Teaching System Dynamics: Looking at Epidemics

William Glass-Husain

System Dynamics in Education Project

Massachusetts Institute of Technology
System Dynamics Group, E40-294
1 Amherst St.
Cambridge, MA 02139

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Introduction: Epidemics, System Dynamics and the Learning Process

Why Study Epidemics?

The lessons presented here use the tools of system dynamics to explore epidemics. When we refer to an epidemic we are referring not just to the number of people infected with a disease, but also to the dynamics of the epidemic; in other words, to how the number changes through time. Epidemics can involve any one of a number of contagious diseases, or can even involve the "infection" of some other item that spreads from one person to another -- such as an idea or information that spreads through word of mouth.

The reason for teaching the dynamics of epidemics is not because of a sudden decline in the number of working epidemiologists, nor is the sole goal of this series of exercises to teach students how to build good computer models. Instead, the intent of these papers, and of the curriculum they describe, is to use system dynamics as a tool to help people learn to think.

Thinking may seem like a natural process no one needs no learn; in particular, this is true when the term is used to mean the process of being conscious. However, thinking as a process of conceptualization and reflection is discouraged by traditional fact-based, teacher to student education that actively discourages the continual questioning, exploration, and discovery that is needed to gain understanding and appreciation of how the world works. Educators need to encourage innovation and develop new methods of instruction to prepare students to face the diversity of today's changing world.

Goals for the Learning Process

To fulfill the rather broad challenge implied in the preceding paragraph, the author suggests four goals that should be incorporated into the learning process.

"Spiral" instruction -- No concept can be learned from one source or in one sitting. The best method of learning is to see the concept presented in many different forms in many different contexts. The ideal process of learning is rather like a spiral, with students exploring different areas in different ways, while connections are continually drawn to central themes by the teacher, the student or (ideally) both. The term "spiral" comes from the continual circling back and reinforcing of old concepts as new ones are introduced. This exploration can be done by discussion, by reading, by writing, and by hands-on experimentation and simulation.

Learner-directed learning -- Something that should go hand in hand with this spiral method of study is learner-directed learning. The teacher should not be solely responsible for directing every loop of the spiral. Discovery of new ideas and new connections to old themes is what makes any subject interesting and exciting and hence more likely to be understood and appreciated. Closely related to this is the idea of inter-activeness -- that students get a chance to interact with each other and learn (at least some of the time) in a "hands-on" fashion.

Relate the concrete to the theoretical -- These two perspectives are complements of each other, not opposites, and should both be included. Learning should be done in context. Examples used should be connected to a framework already held by the student. People learn new things best when they are taught in relation to other things they are already familiar with. However, theory is important. Through the learning of theoretical principles a more general understanding can be gained.

Scientific method -- Finally, a key concept in learning is that of the scientific method. Before any kind of experimentation, hypotheses should be made of the behavior of the experiment. After the experiment, there should be a follow up evaluation asking the question "What happened?" and examining how the behavior of this experiment relates to previously learned concepts and ideas. This is particularly important when using a computer to do simulation. Without this process of introspection, students may fall prey to the "video game" syndrome of "pushing buttons" to "win" the simulation and may not fully stop to consider the larger issues involved.

Studying an Epidemic with System Dynamics

Using system dynamics to explore epidemics, all four of these goals can be approached.

In these lessons many general characteristics of epidemics will be revealed. Yet. the lessons also communicate on a deeper level several fundamental truths. Concepts such as stock/flow models, feedback loops, shifts in dominance, system boundaries, and aggregation will be discovered as the system is explored on many different levels. Other ideas such as the relationship between structure and behavior, the validity of different paradigms for understanding different aspects of a system, and the endogenous nature of behavior are also subtly but strongly interwoven themes that will be touched upon over and over again during the examination of this simple-seeming system.

Different modes of teaching can also be employed. These range from discussion, to presentation of real-world data, to guided and independent modeling and simulation.

Learner-directed learning should be a key component of teaching system dynamics. It is particularly suited to the individual nature of modeling and simulation. When students construct their own models, they can learn at their own pace (within broad guidelines), and will be able to develop their own policies to simulate. Also, because the very nature of system dynamics demands that it cannot be taught as a collection of unrelated facts, students are actively encouraged to place their pieces of information they learn into a framework and apply it while modeling and thinking in general.

All simulation of dynamic behavior should be preceded by students making sketches of what they predict the behavior to be. There should be discussion as to the reasons for their predictions. In the case of disagreement, it is often advantageous to “set one side against the other” and let the students argue (in a guided, controlled fashion). The author has found this technique particularly effective when the correct answer is some combination of both answers proposed (i.e. both sides are right). Each group will try to convince the other, and eventually there will usually be a consensus as to what the behavior should be. It is important to guide the argument so that all students have a chance to present their views, and it is good to clarify points when necessary.

Structure of Lessons

While the sequence can stop at any point, the each of the lessons presented in this packet are designed to build on concepts introduced in the previous lessons. Students participating in lesson 1, the Epidemic Game, will have a valuable learning experience, but those continuing on to lessons 2 and 3 will have a deeper understanding and appreciation of how both an epidemic and system dynamics work.

Lesson 1 *:* ***The Epidemic Game*** *(time: one hour)* -- This lesson approaches both system dynamics and an epidemic from an intuitive perspective. Students play a short simulation game, then engage in discussion to figure out how the epidemic works. Students are encouraged to be critical thinkers, creating and contrasting different hypothesizes until they cooperatively discover an explanation that makes sense. Students discover that different processes cause different behaviors -- a notion fundamental to all systems -- and that two different processes operate in an epidemic causing different behaviors at different times.

Lesson 2 *:* ***Modeling an Epidemic*** *(time: four hours)* -- This lesson has two parts. The first is a short lecture and discussion on the basic principles of feedback in systems. Several examples are explored. In the second part, students follow a worksheet and, working in pairs on Macintoshes, build a model of a generic epidemic. Through doing this they apply many of the general concepts discussed in class to a specific example.

Lesson 3: Epidemic Research Project *(time: variable)* -- A suggested final lesson is an optional project in which students do research on other, historical epidemics. The students then create more sophisticated, accurate epidemic models based on their research. The lesson could end with a written report and oral presentation of the completed model. *(not included in packet)*

Lesson 1: Playing the Epidemic Game

Why Play the Game?

The epidemic game is a role playing simulation in which the students one by one become infected with a fictitious malady. The game and debriefing for the game can be used independently in the classroom to give an intuitive introduction to how an epidemic works, or it can be combined with the next lesson, Modeling an Epidemic, that uses a slightly more formal, complementary approach of building a computer model of an epidemic.

The epidemic game will give students an intuitive, hands-on introduction to the following concepts:

1) Dynamics of an epidemic

2) Influence of structure -- "rules of the game" -- on system's behavior

3) Feedback in dynamic systems

The Epidemic Game

The epidemic game is outlined in a set of rules given in Appendix II. While the instructions may seem complicated, the idea is simple enough. One student begins the game infected with a disease. While interacting through handshakes with the rest of the group that student begins the epidemic that results in everyone becoming infected. The time at which each person becomes infected is privately recorded. Later, this information will be collected and graphed to show the behavior of the system. After the game is played, students are challenged to determine the dynamics of the game, in other words, the changes in the cumulative number of infections during the course of the game. Then, using the recorded data, the number of new infections for each turn is tallied up to produce graphs of both the actual number of new infections and the number of cumulative infections versus time. Finally, a computer is brought in with a model of the epidemic that can simulate almost identical behavior to the game just played.

A typical session with the epidemic game will go in these steps:

Read the rules. Skip the description of what the disease actually is. Tell them the game will run for twenty turns, each turn representing one month.

Choose an initial infected person. Have all the students close their eyes and tap one student on the shoulder to indicate that he or she is the first infected student.

Play the game. Count off turns, writing the month number on the board each turn, and watch each student shakes hands twice (or to be more precise, each hand once). Then, sometime around the twelfth turn when everyone should be infected, stop the game.

Begin the discussion.

There are a couple of features of the game that need a bit more elaboration. First of all, because of the limited size of many classes, each student represents two people. An easy way for people to keep track of both identities is to picture them as their two hands. Each hand should shake hands with one other hand every term (either the left or right hand can shake any other hand). If a healthy person shakes hands with a Sick Person and receives the “secret” handshake, that “hand” will become infected. It is important to emphasize when you read the rules that students should keep track of the month in the game when each hand becomes infected, as much of the rest of the time after the game is over will be spent discussing that data.

A second slightly tricky aspect of the game is that, just like the real world, not every contact between infected people and non-infected people brings a new infection. In the epidemic game, when a Sick Person shakes hands with a Healthy Person, there is only a 50% probability that the Healthy Person will be infected. To ensure this, before each turn begins, each Sick Person picks either the number 1 or 2 for each infected hand. The leader of the game then picks the 1 or 2 and announced the number, as he or she writes the month number on the board. For each hand, if the Sick Person’s number matches the leader’s number, the Sick Person gives the secret handshake. The probability can be varied by changing the possible range of numbers both the leader and the Sick Person choose from.

Finally, because it is important that the rules be followed exactly in order for the game to produce the correct results, it is a good idea to stop several turns into the game, tell everyone to close their eyes, and then have the Sick People raise their hands. If their are more than two or three Sick People at this point, something is wrong. Also, do a similar head count around the tenth or eleventh turn to determine if it is time to halt the game or not.

Discussion: What Happened? Why Did It Happen?

The discussion that follows the actual simulation is probably the most important part of the exercise. During the discussion, students need to take their raw experiences from the game and put it into a systems framework -- enabling them to understand how and why this epidemic worked.

As a teacher, your role is important, but difficult. While the temptation may be great to tell your students what to see, they will understand these concepts best if they figure them out on their own under your guidance. Your role for the purposes of this discussion will be as a facilitator than a lecturer.

Facilitating the discussion will involve basic issues such as making sure everyone gets a chance to speak. Clarification and restatement of what students are saying is often necessary. At times, however, you may just need to stand to the side and let students talk it out without your explicit involvement.

You should, however, guide the discussion through several steps:

- Step 1: Making a first hypothesis
- Step 2: Presentation of hypotheses
- Step 3: Reason for hypotheses
- Step 4: Resolution
- Step 5: Graph of results from game play

Additionally, there are a few general issues involving system thinking that can run through the discussion as well. Finally, if students do not mention some of the issues you would like to see discussed, or they seem stuck in a particular rut of thinking, you will probably want to get more involved..

Step 1: Making a first hypothesis -- To begin the discussion, ask your students to draw their impression of how the number of infections changed through time. Draw a sample axis on the blackboard, label the y-axis “total infections” and the x-axis “time” and ask the students to fill out a similar axis on paper by themselves. When they are done ask them to write a sentence or two of why they think their guess is correct.

Step 2: Presentation of hypotheses -- Have some students put their hypotheses on the black board. You might want to select the ones for presentation based on uniqueness, e.g. if 5 people all guess exponential growth there is no need for more than one to be drawn on the board. You should have guesses split between Figure 1 (exponential growth) and Figure 2 (goal-seeking growth), with a few people guessing figure 3 (linear growth) and Figure 4 (s-shaped growth). If for some reason, no students predict behavior similar to either figure 1 or 2 you may want to draw them and present arguments in favor of them yourself.

Step 3: Reason for hypotheses -- Now, go back through the students who graphed their predictions on the board and ask each one to give a short argument in favor of their theory.

Step 4: Resolution -- Guide the discussion so that students realize that both the arguments for Figure 1 and figure two have merit in some circumstances, and not in others, and that in fact the answer is Figure 4, a combination of figures 1 and 2.

Step 5: Graph Results from Game Play -- Create a graph based upon the recorded data of the number of new infections each turn ("infection rate"). Add up the new infections and create a graph of the total number of infections so far for each turn ("cumulative infections"). This can either be done by hand on the blackboard, or using a spreadsheet program on a Macintosh such as Excel. Compare the actual behavior with the behavior predicted by the class's hypothesis.

In this discussion students get their first taste of several important system concepts:

- circular feedback nature of systems
- distinction between flow variables that indicate change from one time period to another (the number of new infections) and stock variables that accumulate (number of total infections)
- the use of different models to explain different aspects of a system

- the need to explain the behavior of systems (the dynamics of the game) in terms of the structural interrelationships between the elements of the system (the rules of the game)

Each of these are themes that can be presented in many different systems and at many different levels but that are particularly explicit in the epidemic game.

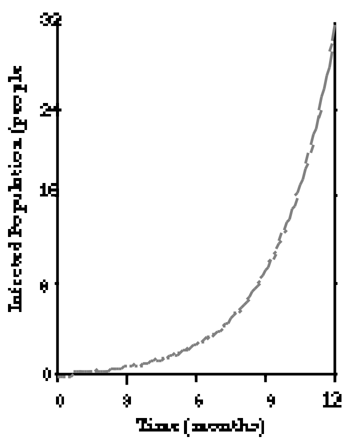


Figure 1: Exponential Growth

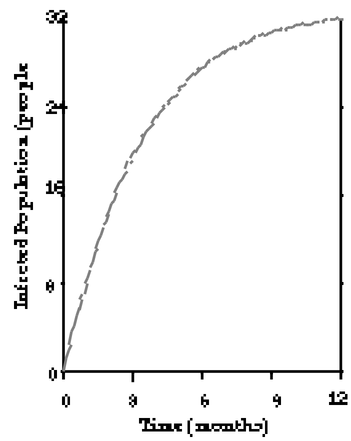


Figure 2: Goal Seeking Growth

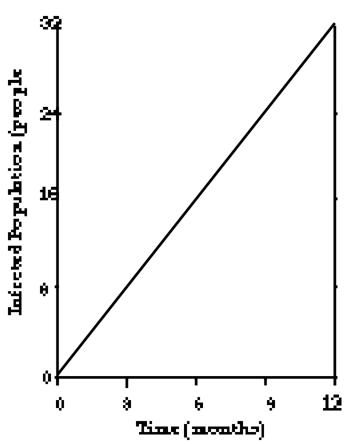


Figure 3: Linear Growth

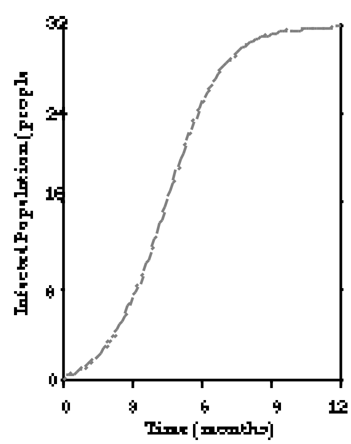


Figure 4: S-shaped Growth

Epidemic Behavior: "The Right Answer"

Figures 1 through 4 show possible graphs of how the stock of Sick People varied through the game. Out of the four possibilities in Figures 1 through 4, which is the "right answer" students should decide on?

We can eliminate linear growth, Figure 3, pretty quickly. As the number of Sick People and Healthy People varies, the number of infecting handshakes per turn, and hence the new number of nerds, is going to change. This means that the growth in the Sick People population cannot be constant, in other words, the graph cannot be a straight diagonal line. Let's study some other possibilities by examining Figures 1 and 2 in more detail.

Exponential growth has some appealing evidence in favor of it. Remember, infected people cause others to be infected. The more infected people, the higher the infection rate (number of new people infected each turn). This means that the infection rate has got to be very low when there are only a few people already infected. As the number of infected people rises, more infectious handshakes will be given, and the infection rate will rise.

Sounds good, right? Unfortunately, there is a serious problem here. What happens when you run out of people? Students arguing in favor of goal-seeking growth (figure 2) will be quick to point out that after they caught the disease, they received many infecting handshakes that had no effect because they had already caught the disease. In fact, by the end of the simulation very few people are left who have not yet been infected, and most infecting handshakes delivered are useless. This means that the number of new people being infected must slow down as the number of Sick People rises. While the number of infected people never goes down (there are no cures in this simulation), as the un-infected population decreases, the infection rate decreases.

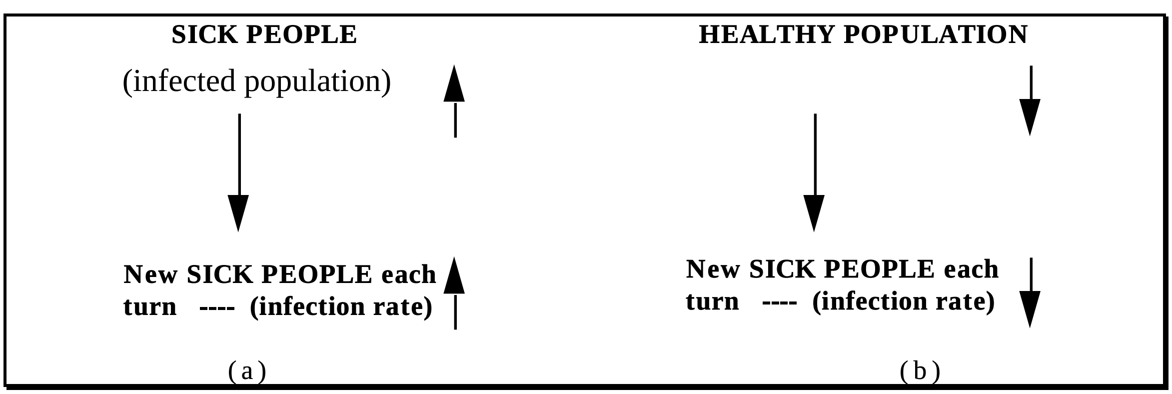


Figure 5: (a) Argument for exponential growth: As the number of Sick People increase, the infection rate increases; (b) Argument for goal-seeking

behavior: As the number of Healthy People decrease (and the Sick People increase), the infection rate decreases.*

This justification for goal-seeking behavior also has a serious flaw. According to the graph in Figure 2, new infections are large in the first turn but slowly drops to zero by the time that there are no un-infected people left. But, we know that there can only be a maximum of one infection the first turn -- after all, the game begins with only one Sick Person to do the infecting.

Both exponential growth and goal-seeking behavior seem to fit different aspects of our game, but each has flaws. The exponential growth does not adequately explain the behavior near the end of the simulation, while the un-infected population is low. The goal-seeking growth does not seem to fit in the beginning when the infected population is low.

The answer is that both Figure 1 and 2 are correct answers, but for different times in the simulation. Each is a different aspect of the full behavior of S-shaped growth, shown in Figure 4. Early on in the simulation, when the upper limit is very far away, Figure 5a is the most prominent rule that determines the behavior, and we see near-exponential growth. However, as the infected population grows nearer to the upper limit, the explanation shown in figure 5b becomes important, and the growth slows down and becomes goal-seeking.

* It is important to note that the relationship between the SICK PEOPLE or the HEALTHY PEOPLE and the infection rate is circular and not just one way. For example, if the number of SICK PEOPLE increase, the infection rate will increase. This then causes an even greater increase in the number of SICK PEOPLE. This idea of *feedback* will be examined in great detail in the next chapter.

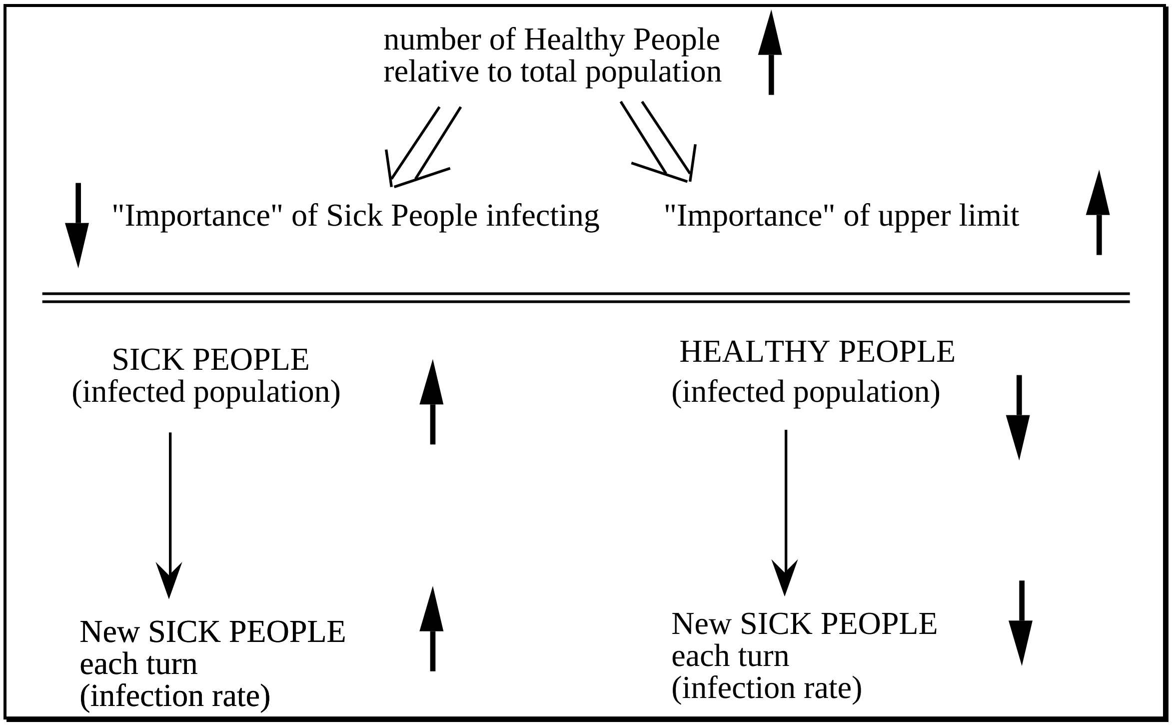


Figure 6: As the Sick population rises, the influence of the number of Sick People on the infection rate becomes weaker and the influence of the number of Healthy People on the infection rate becomes stronger.

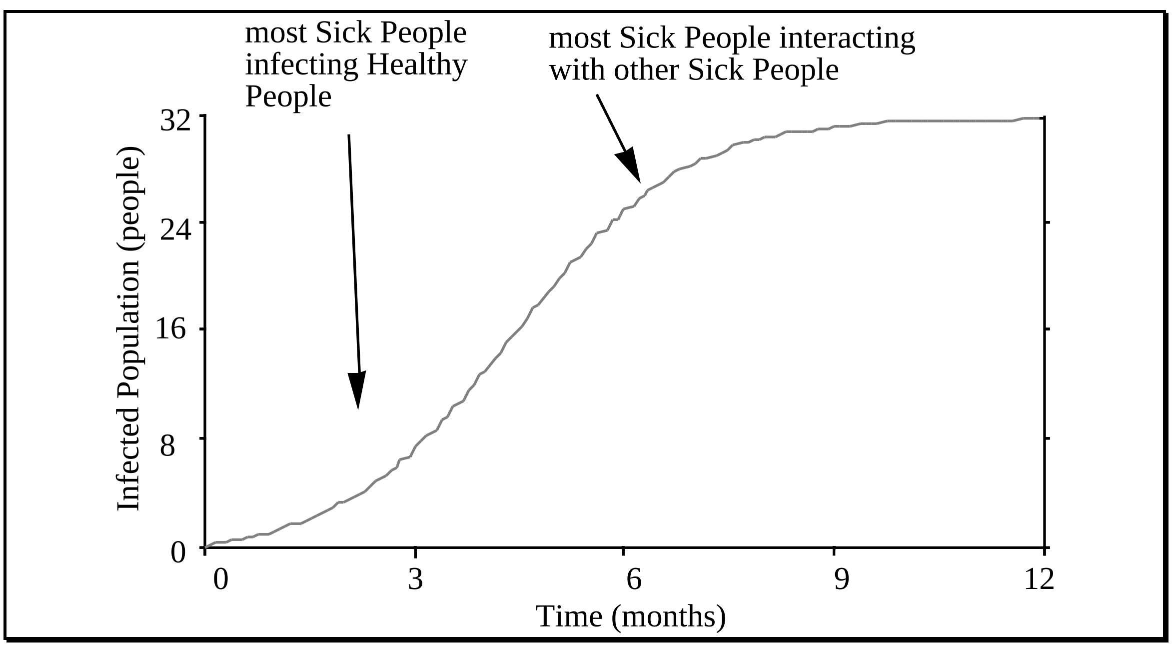


Figure 7: The S-shaped growth caused by the shift from exponential growth to goal-seeking behavior

The Final Reinforcement

An important ending to this exercise is to let students experiment with a STELLA model of an epidemic such as the one presented in Appendix III. Through guided experimentation, students will gain a fuller appreciation of the behavior produced by the epidemic system.

When presenting the model, give a quick explanation of how the model works and then show students how to vary the parameters in the model, to simulate the model, and to graph the simulation. The parameters to vary are the initial number of Sick People and Healthy People, the probability of infection per contact between a Sick Person and a Sick Person, and the number of handshakes per person per turn. Students should discover that except for trivial cases such as an initial number of zero Sick People, changing the inputs of the epidemic has no effect upon the behavior pattern of the epidemic (although sometimes the scale or length of the simulation will need to be adjusted to show full S-shaped growth).

Appendix I: Sample Outline of Epidemic Lesson 1

I. Play Game

II. Guess Dynamics

A. Individually

B. Arrive at Consensus

III. Graph Actual Dynamics of Game

IV. Experiment with Computer Model

Appendix II: The Epidemic Game

Background

In this game we are going to simulate an epidemic of a disease. One person among you has just been infected. Most of you may think that one person is no big deal, but medical experts versed in system dynamics are concerned, and have begun a program of research. They have determined that this disease is an unusual disease for three reasons. First, the disease is only spread through the shaking of hands. Second, the symptoms do not appear for three years after infection even though an infected person is contagious immediately. Third, infections are not guaranteed to spread with every contact of the disease; rather there is a probability of infection with every contact.

The symptoms of the disease are quite striking. The first signs of the disease is a slight slouching, usually beginning around 3 years after infection. After that the bone structure of the hips is altered, most noticeably resulting in a tendency for one to pull one's pants as high as possible. Other features include a smoothing of the nose-skin (which can be corrected by placing adhesive at strategic points on eye wear) and craving for tee-shirts with obscure mathematical symbols. This sounds minor, but usually culminates in attacks so severe victims must be confined to the famous treatment center, the Masochistic Institute of Terminology.

Rules of the Game

In order to increase the playing population in the simulation, think of each of your hands as a separate person and repeat the steps of the game for each hand. With minutes simulating months, the game will be run at one minute intervals allowing one contact per person per minute with a 50% infection probability. The disease will be passed by using the “secret” handshake, which your teacher will demonstrate.

Each Time Period:

1) Designate your left hand or right hand as the first to shake during the period.

2) Select a random person in the room with whom to shake hands.

3) If your designated hand is infected, pick either the number 1 or 2 and remember your selection.

4) If your number is called and your designated hand is infected, prepare to administer the “secret” handshake on your next turn.

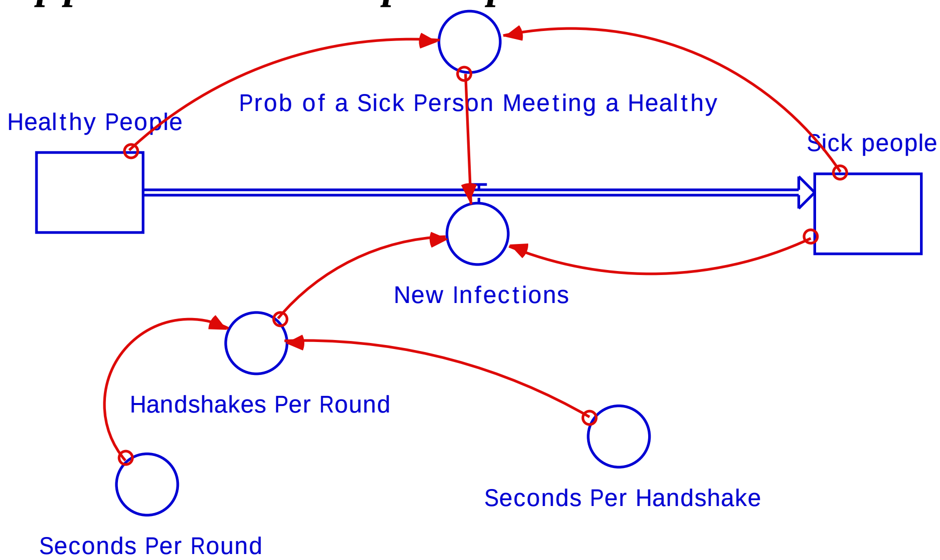
5) Shake the hand of a random person.

6) Record on your score card the infection status of your designated hand.

7) Repeat steps 2 through 6 using your non-designated hand.

8) Go back to step 1 and repeat process for next time period.

Appendix III: Sample Epidemic Model



Healthy_People(t) = Healthy_People(t - dt) + (- New_Infections) * dt
INIT Healthy_People = 26 {People}

New_Infections =
Prob_of_a_Sick_Person_Meeting_a_Healthy*Handshakes_Per_Round*Sick_people {Infections/round}

Sick_people(t) = Sick_people(t - dt) + (New_Infections) * dt
INIT Sick_people = 1 {People}

New_Infections =
Prob_of_a_Sick_Person_Meeting_a_Healthy*Handshakes_Per_Round*Sick_people {Infections/round}

Handshakes_Per_Round = Seconds_Per_Round/Seconds_Per_Handshake
{(handshakes/round)/person}

Prob_of_a_Sick_Person_Meeting_a_Healthy =
Healthy_People/(Healthy_People+Sick_people) {dimensionless}

Seconds_Per_Handshake = 5 {seconds/handshake}

Seconds_Per_Round = 10 {seconds/round}

Epidemic lesson 1 / transparency 1

Rules of the Game

Remember:

- Each of your hands is a separate person.
  - + So, repeat the steps of the game for each hand.
- Each minute represents one month.
- For each Sick Person handshake, 50% probability of infection.
- Sick People use "secret" handshake when infecting.

Each Time Period

1) Designate your left hand or right hand as the first to shake during the period.

2) Select a random person in the room with whom to shake hands.

3) If your designated hand is infected, pick either the number 1 or 2 and remember your selection.

4) If your number is called and your designated hand is infected, prepare to administer the "secret" handshake on your next turn.

5) Shake the hand of a random person.

6) Record on your score card the infection status of your designated hand.

7) Repeat steps 2 through 6 using your non-designated hand.

8) Go back to step 1 and repeat process for next time period.

Epidemic lesson 1 / handout 1

Name:_________________ Epidemic Game

Score Card

(fill out during the game)

Month	Left	Right	Month	Left	Right
1			11		
2			12		
3			13		
4			14		
5			15		
6			16		
7			17		
8			18		
9			19		
10			20		

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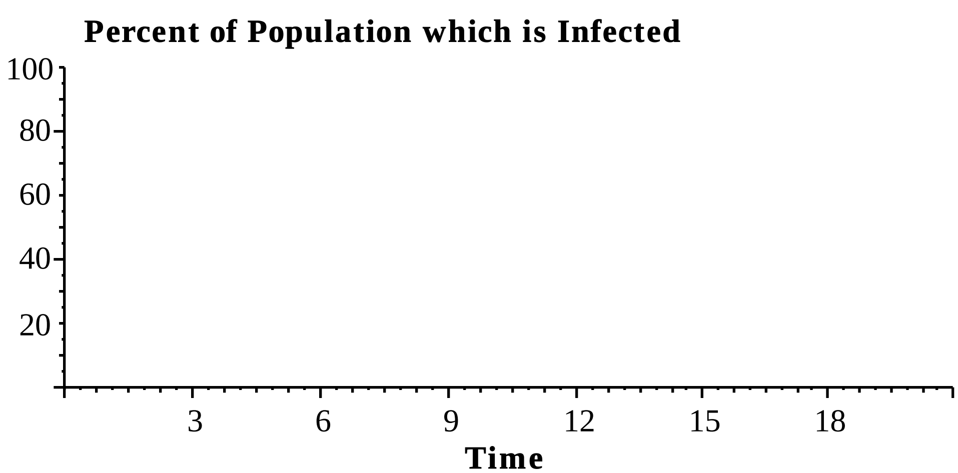
Hypothesized System Behavior

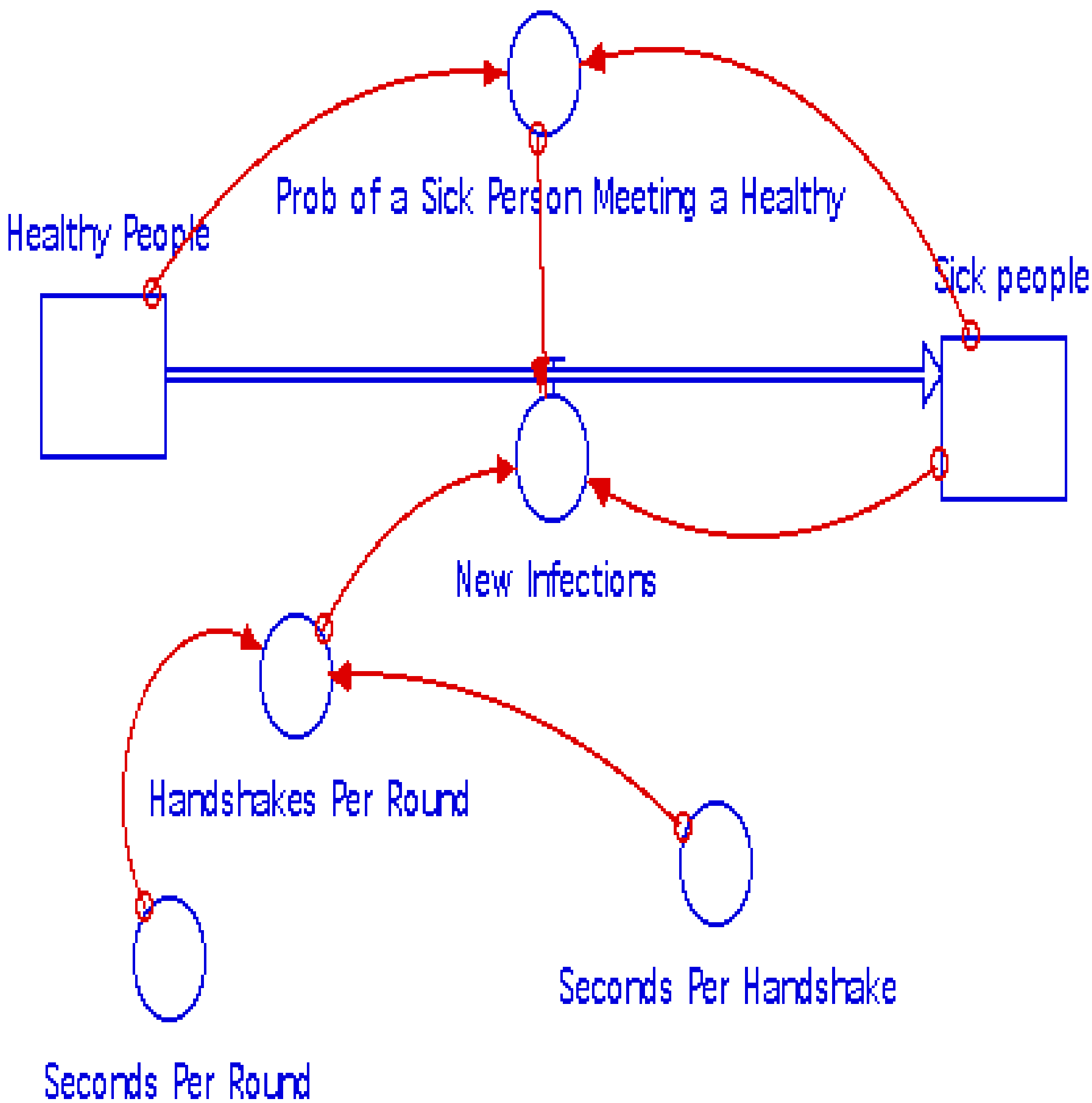
(fill out after game)

On the axis below, sketch how you think the percentage of people in the infected population changed over time.



Write a sentence or two describing why you believe the epidemic showed the behavior sketched above.

Epidemic lesson 1 / transparency 2



Lesson 2: Modeling an Epidemic

Goals of Lesson:

In the last lesson, students engaged in an intuitive exploration of the structure of the epidemic — the set of interrelations that make up the epidemic system. In this lesson, students gain understanding of the connection between the structure and the dynamics of an epidemic by modeling the epidemic from the previous lesson. At the same time as they learn about the epidemic students will learn these system skills:

1) Ability to discern feedback loops in different situations,

2) Ability to explain behavior of a one or two loop system in terms of structure,

3) Basic familiarity with STELLA building blocks, and

4) Experience building in stages a small model using STELLA.

Format of Lesson

This lesson is organized in two parts. The first half involves a short introduction to the terminology and concepts of feedback and STELLA modeling, presented by the teacher. During the second half, students work on Macintosh computers in pairs and build a model of the epidemic by following a highly structured, hands-on worksheet. By building the model, students gain self-confidence and motivation as they form a deeper understanding of how the epidemic works.

Feedback loops

Begin the class by pointing out the structural importance of feedback in driving the behavior of the epidemic simulated in the previous lesson. In the simulation, Sick People infected Healthy People creating more Sick People. Just as important, however, those newly infected Sick People helped to create even more Sick People! Similarly, there was another kind of feedback in the later stages of an epidemic. More Healthy People being infected meant less Healthy People stayed around, which meant less Sick People became infected. The circular aspect of each structure was a key factor in producing in both the early exponential growth in infections and the infection rate and the leveling off of infections near the end.

Positive feedback

Next, explain the general concept of both positive and negative feedback. Positive feedback is a self-reinforcing process that causes exponential growth. A good first example of positive feedback is something that should be familiar to most of your students: a savings account (see Figure 1). Many people view a bank account as a straight cause and effect system. Savings generate interest. However, a bank account is actually a positive feedback loop: savings in a bank generates interest, which gets added to the savings, generating more interest.

Other good examples of positive feedback include a population of rabbits and a shouting match. Rabbits give birth to produce more rabbits. These new rabbits give birth to even more rabbits. One person shouts at another, causing the other person to become angry and shout back. This results in the original person becoming angrier and shouting even more. Each of these systems is often thought of as a one way relationship but is really a positive loop.

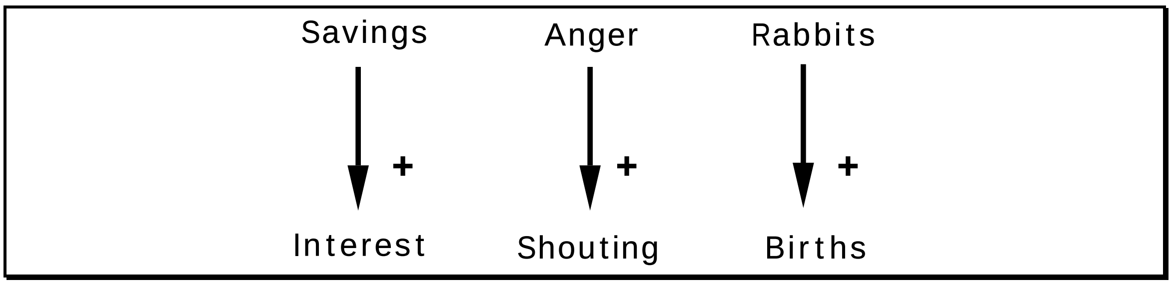


Figure 1: Three cause and effect open loops.

We can represent these systems with *causal loop diagrams* (Figure 2). The “+” sign next to the arrows indicates that as the first item changes, the second changes in the *same* direction. Thus, more savings will cause more interest, more anger means more shouting, and more rabbits will produce more births. Similarly, less savings causes less interest, less anger causes less shouting, and fewer rabbits cause fewer births. The “+” sign within the circular arrows in the feedback loops tells us that these are positive feedback loops.

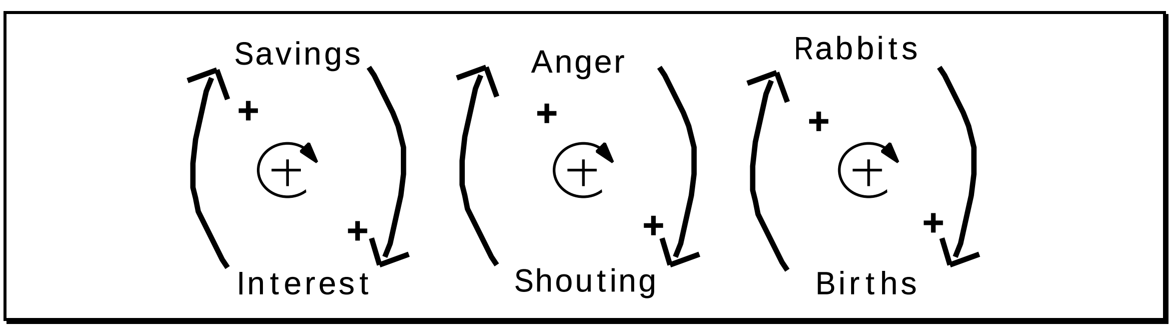


Figure 2: Positive feedback loops

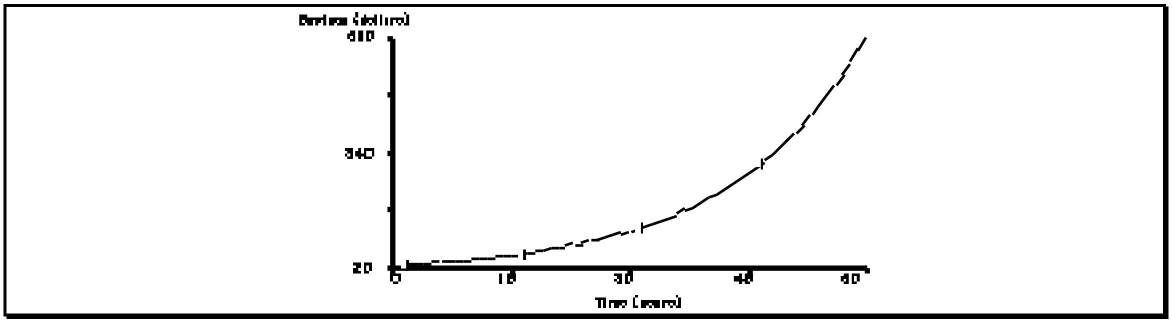


Figure 3: Savings in a bank with 6% interest

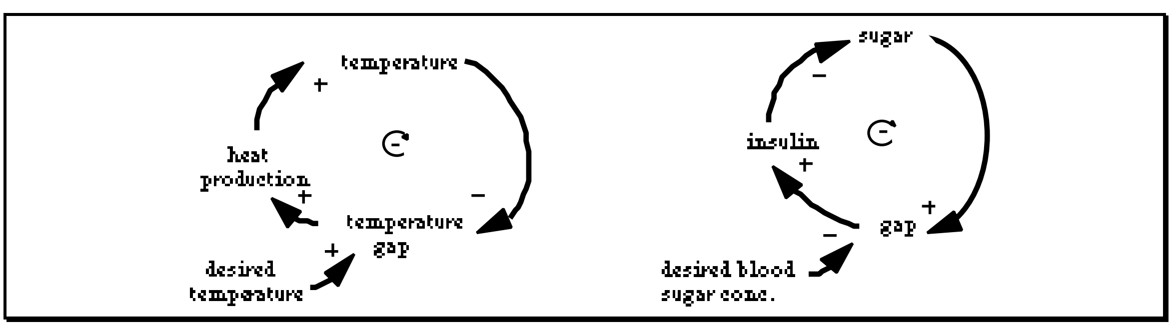
If we look at the dynamics of a variable in a positive feedback loop, we see the *behavior pattern* of exponential growth. For example, in Figure 3 is a graph of a savings account that initially had $20 deposited, with an interest rate of 6%. In 60 years, the amount of savings has increased to $660, 33 times the original amount!

This exponential growth occurs in the savings/interest loop of the positive feedback structure. Each time unit, the interest earned causes a increase in the savings of a certain increment. As the interest is proportional to the amount of savings, in the next time unit there will be a greater amount of interest, causing an ever greater increment in the amount of savings. The positive feedback causes both the savings and the rate that savings increases (the interest) to increase exponentially. The same behavior occurs in the cases of a shouting match and rabbit populations as seen in Figure 2.

Negative Feedback

Unlike self-reinforcing positive feedback, negative feedback is a process that adjusts a variable to a goal. In various disciplines, this can be referred to as a homeostatic, self-governing, or goal-seeking process.

In Figure 4 are several causal diagrams of systems containing negative feedback. Note that here the "—" sign by the arrows refers to changes in the *opposite* direction. For example, in a house with central heating, if the temperature of the house drops the gap between the temperature and the desired temperature will increase. As the gap increases, the furnace will increase its heat production. As the furnace produces more heat, the temperature will begin to rise again and the gap will down, lowering the heat production until the gap is zero and the furnace shuts off.



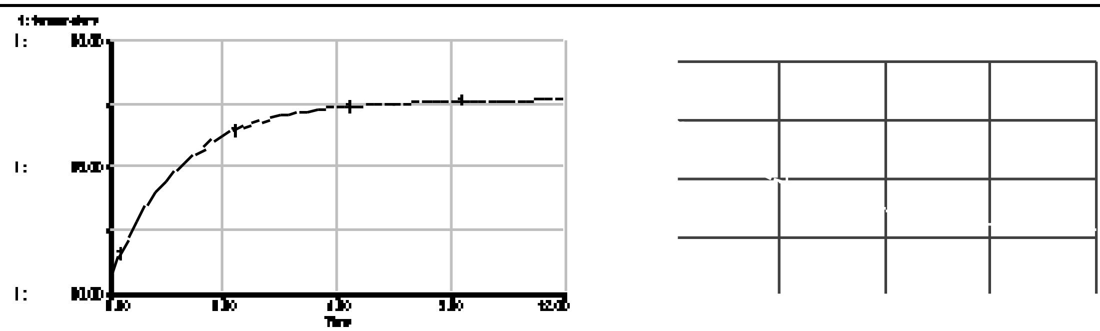
(a) (b)

Figure 4: (a) central heating system (b) insulin regulation of blood sugar

Similarly, if a person increases the amount of sugar in their blood, by eating a candy bar, the gap between the desired concentration of sugar in the blood and the actual concentration will increase. The increased gap will cause the production of insulin by the pancreas. Insulin will then increase the rate of sugar absorption by body cells from the blood stream, lowering the amount of sugar in the blood.

Both the central heating system and the insulin/glucose system show *goal-seeking behavior*. In each case there is a desired goal that the system gradually approaches. The system changes most when it is far from the goal and least when it is close to it. In the central heating system the temperature is initially lower than the desired temperature, and rises to meet it. In the insulin/glucose system, the blood sugar is higher than desired, and is lowered until it is at the correct level.

Something that is important to remember is that the "+" sign does not necessarily mean that one variable causes another variable to increase, only that it causes it to change in the same direction. Similarly, the "–" sign does not indicate a decrease, only that there is a change in the opposite direction.



(a) (b)

Figure 5: Behavior of (a) central heating system and (b) insulin regulation of blood sugar

Modeling feedback loops: stocks and flows

Understanding the connection between the structure of feedback systems and their dynamic behavior is essential to understanding and using system dynamics. Causal loop diagrams such as the ones above are useful in understanding structure, but tell very little about behavior. Modeling a system using the program STELLA can help your students to gain an understanding of the behavior produced by a given structure.

Before your students are ready to use the computers to begin modeling they need to learn about the basic building blocks that make up STELLA. These modeling elements are stocks, flows, converters, and connectors (see Figure 6).

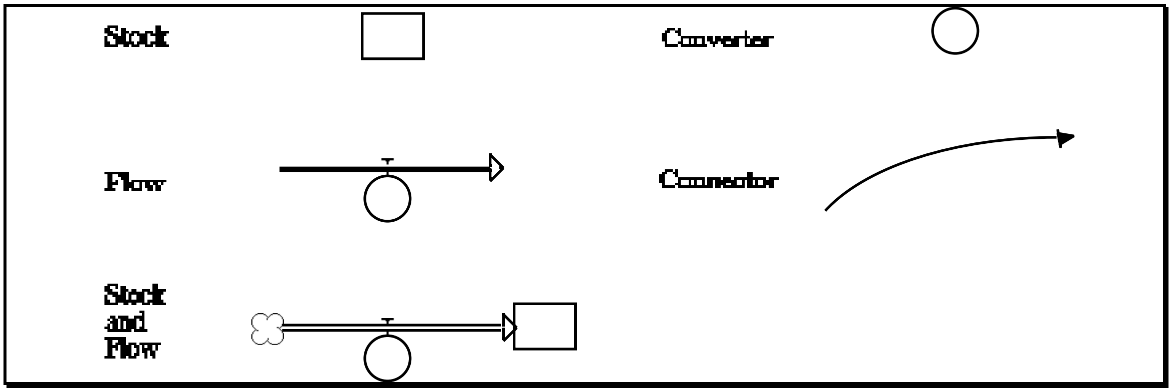


Figure 6: STELLA building blocks

The most important element in STELLA is the *stock.* A stock is something that accumulates. Stocks can not change instantly, instead they are raised and lowered by *flows*. A classic example of a stock/flow system is a bathtub full of water with a faucet and a drain (see Figure 7). The water is a stock. It is increased by an *inflow* of water pouring in from the faucet, and is decreased by an *outflow* of water exiting the bathtub through the drain. The stock of water is an accumulation. Faucets and drains can be turned off and on almost at once, but the stock of water has to change at a rate dictated by its flows. If the bathtub is frozen in time, the stock of water in the tub is the only variable that can be seen.

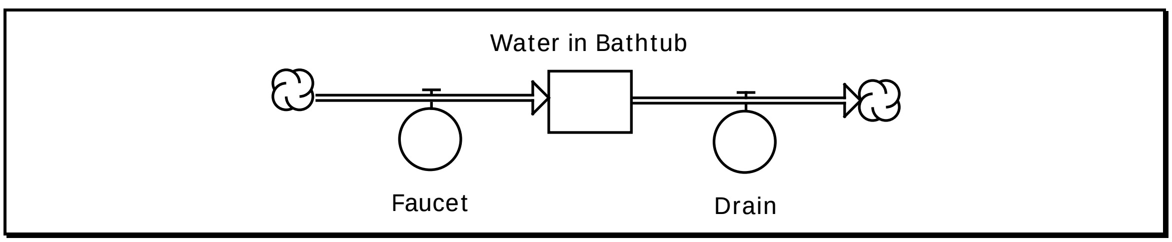


Figure 7: Stock/flow diagram of bathtub system

The other two STELLA elements are relatively minor. *Converters* are used to either hold a constant value, or to apply an equation and *convert* a set of inputs into an output. Connectors indicate that one variable causes another variable to change.

Here is another stock and flow system — savings in a bank account. Notice the amount of savings is the stock, which increases according to the rate set by the inflow of interest.

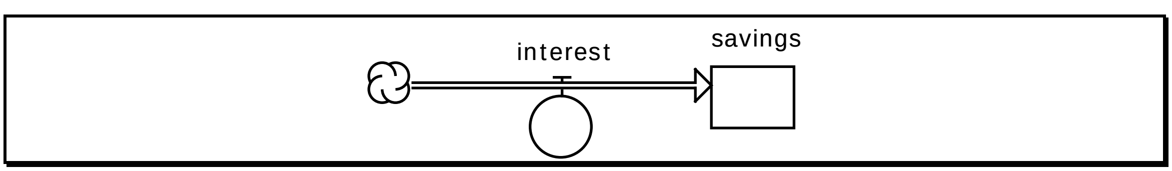


Figure 8: Stock and flows in a savings account

To show the feedback in the system, we can draw connectors to show cause and effect. For example, when the savings increases, it causes the interest to increase. The interest is a function of the savings.

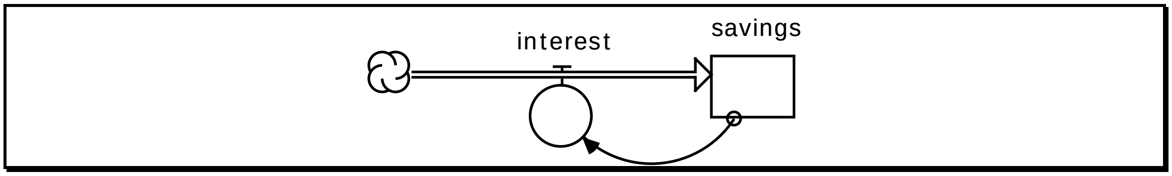


Figure 9: Feedback in a savings account

The savings is not the only thing that the determine the amount of interest, however. There is a constant interest rate that, with the savings, sets the interest each time unit. This is a circular converter, and a connector is drawn from it to the interest to show that the rate of interest payment is a function of interest rate and savings.

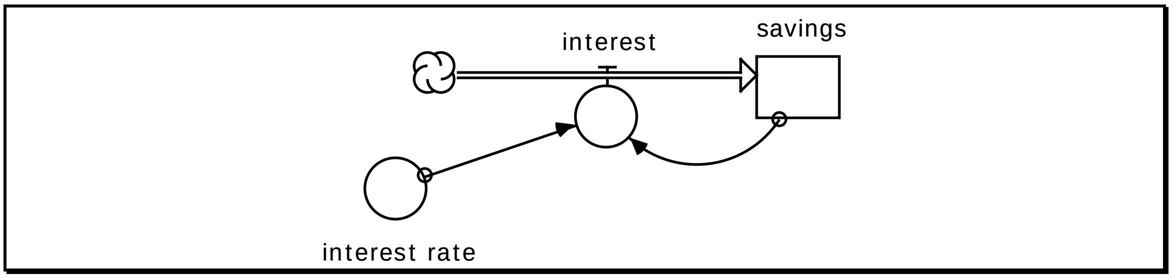


Figure 10: Complete STELLA model of a savings account

Finally, to show the exact interrelationships between the elements, the equation for the interest is:

interest = interest rate • savings

By using stocks, flows, converters, and connectors to pictorially represent the system, your students are forced to make many of their assumptions explicit. This allows them to more easily test the validity of their assumptions. By showing that the interest is the rate as which the savings increases, students can better see how positive feedback produces exponential growth. Finally, by representing the relationships of our system as stocks increased by flows and flows mathematically related to stocks, stock/flow diagrams lets us model our system and simulate the behavior on a computer using the STELLA software.

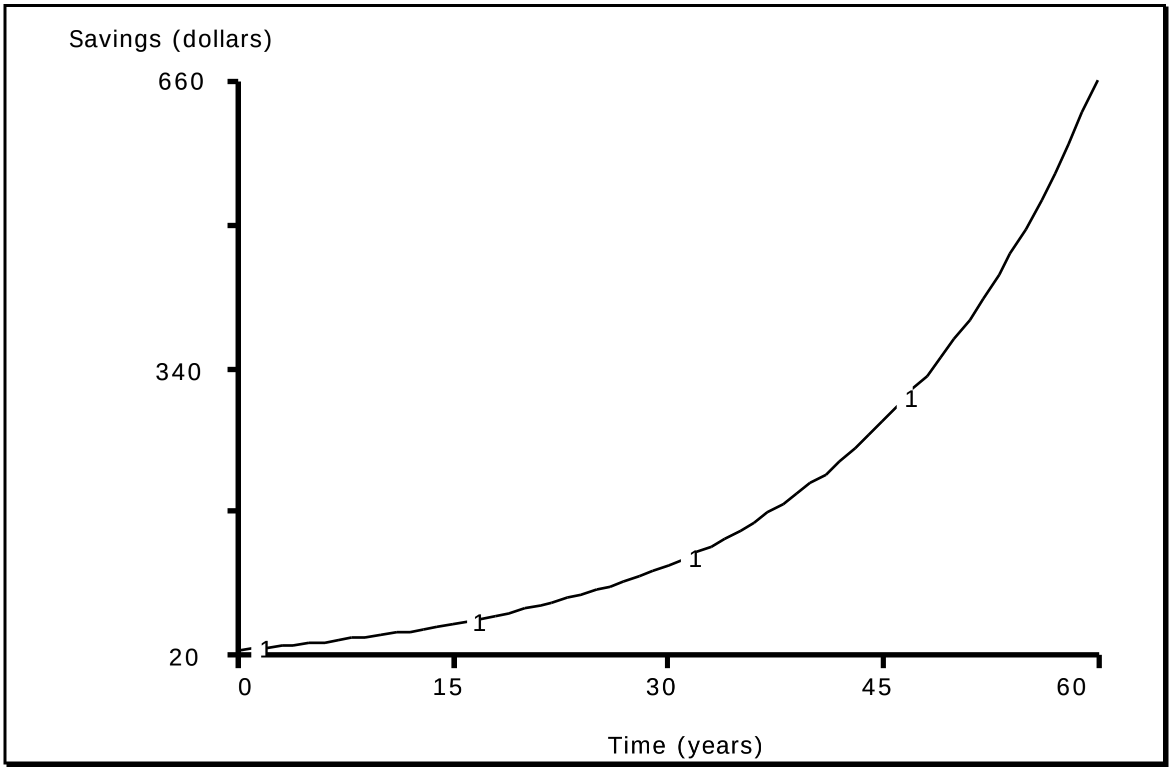


Figure 11: Graph of saving account showing exponential behavior pattern.

Student Worksheet: Modeling an Epidemic

Note: In this section of the paper, positive feedback loops are referred to as reinforcing loops, (R), and negative feedback loops are referred to as balancing loops, (B). This is just another form of terminology for the feedback loops.

Purpose:

1) To gain a deeper understanding of the structure and behavior of an epidemic.

2) To be able to use STELLA to build, simulate and test simple models.

0 The Handshaking Game -- What happened?

After your role-playing game with epidemics, you probably discovered that the graph of the number of sick people over time looked something like Figure 0.1. This can be broken up into two parts, reflecting different processes at work during your simulation.

1) Early on, there was a behavior of *exponential growth.* The number of sick people increased more and more in the first part of the simulation.
2) This was followed by a behavior of *exponential approach.* As the number of sick people grew large, it began to level off, changing less and less, as it approached the total number of people playing the game.

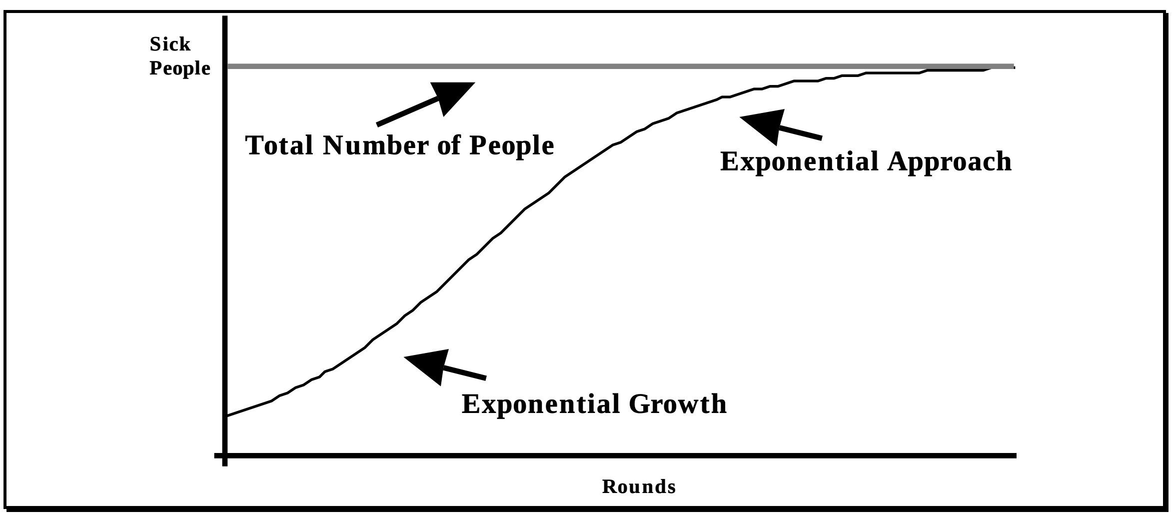


Figure 0.1: Behavior pattern of a typical session of the handshaking game

What caused those two distinct things to happen? The rules of the role-playing simulation were the same from the beginning to the end, yet the graph of the people changed considerably. What would happen if you changed the rules of the game?

In this lesson, you will create a computer model to explore epidemics and to answer these questions. The computer will let you represent the game and then change it, allowing you to study the consequences.

1 *Feedback loops*

Below are two causal loop diagrams describing how these two feedback loops operate. The arrows show how a change in the amount of one factor can change the amount of another factor. In the box next to each arrow put either a “S” or a “O”. Mark the arrow with a "S" if the arrow indicates a change in the *same* direction. Mark the arrow with an "O" if the arrow indicates a change in the *opposite* direction.

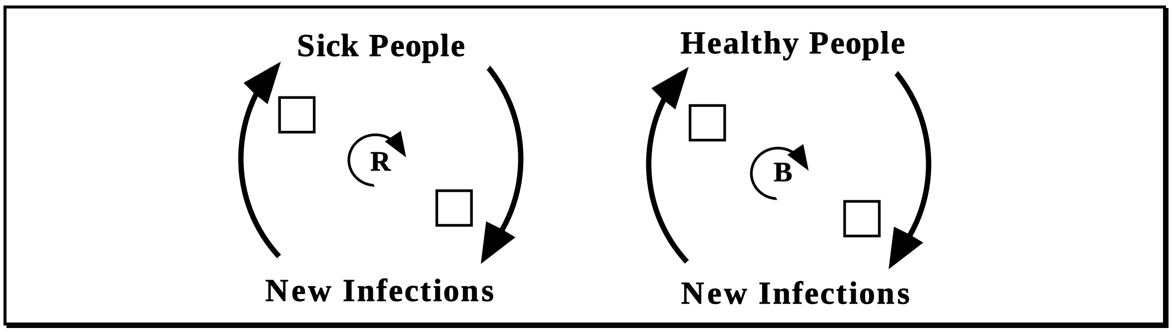


Figure 1.1: Feedback in an epidemic

The “R” inside the circular arrow indicates a **reinforcing** positive feedback loop, and the "B” inside of the other circular loop indicates a **balancing** negative feedback loop. We call them *feedback* loops because changes feed back on themselves—when a condition or factor changes, the change affects another factor which causes more changes in the original condition.

Question 1.1

What is different between the two loops shown above? Why is one loop reinforcing while the other is balancing?

____

____

____

____

If we say that at a particular time one feedback loop is stronger or *dominant* over another we mean that the system is undergoing behavior associated with the dominant type of feedback at that time. In an epidemic, one type of feedback is dominant in the early stages of the epidemic and the other type of feedback is dominant in the later stages.

Question 1.2

What kind of feedback drives an epidemic in its early stages? Look at your causal loop diagrams and graph above and check to see that your answer makes sense. Explain.

Question 1.3

What kind of feedback drives an epidemic in its later stages? How?

2 *Stocks and flows*

STELLA models are made up of two principal elements: stocks and flows. Stocks are things in a system that *accumulate* over time. Stocks cannot be directly changed. Instead, every stock has an associated flow that increases or decreases the stock. For example, water in a bathtub is a stock that is increased by an *inflow* of water from the faucet and is decreased by an *outflow* of water down the drain. A population of rabbits is a stock that has an inflow of births and an outflow of deaths.

Question 2.1:

Test your knowledge of stocks and flows by labeling each variable as either a stock or a flow by circling the appropriate answer. What units can each variable be measured in?

variable	type		units
population	stock	flow	
factory production	stock	flow	
atmospheric pollution	stock	flow	
interest on savings	stock	flow	
high school students	stock	flow	
yearly salary	stock	flow	
distance	stock	flow	

Question 2.2:

What are the flows associated with the following stocks? What units would you use to measure the stocks? What units would you use to measure the flows?

stock	inflow	outflow	units of stock	units of flows
money in a bank				
computers in a store				
nuclear weapons				
books in a library				
tree forest				
heat				
distance				
velocity				

Question 2.3

What is the stock in the reinforcing loop in the epidemic? What is its flow? What are their units?

Question 2.4

What is the stock in the balancing loop in the epidemic? What is its flow? What are their units?

3 Reinforcing feedback

In this lab, you are going to build and simulate a STELLA model of an epidemic. However, **you will do this in two parts.** Right now, you will create just the *early part* of an epidemic. To do this you need to make the following assumptions:

1) Sick People always meet and infect healthy people, causing new infections and hence, more Sick People.

2) **There is an unlimited supply of healthy people.** In other, words, *there is no upper limit* on the growth of the epidemic.

You are not trying to make an accurate model of the epidemic -- yet. In the next section you will change assumption two and model the full epidemic from your role-playing simulation. This model is similar to the first part of the epidemic, but not identical.

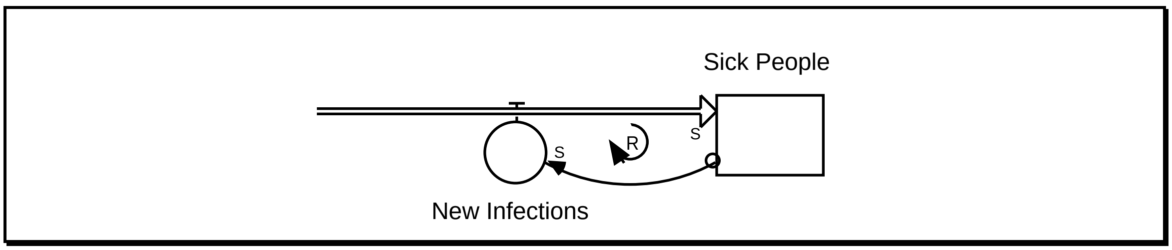


Figure 3.1: Stock/flow causal loop diagram of epidemic positive feedback

Step 1: Start the program STELLA.

If you don't know how to do this, ask a teacher or friend who does. Your screen should look something like this:

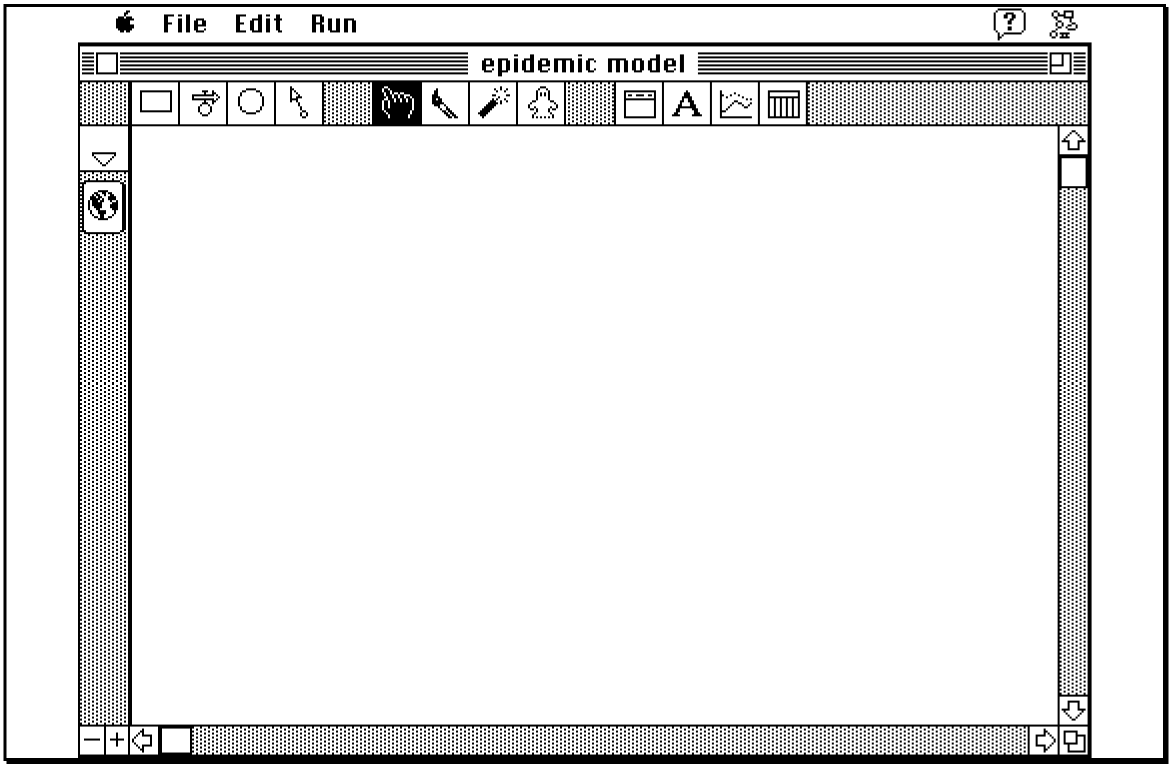


Figure 3.2: Blank STELLA screen

On the top of the screen is a menu of the 4 basic building blocks of STELLA: stocks, flows, converters, and connectors. To use any of them, just click the mouse button to choose a building block from the top menu and then click the mouse button again to place the building block it on the main screen.

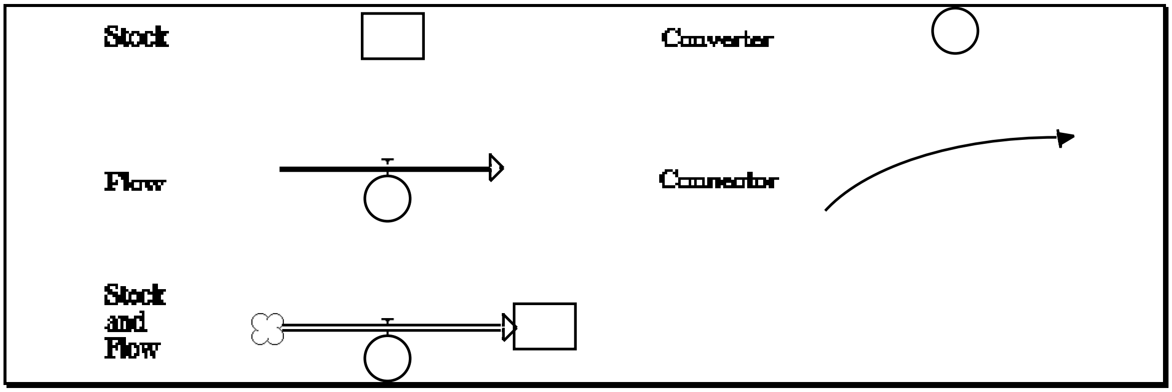


Figure 3.3: STELLA building blocks

Step 2: Place the stock.

The first thing to do is to place the stock. Choose a stock by clicking on the picture of a stock on the top of the screen. Place the stock on the screen by clicking the mouse again while the cursor is in the middle of the screen. Then, while the stock is highlighted, type "Sick People" to name it.

Step 3: Place the inflow.

Click the mouse button on the flow icon at the left side of the screen. Click and hold the mouse about an inch to the left of the stock; then hold the mouse button down and drag the flow over the stock **until the stock turns grey**. Release the mouse button. Label the flow, "New Infections".

Step 4: Place the connector

As the stock of Sick People changes it will affect the flow. You can tell STELLA this by connecting the stock to the flow with a connector. Choose the connector, move the arrow to the stock and click, then hold down the mouse and drag the wire to the flow. **Don't lift the mouse button until the flow turns grey.**

Your screen should now look roughly similar to Figure 3.4.

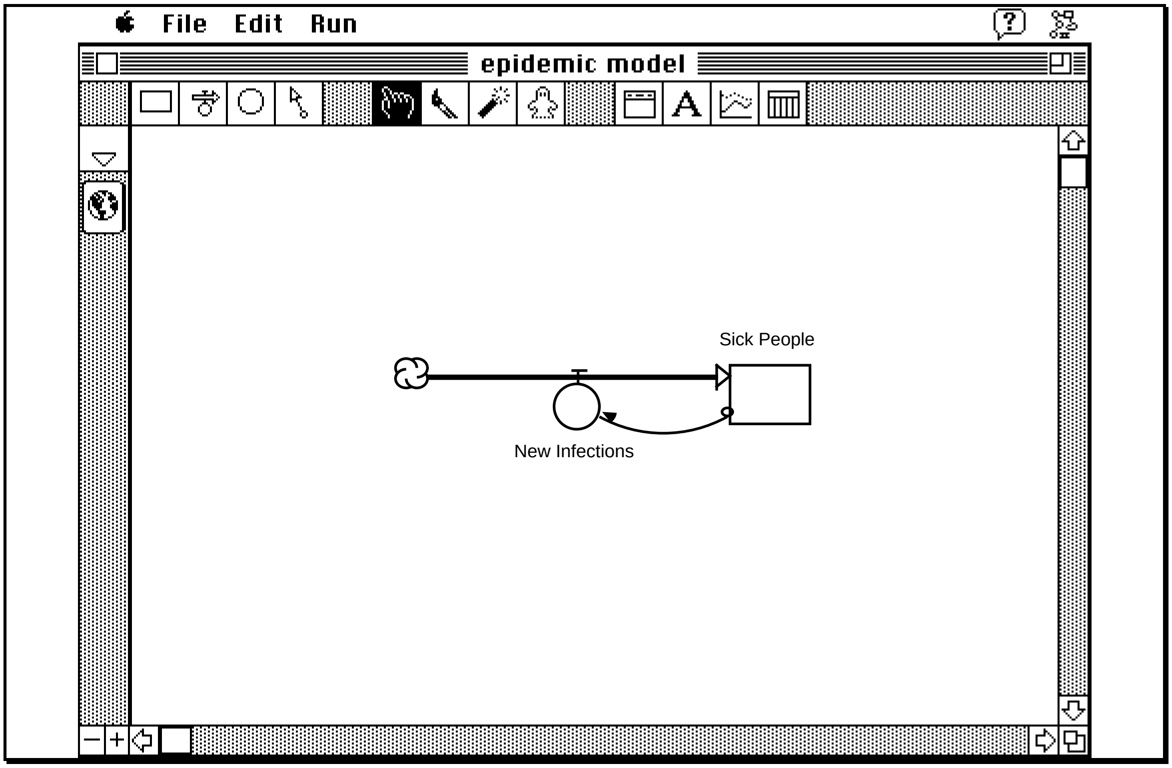


Figure 3.4: Stock/flow diagram

Step 5: Determine the Parameters

This stock/flow structure is the core of your model of an epidemic's positive feedback. However, more information needs to included before you are ready to simulate. In particular, the model needs *parameters*, constant converters that serve as inputs to the system. It also needs mathematical descriptions of the relationship between the number of Sick People and New Infections.

A parameter is an input to a system – a value or assumption in a system that we can modify and see the resulting changes in the behavior. We model parameters as constant values inside of converters. For example, in a model of a savings account with interest, an important parameter would be the interest rate (see Figure 3.5). Changing the interest rate will causes changes in how much money is generated during the simulation.

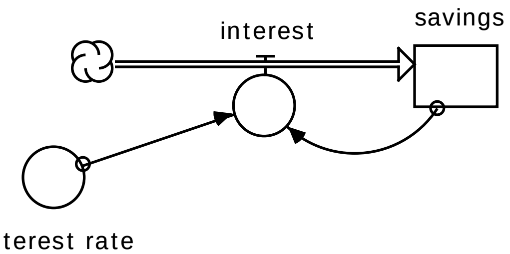


Figure 3.5: Model of savings in a bank. Note that the interest rate is a parameter.

These constants could just be buried in an equation, but it is often a good idea to make them explicit. Giving the constants explicit names by modeling them as converters reminds you that they exist and makes them easy to change.

Question 3.1

In the handshaking game, what numerical assumptions were in the rules that we should make parameters to the model?

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____

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Two possible parameters to include are:

1) How many seconds are there in each round?

2) How long does it take to shake someone's hand?

From those two numbers we can calculate:

3) How many handshakes per round?

You may not have initially thought of it, but another important parameter to consider is:

4) The probability of a Sick Person shaking hands with a healthy person during each particular round.

This last parameter will be particularly important in the second section when we complete the model of the epidemic.

Step 6: Add these parameters to the model.

Choose the converter from the top menu (it's the circle). Place it near the bottom of the screen and label it, “Seconds per Round” (see Figure 3.6). Place a second converter near the bottom and label it "Seconds per Handshake". Between those converters and the stock/flow combinaton, place a converter labelled "Handshakes per Round." Since changes in either one of the first two converters will change the number of Handshakes per Round, take a connector, and connect Seconds per Round to Handshakes per Round. With a second connector, connect Seconds per Handshake to Handshakes per Round. Handshakes per Round will directly affect the infection rate, so put another connector from Handshakes per Round to New Infections. *Make sure the (single) arrows are pointing in the right direction.*

Add your last converter near the top of the screen, calling it "Prob of a Sick Person meeting a Healthy Person." Since this converter will also influence the number of infections, string a connector from it to New Infections.

Check that your screen matches the diagram below. *Do not go on until it looks the same!*

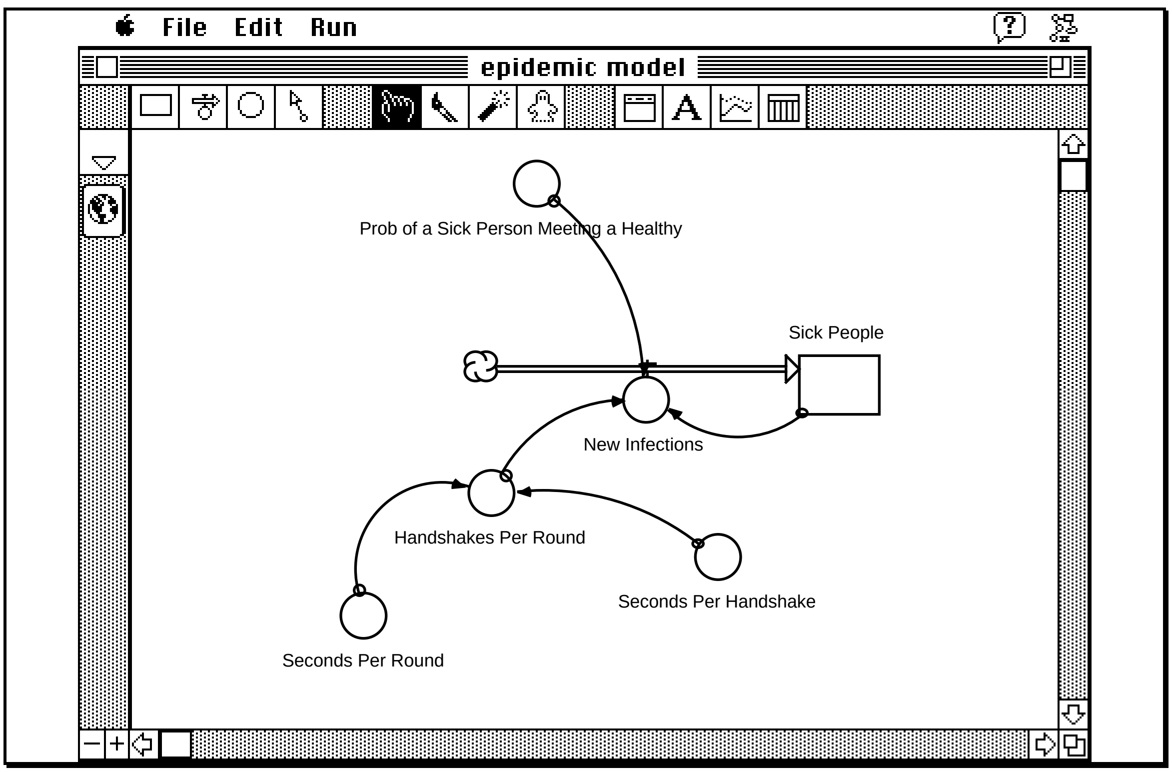


Figure 3.6: The “plumbing” of the epidemic model

Now that you have “laid out the plumbing” of your model, you need to enter the mathematical relationships in the model. This includes both the Handshakes per Round, and the New Infections (each round).

Question 3.2

Write a mathematical equation to determine the number of Handshakes per Round using Seconds per Handshake and Seconds per Round.

Handshakes per Round = ____

Question 3.3

Write a mathematical equation to determine the New Infections (each round) based upon the number of Handshakes per Round and Prob. of a Sick Person meeting a Healthy Person (PSPMHP).

New Infections = ____

Step 7: Enter the equation for Handshakes per Round and New Infections

Important! Click the globe in the top left side of the screen. It should now say X^2. The globe meant that you were looking at general relationships in the model. The X^2 indicates that you are now going to enter the precise mathematical equations defining those relationships.

Double-click the converter Handshakes per Round. Your screen should look like Figure 3.7. In the upper left corner are a list of *Required Inputs*. Each of these variables should be part of your equation. You can put any of these variables in your equation by clicking on them with the mouse.

Enter the equation you wrote above. Remember, "*" is the symbol for multiplication and "/" is the symbol for division. Click **OK** when you are done. If you get an error, that means you have entered the equation wrong – try again. If everything goes well, you should find yourself looking at the full diagram.

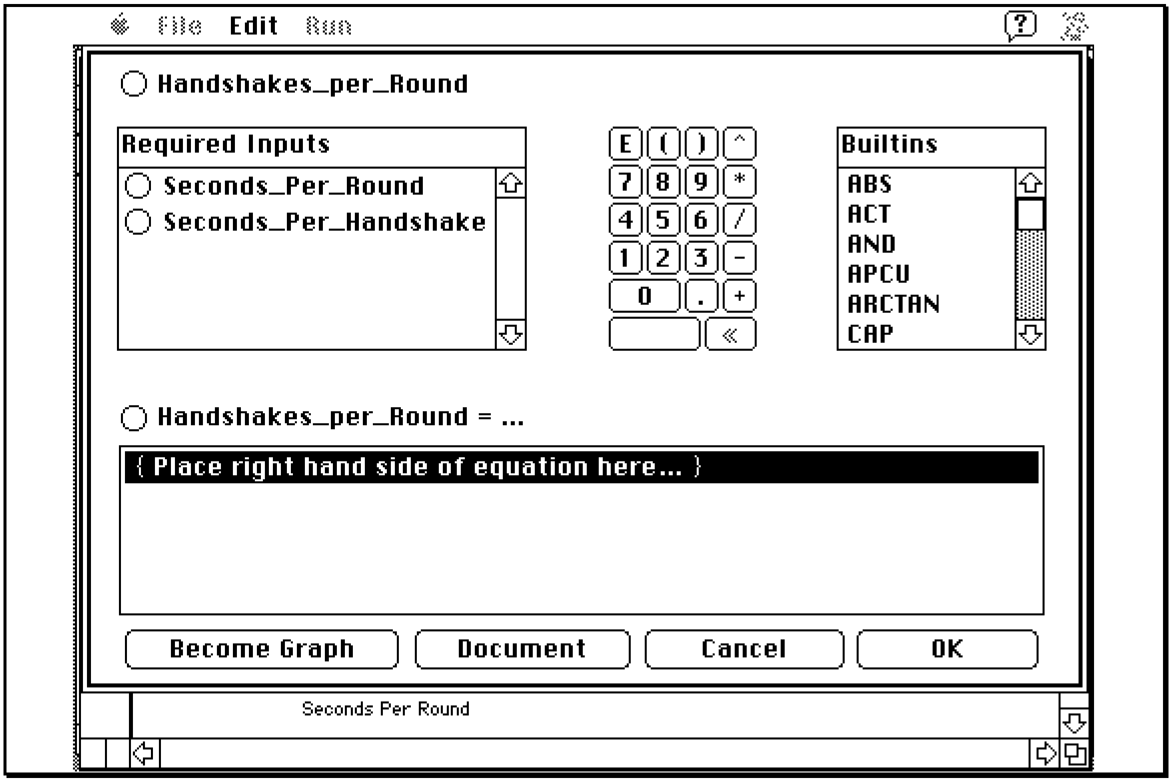


Figure 3.7: Entering an equation

Notice that the "?" in the variable Handshakes per Round has disappeared. That is because there is now an equation for that variable. Before you can simulate the model, the "?" must be gone from all the variables.

Double-click the flow New Infections. Enter the equation you wrote above the same way you entered the previous equation. When you are done, click **OK**.

The final thing we need to do to make our model complete is to set the initial value of the stock and the parameters of the model.

Question 3.4:

In the handshaking game you played, what was the initial number of Sick People?

Initial value of Sick People = ____

Question 3.5

How long (approximately) did it take to shake a hand? Include the time it took to walk from one person to another.

Seconds per Handshake = ____

Question 3.6

How many seconds did you take per round?

Seconds per Round = ____

Question 3.7

If Sick People never shook the hands of other Sick People, what is the probability a sick person would meet with a healthy person in a round?

Prob of a Sick Person Meeting a Healthy Person = ___________________________

Step 8: Enter the parameter values.

Double-click on the stock of Sick People. Enter the initial value from your answer above. Click **OK** when you are finished. In turn, enter the values you wrote above for Seconds per Handshakes, Seconds per Round, and Prob of a Sick Person Meeting a Healthy Person.

Step 9: Setting up a graph.

In order to be able to view the behavior produced by our model when it is simulated, you need to set up a graph. Click the graph symbol at the top of the screen. Then, click again somewhere in an empty space in your diagram. You should then see an empty graph. Choose **Define Graph** from the **Edit** window and you will see this:

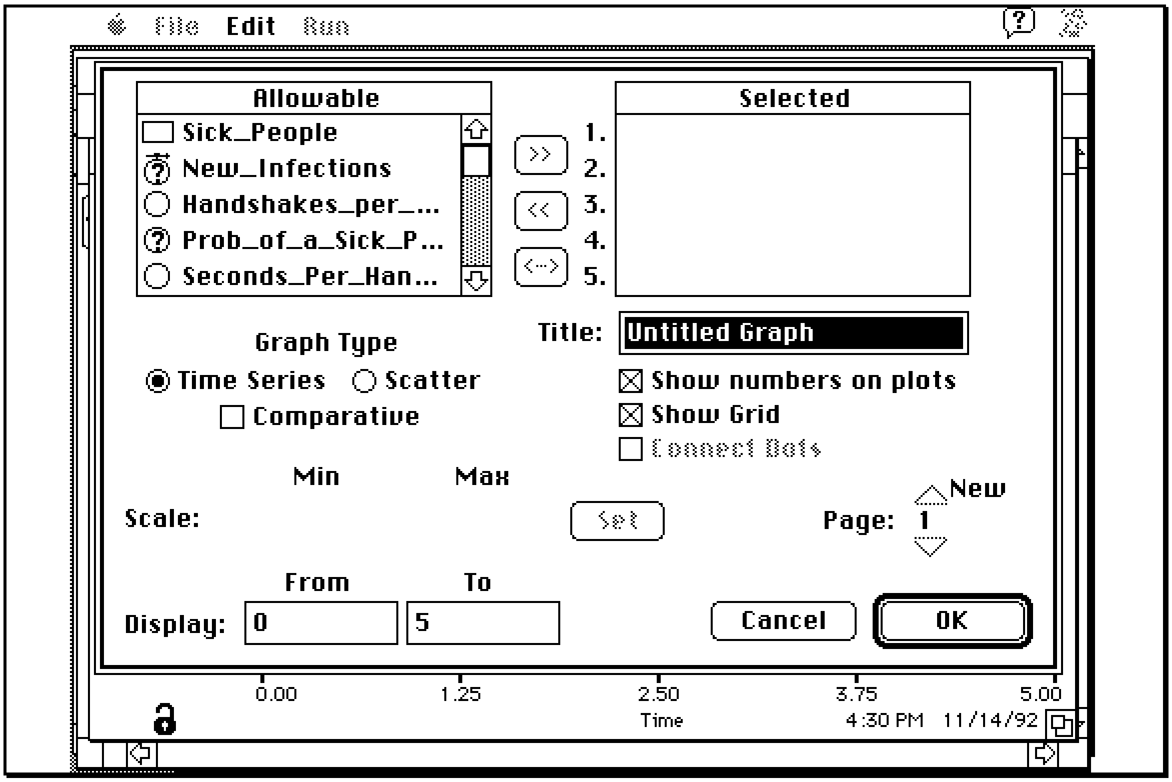


Figure 3.8 An empty graph of Sick People.

To tell the computer to display on a graph the variable Sick People, click **Sick People** in the table of allowable inputs, then click **>>**. Click **OK** to see your graph again.

Before you go on, you also need to tell the computer how long it should run the simulation. Choose **Time Specs** from the **Run** menu. Set the box next to **To:** to 5. **Important!** Also set **DT** to .05 (it's needed for this simulation to work properly -- don't worry about what it means). Finally, set the unit of time by typing “Rounds” under other. Then click **OK**.

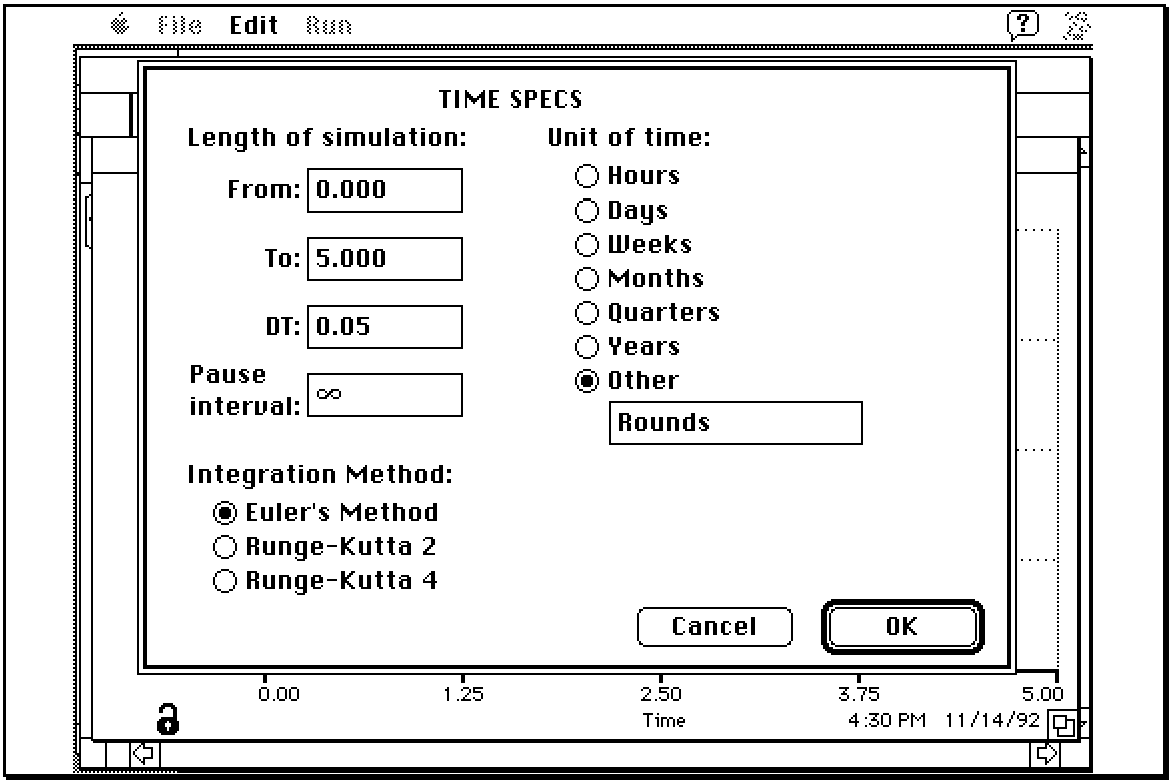
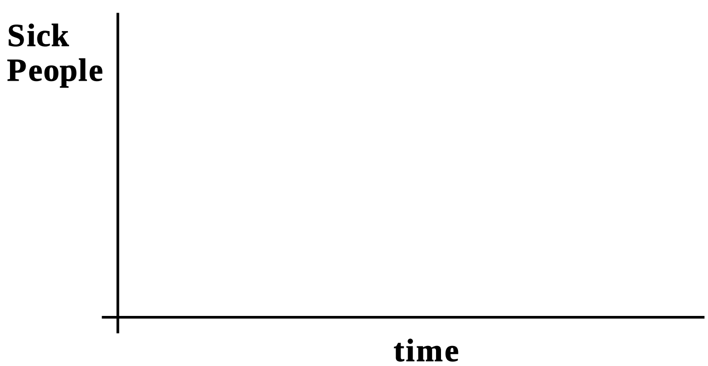


Figure 3.9: Time Specs screen.

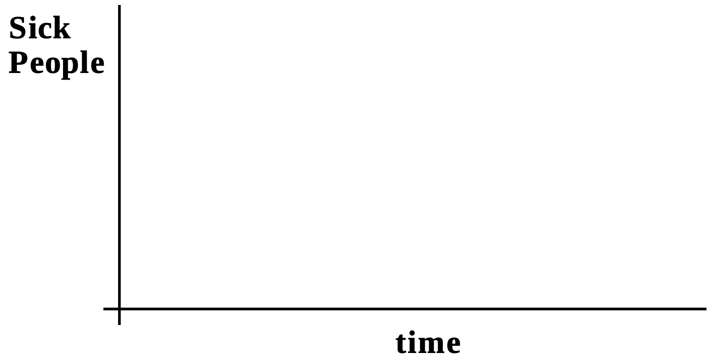
Step 10: Predicting the behavior.

You are now ready to simulate your model. Before you do that, however, draw on the graph below what you think the behavior of the Sick People in your model will look like. The exact numbers are not important, just draw the general shape.



Step 11: Simulate your model and graph the results.

In the **Run** menu, choose **Run**. Draw a copy of the graph on your screen onto the axis below.



Question 3.8

Did the graph match your predictions? Why or why not?

____

____

____

Step 12: Save your model

Congratulations! You now have a complete model of the exponential growth aspect of an epidemic. Be sure to save the file before you leave.

4 Combining feedback loops

In the previous section you modelled the reinforcing loop that drives an epidemic in the early stages. However, as you found out in the epidemic game, positive feedback is only half of the story. Your task in this section is to modify the model you built to become a more accurate model of the handshaking epidemic. In order to do this you will add in a balancing loop that restricts the growth of the epidemic when the number of sick people rises.

When you made your first model of the epidemic, you made these two assumptions:

1) Sick People always meet and infect Healthy People, who become Sick People.

2) The system has an unlimited supply of Healthy People causing Sick People never to interact with other Sick People. In other words, there is no upper limit on the growth of the epidemic.

You will now remove assumption two and replace it with the following new assumption:

C) **There is a limited number of people in this simulation.** Most people will begin in an healthy state, and through handshakes, become infected Sick People. As the number of Healthy People decreases, there will be less meetings between Sick People and Healthy People, and consequently, less New Infections each month.

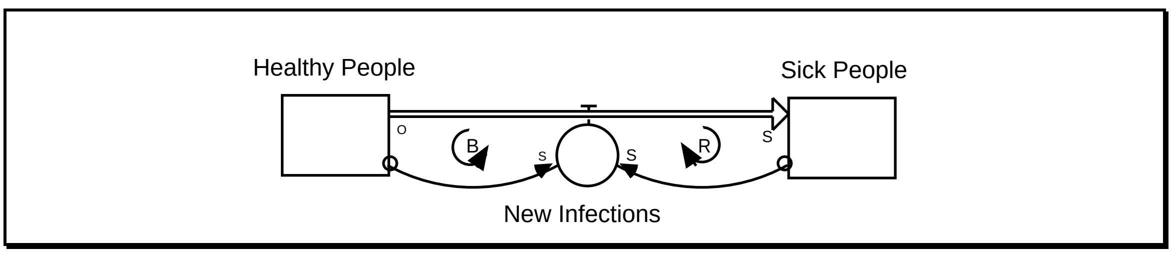


Figure 4.1: Causal stock/flow diagram of epidemic

Load the model you built in the previous section onto your computer. Your screen should look roughly like this:

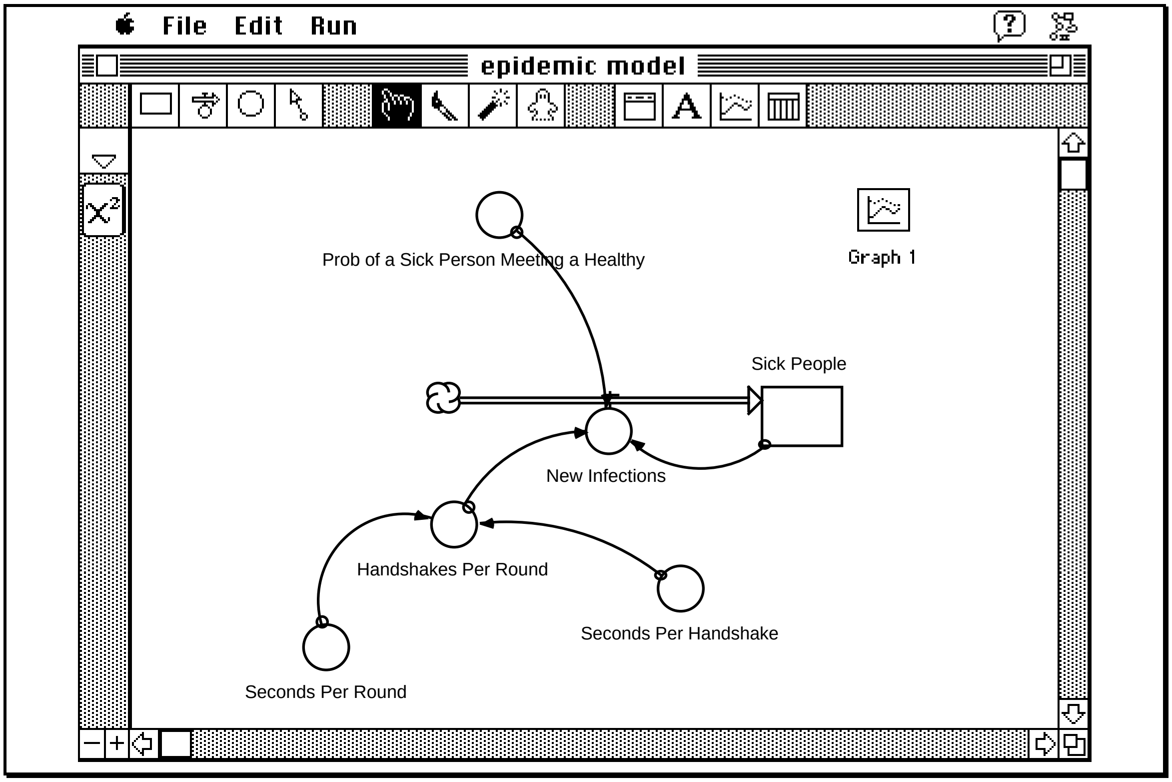


Figure 4.2: Reinforcing feedback epidemic model from section 3

To build a more complete model, the first thing you need to add is a new stock of people susceptible to the disease – in other words the healthy population.

Question 4.1

What should be the outflow from this stock of Healthy People?

____

The outflow from the uninfected people is the same as the inflow to Sick People: New Infections. As people become infected with the disease they leave the stock of uninfected people and enter the stock of Sick People.

Step 1: Place the stock of Healthy People

Place a new stock on the screen called Healthy People. Connect it to the flow New Infections by holding down the mouse button, dragging the stock on top of the cloud **until the cloud turns grey**, and releasing the button.

Question 4.2

What should the be initial value of Healthy People? How many people began the epidemic game uninfected?

Initial value of Healthy People = ____

Step 2: Set the initial value of Healthy People

Set the initial value of Healthy People to what you wrote above.

Step 3: Determine the behavior of Healthy People in the current model

Make a graph that shows both Healthy People and Sick People. Do this by first double clicking on the graph picture in your diagram, then choose **Define Graph...** from the **Edit** menu. Select Healthy People and click **>>**, then click **OK**. Simulate the model by choosing **Run** from the **Run** menu.

Question 4.3:

Draw on the graph below the behavior of both Sick People and Healthy People. Label the maximum and the minimum values of each graph. How are the graphs related? Has your graph of Sick People changed from your last simulation?

____

____

____

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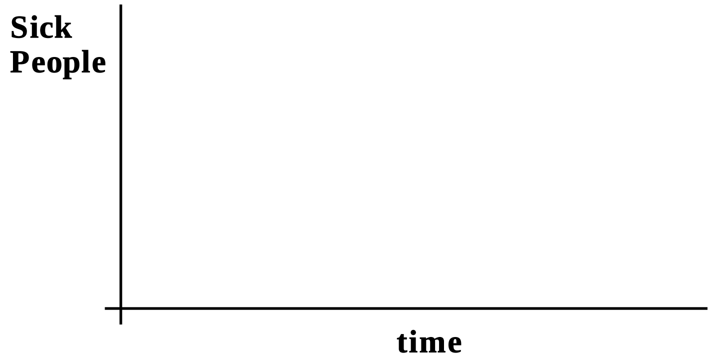

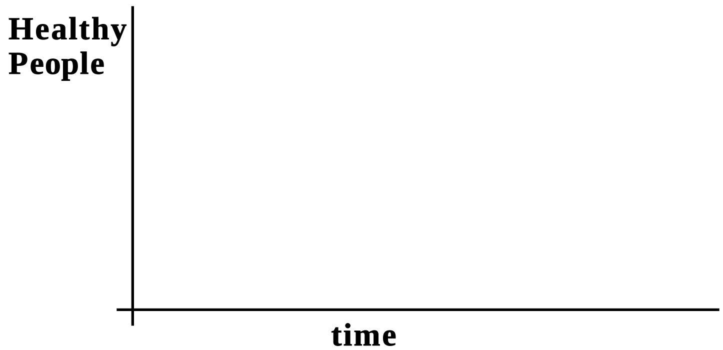

Question 4.4

Besides the fact that the graphs do not show s-shaped growth, what seems strange about the graphs? What problems or inaccuracies do you see with the behavior of the Sick People or the Healthy People?

Although you have included another stock, Healthy People, you have not changed the model to reflect your new assumptions.

Question 4.5

Under the old assumptions there are three constant parameters that affect the flow New Infections: Seconds per Handshakes, Seconds per Round, and Prob of a Sick Person meeting a Healthy Person (each round). Under the new assumptions, one of these variables will no longer stay unchanged as Healthy People become Sick. Which of these three variables will be affected?

____

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Question 4.6

In a sentence, describe the general relationship between Healthy People and this variable. Will the relationship be a "S" (change in the same direction) or an "O" (change in the opposite direction).

____

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Question 4.7

What is the relationship between the number of Sick People and this variable?

____

____

____

Step 4: Make the model reflect correctly reflect your causal assumptions

Use connectors to link the stock of Sick People and the stock of Healthy People to the variable you think should be affected by them.

By now, your epidemic model is almost complete. You have all the elements of your model and you have the “plumbing”. All that is needed is to come up with the exact relationship between Healthy People, Sick People and the variable you chose.

Deciding on an exact relationship is not easy -- in fact it is probably the most difficult part of model building. Some suggestions on how to make this easier:

1) Remember the epidemic game. Your model should directly reflect your experiences playing the game.

2) Think through the situation in terms of actual numbers. Your answer should make sense both near the beginning and near the end of the simulation.

Question 4.8

If there is 1 Sick Person and 9 Healthy People, what is the probability of a sick person meeting a healthy person? Show your work.

Question 4.9

If there are 2 Sick People and 8 Healthy People, what is the probability of a sick person meeting a healthy person? Show your work.

Question 4.10

If there was 5 Sick People and 5 Healthy People, what value should this variable be? Show your work.

Question 4.11

If there was 9 Sick People and 1 Healthy Person, what value should this variable be? Show your work.

Question 4.12

What is the mathematical equation determining the Probability of a Sick Person Meeting a Healthy Person based upon the number of Sick People and Healthy People?

Prob of a Sick Person Meeting a Healthy Person = ______________________________

____

____

Question 4.13

In a sentence, explain how your equation works:

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Step 5: Enter the equation

Enter in the appropriate variable the equation you wrote above. Your model should now look roughly the same as Figure 4.3.

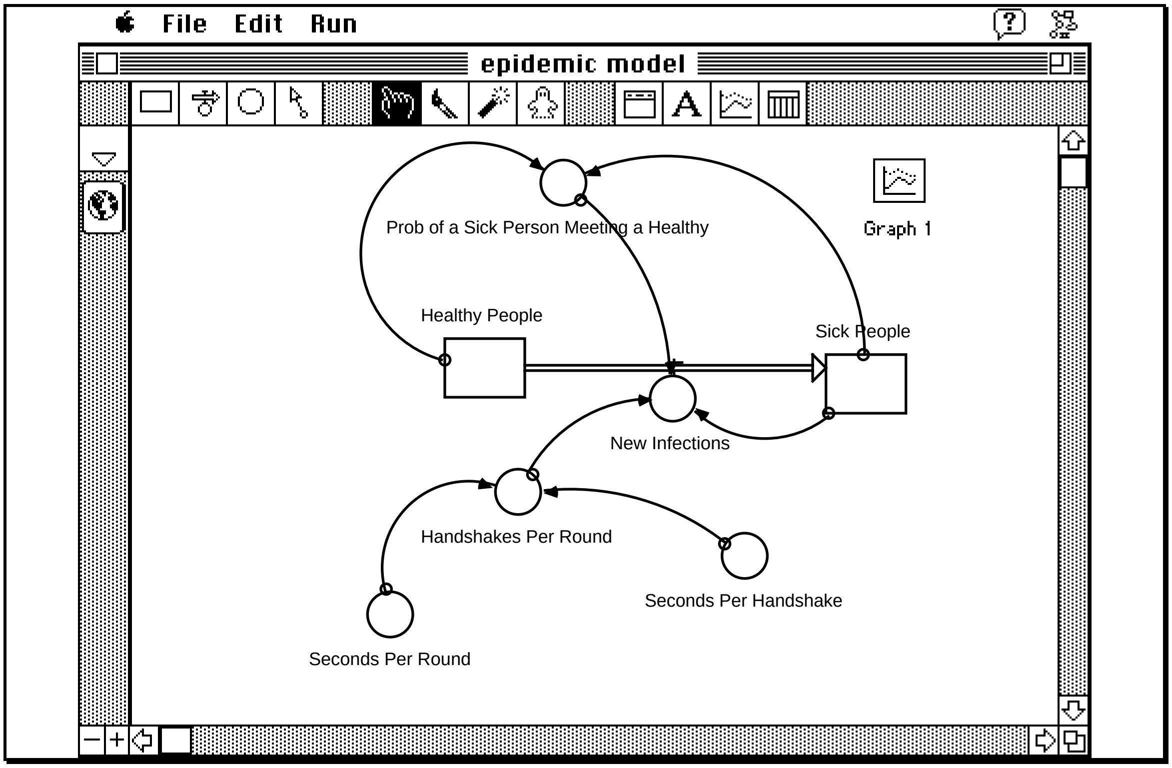
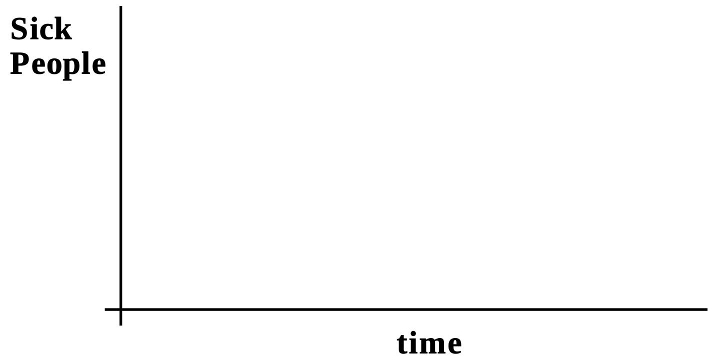
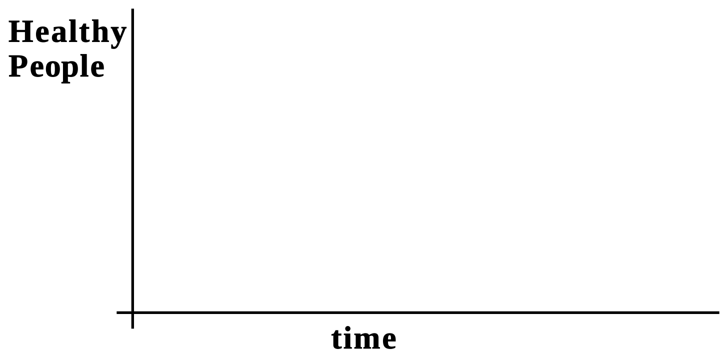


Figure 4.3: Complete model of the epidemic

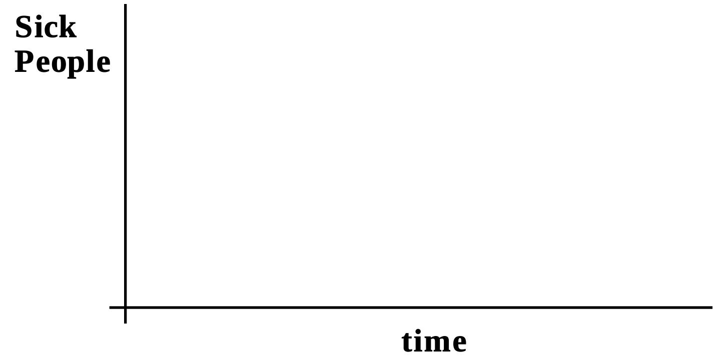
Step 6: Predict the behavior

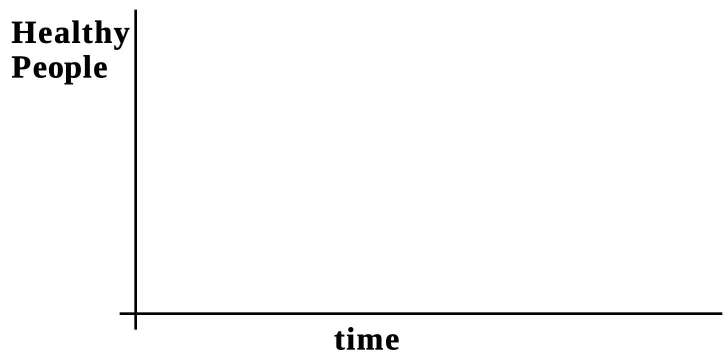
Your first cut at a complete model is now ready to test. **Before you simulate,** draw on the two axis below the dynamic behavior you expect from the Sick People and Healthy People, based on your experience playing the epidemic game.





Step 6: Simulate your model and graph the results:





Question 4.14

Why did you get this behavior? What in your equations caused this behavior?

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Step 7: If not correct, try again.

If the behavior you got did not match the s-shaped growth you expected, go back and come up with a new equation and simulate again. Keep trying until your model's behavior matches the reference behavior you expect.

Question 4.15

What was your final equation?

Question 4.16

Is there a balancing loop in your model? Where is it?

Question 4.17

How does the "strength" of the balancing loop change from the beginning to the end of the simulation?

Question 4.18

How does this change in loop dominance (strength) change the behavior from the beginning to the end of of the simulation?

Step 8: Model Enhancements

You have completed the major tasks of this worksheet. If there is time, feel free to modify your model. What happens when you change it? Some suggestions:

- Change the length of time each handshake takes.
- Add more flows -- make people die or be cured.
- Add a stock of immune people with a flow from Sick People to Immune People. See your teacher for information about delays.
- (Difficult) Bring carriers into the model. Add the stock and the appropriate flows.
- (Very Difficult) What conditions are needed for a recurring epidemic? Try and create them.