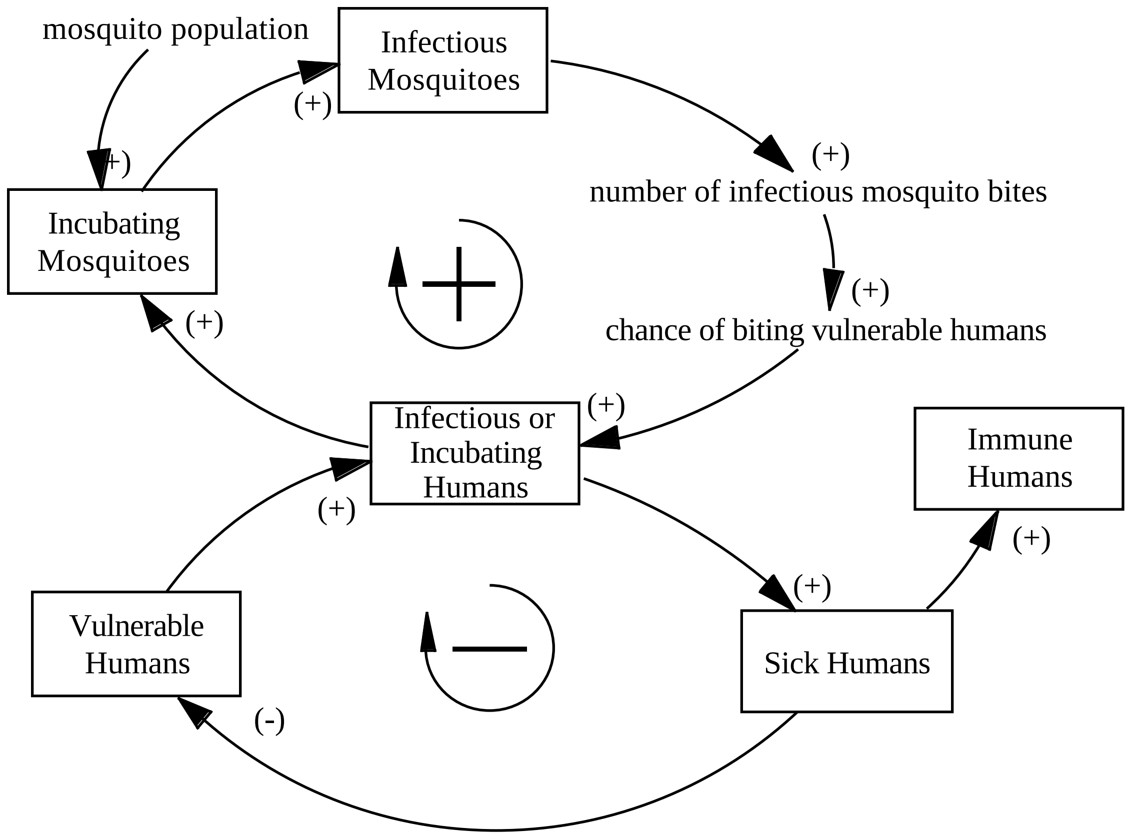

Figure 16: Causal-loop Diagram of the Basic Mechanisms of the Yellow-Fever System

7. Appendix A: Modeling Worksheet

The following modeling worksheet can be used as a guide to the conceptualization stage of model building.

Problem Area:

Purpose of Model:

Model Audience:

Model Boundary Initial Component List:

Model Boundary Column Component List:

ENDOGENOUS COMPONENTS	EXOGENOUS COMPONENTS

Assumptions/Comments on Column Component List:

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____

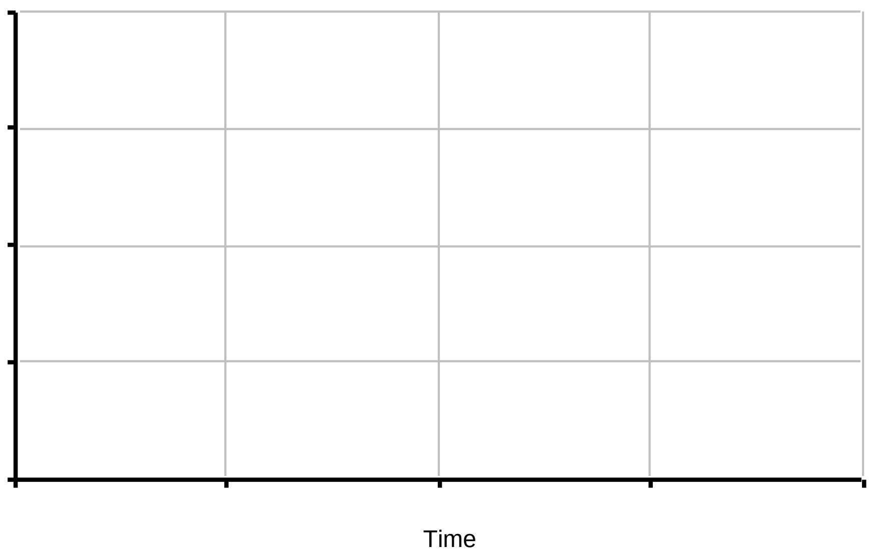
____

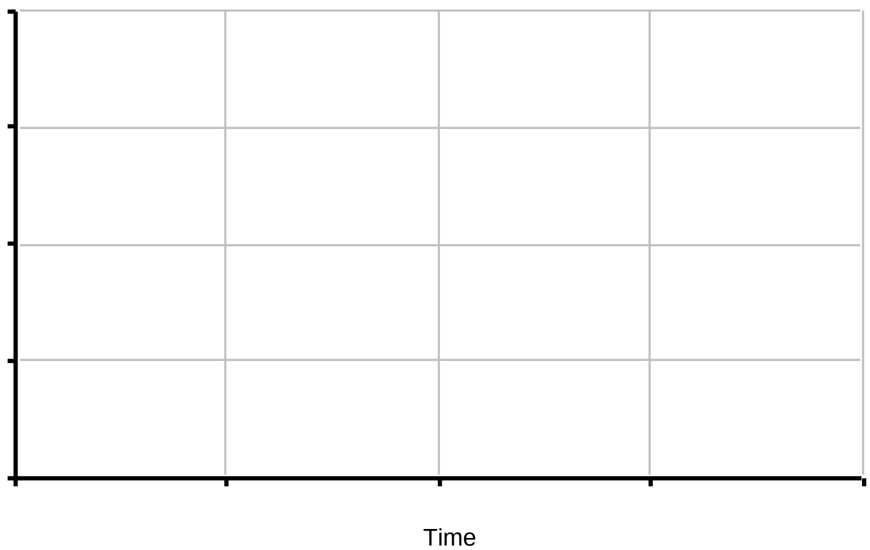
____

On the Column Component List above, mark each stock with the letter “S” and each flow with the letter “F.”

Reference Modes:

(Note: It is essential to fill in values for the time horizon on the horizontal axis of the reference mode graphs.)





Assumptions/Comments on Reference Modes:

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____

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Hypothesis for the dynamics of the model behavior:

Stock-and-flow Diagram of the basic mechanisms:

8. APPENDIX B: RELATED READINGS

The following is a list of readings related to the heroin-crime sample system used in this paper.

Keith Gardiner and Raymond Shreckengost, 1987. "A system dynamics model for estimating heroin imports into the United States." *System Dynamics Review*, Vol. 3, No. 1, pp. 8 - 27.

Gilbert Levin, Gary B. Hirsch, and Edwards B. Roberts, 1975. The Persistent Poppy: A Computer Aided Search for Heroin Policy. Cambridge, MA: Ballinger, 229 pp. (out of print)

Nancy Roberts et al (ed.)1983. *Heroin Addiction and its Impact on the Community.* Chapter 24 in Nancy Roberts et al (ed.). Introduction to Computer Simulations, a System Dynamics Approach. Portland, OR: Productivity Press, 562 pp.