

Creating Content Specific Lessons Incorporating System Dynamics Models

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Abstract: There are a number of experienced K-12 teachers who have created useful lessons involving system dynamics (SD) concepts. This paper will focus more on those lessons involving the creation of SD models (high school level) as part of the learning experience for students. Examples of system dynamics lessons will be explored. These lessons fall roughly into one of four categories: Introductory SD lessons that reinforce simple core content; Second level lessons to study more sophisticated behavioral interactions over time; and two additional levels that require students to create original models.

Introduction:

For those teachers who have used SD concepts and SD models in the classroom, the journey has not been smooth. Now, however, there are some useful guidelines that will provide the interested teacher a path, examples, and experience caveats that should help focus their initial efforts in designing useful SD lessons.

On the Creative Learning Exchange website one will find many useful documents that can guide the teacher who has had little experience writing lessons that include system dynamics concepts. Studying one such document, “Rubrics for Understanding: Using System Dynamics Tools,” prepared for DynamiQuest¹ 2000, is a useful place to start. The document was intended to assist teachers/coaches whose students present their SD work at DynamiQuest. Beyond its original purpose it has pertinent information for teachers who want to create SD lessons for the classroom.

Additionally, “Getting Started with Behavior Over Time Graphs: Four Curriculum Examples,” by Gayle Richardson and Debra Lyneis provides guidelines for not only the use of BOTGs as a stand-alone SD tool, but for establishing reference behavior graphs for modeling assignments. “The Mammoth Extinction Game,” by Gene Stamell, Alan Ticotsky, Rob Quaden and Debra Lyneis is another excellent example of an SD lessons that starts with a hands-on activity and extends to the building of a STELLA model, with many excellent questions the teacher can ask as the lesson progresses.

High School:

Although the previous lessons are designed for the elementary classroom they provide a useful sequence of thought/design that can be applied in many high school classrooms as well. Specifically, starting with a topic whose behavior of interest is changing over time, establishing a reference behavior, designing a model, and asking the student to think reflectively about the design of the model and the system behavior displayed in the graphs produced as the lesson progresses. Additionally, designing what-if scenarios to illicit deeper analysis/questions highlights the usefulness of incorporating SD tools in the classroom.

Lessons designed to incorporate system dynamics models provide students another means to explore, absorb, and retain core content in various subjects (most notably mathematics, social science, environmental science, health, biology, and physics) taught at the secondary level of instruction. The type of lesson used depends upon various factors, and should be expected to

¹ DynamiQuest is an annual celebration of student work (grades 3-12) in system dynamics that takes place in Massachusetts, coordinated by Lees Stuntz of the Creative Learning Exchange.

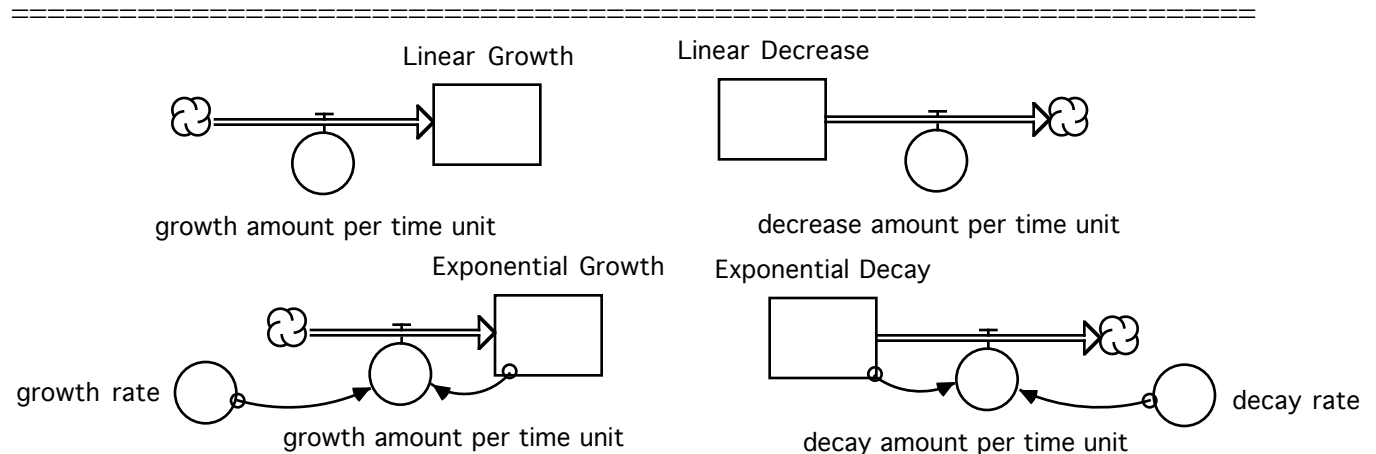
produce testable results consistent with the purpose of the lesson. At this point lessons may conveniently be grouped into four categories.

Level 1 Lessons: In the first category are those introductory system dynamics lessons designed to reinforce a content topic which easily lends itself to SD analysis. One such topic is the observation of growth or decay patterns over time. This is basic to the study of algebra and especially calculus, to biology, environmental science, and the physics of motion, among others. Lessons in this category could include analysis of graphical representations of the change of important entities being studied. They could include deciding between generic modeling structures that appropriately capture the dynamic of the problem being analyzed. The focus is to begin to identify simple dynamic patterns and understand the reason the pattern fits the situation.

Behavior-over-time graphs are especially useful at this level. In these lessons students might be given a brief scenario and asked to identify the important entities in the sketch, to choose one entity and to sketch a graph of the growth or decay of a characteristic quantity over the course of the time frame suggested in the scenario. Or students could be given a graph and a suggestion as to context and be asked to explain what could be happening to create a given pattern of growth and/or decay.

Additionally, in the level one lessons, a modeling tool such as STELLA, could easily be introduced. In these lessons generic structures that produce simple growth and decay behaviors (especially linear and exponential) would be included. The lessons might require students to design the structure that matches a given pattern of behavior, as explained in a written description or displayed in a graph. Students may or may not be taken to a lab to execute the design. In math, the generic structure would be introduced in parallel with a traditional method (equation, graph, table) of identifying the behavior pattern. The purpose of the lesson is to introduce an alternative representation for expressing the structure underlying the behavior pattern and to develop some intuition with the basic pattern characteristics. The lessons are used to set a foundation for more sophisticated analysis found in level 2 lessons.

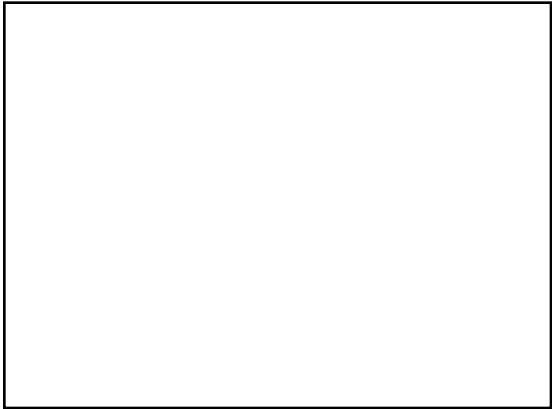
For example: in biology (or math) a student might be given the following problem:



(Bacteria) Suppose you have been doing an experiment in your biology lab with bacteria. You started the experiment on Wednesday and measured 1000 bacteria per square millimeter. You measure the number of bacteria each successive day for a week and determine that the growth rate is 30% each day (that is, if you take yesterday's amount of bacteria and multiply it by 30% and add it to yesterday's amount of bacteria, you get today's

amount of bacteria.) Do you think the bacteria is growing linearly or exponentially?
 Why? _____

In this problem there are three important components to consider: the amount of bacteria you have on any given day, the growth rate of the bacteria each day, and the amount of new bacteria that are added each day.



- a. Determine which STELLA diagram above to use for this problem. Draw the diagram, label each icon correctly using words that represent the ideas in the bacteria problem, and place the correct value or symbol in each icon so it will model the problem described above.

Notice that, in this diagram (which is very similar to a linear model) there is a connector from the stock (rectangle) back to the flow (growth amount per time unit). This connection didn't happen in the linear model. Why is this connection critical in an exponential model? _____

- b. Construct the model you drew above, using the STELLA software. When you double click on the flow icon, to define the value, you will notice that there will be two items listed in the "Required Inputs" box. You MUST use those items in your definition. You should multiply the two "Required Inputs" together for this model. Just click on the name of the first required input, click on *, then click on the second name. Then click OK. Did you remember growth rate must be in decimal form? Under Run/Run Specs... set the **DT** to **1**, do not change anything else. Then define a table in STELLA. Include your stock name in the table. Run the simulation.

On which day did the bacteria triple? _____ Determine the number of bacteria per square millimeter one week (7 days) after the start of the study. _____ . How many bacteria per square millimeter are there 12 days after the start of the study? _____ .

- c. If the growth rate is doubled (to 60%) are there twice as many bacteria per square millimeter after 12 days? First predict (Yes/No) _____. Now run the simulation and write down how many bacteria per square millimeter there were after 12 days _____ .
- d. Let's see what influence the growth rate has. Fill in the table at the right using your simulation to get the answers.

Growth Rate %	Amount of Bacteria on day 12
1	
10	
20	
30	
60	
90	

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In math students might be given the following description and be asked to build the structure and indicated what each component of the structure represented and how each should be defined. Then they would be required to write the corresponding mathematical equation.

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If you jump out of an airplane, you've got a lot of guts! If you don't open your parachute for a while, you will soon be falling at a constant velocity called your "terminal velocity." Assume you are **2100 meters** above the ground when (after you jump) you reach **terminal velocity (48 meters per second)**. Set up a STELLA diagram for this situation. Use a graph and/or table to answer these questions.

- a) If you neglect to open your parachute, when will you hit the ground? _____
- b) How many meters did you fall between the 20th and 30th second? _____
- c) What do the height-intercept and time-intercept on the graph represent in real life?
 h-intercept? _____
 t-intercept? _____
- d) Determine the math equation for your height above the ground after t seconds: _____
- e) What is the slope value and what does it mean? _____

What is the y-intercept value and what does it mean? _____

How do these numbers relate to the numbers you used in the STELLA model?

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In introductory lessons simple variations in growth and decay would be explored. For instance, what is the difference, over time, between doubling a linear growth rate versus doubling an exponential growth rate? What part does altering the initial amount of a quantity play in its pattern of growth or decay? What effect does time duration play in growth or decay? Comparisons of different simple patterns of growth/decay, such as money added to a bank account versus money added that does not accrue interest, might be made in an algebra class.

Assessment at level 1: In each of these initial lessons students would be expected to perform simple well-defined tasks similar to the lessons they experienced. No previous experience (in prerequisite courses) with the pattern concepts or modeling software would be necessary for students to complete assessments.

Level 2 Lessons: A second category of lessons involves the study of behaviors that are no longer simple growth or decay. In this category content concepts graduate to a level requiring more sophisticated interaction between entities. In biology, a carrying capacity might be considered, or some cap on a resource that changes a growth pattern over time. In any event, some discussion of feedback, whether identified as feedback or not, will be incorporated into the scenario.

In math, although convergent, logistic, and oscillatory equations are studied in some second year algebra classes, most scenarios describing this type of behavior are reserved for pre-calculus, since the equations are so difficult for many students to manipulate. Using SD modeling structures, second year algebra class lessons can include these more sophisticated patterns.

Here is part of a question that is used in second year algebra:

(Ecology) Rabbits were introduced into Australia in the mid 1800s. Actually it was in 1859 that 24 wild English rabbits were brought to Australia. At that time they had no natural enemies so they reproduced freely. As a matter of fact, a reproduction rate (birth rate) of 4.15 is reasonable for rabbits. We do not have any real data on the death rates for rabbits in Australia, so we will assume a death rate of 3.8 per year. Reference books indicate that there were a huge number of rabbits in Australia in 1930.

- a. Construct a STELLA diagram using the exponential growth, due to the birth rate, and the exponential decline, due to the death rate, for this rabbit population. Start the simulation time at 1859 and run it to 2000. Use Runge-Kutta 4 method of integration and a DT of 0.1. Approximately how many rabbits does our model estimate there were in 1930? _____

- b. You probably noticed that the rabbit population grew to outrageous numbers by the year 2000. Why do you think the model estimates for the latter part of the 20th century are probably not reasonable? _____

- c. Most populations cannot grow exponentially forever. There are many additional factors that influence death rate when the population grows to a certain critical level. This means the death rate cannot remain constant over the entire simulation time. As the population grows beyond this critical value the death rate will grow. To add this factor to your model we will need to create a special death rate converter that changes value over time.

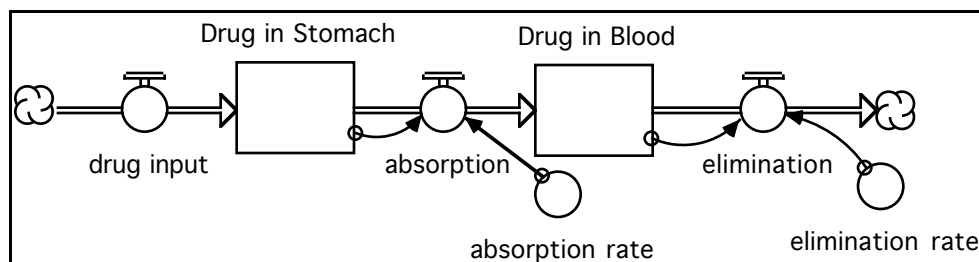
Draw a connection from your rabbit population stock to the death rate converter (since the new death rate will depend upon the size of the population). Draw the STELLA diagram for your new model below...

It is at the level two lesson that the few system dynamics concepts and model structures introduced in the level one lessons begins to reap reward. Using the modeling structures students now have a vehicle for conceptualizing how carrying capacity might actually play out in an environment. In a social studies classroom a simple resource structure can be added to a population structure and multiple scenarios can be simulated.

For example: A global studies class at Franklin High School in Portland, Oregon was broken into groups, each choosing a different country. A simple population structure was created for each country. One resource, available land, was added to the model to determine what might happen over the next hundred years, if the population grew at its current rate. Then another resource, potable water, was added. Although the third component was added, it was never made into a working model. The point of the sequence of lessons centered around the discussions about which resource components to consider, what the constraints might be on that resource, and how the resource availability might affect the overall population over 100 years.

The students did not build the model initially, but rather the class began with a discussion about factors that affect the growth of a population. A simple population model was built as part of the discussion. Topics about factors limiting growth ensued. Students were then given assignments to choose a country and find some data pertinent to the discussion. Then another class discussion occurred two days later as the model was enlarged to include the land component. Students then formed groups and built their population & land models, altering parameters to determine how outcomes might be affected. Another class discussion occurred the following day where the suggestion that amount of potable water be added to the model. This was the last lesson, since the time allotted for this activity had expired, but students were beginning to get a feeling for the number of factors that were acting to affect population growth.

Another example of a second level lesson in several second year algebra classes at Wilson High School in Portland, Oregon involved two simple growth patterns (linear and exponential), connected to allow the students to study pharmacokinetic² models. Students work through simple lessons for two days in an all-class discussion, culminating with the development of a two compartment pharmacokinetic model (shown below).



Then they are given a packet that describes alcohol consumption. Students are to build the model in the lab, test and explain the behavior caused by altering certain parameters. The scenario is reasonably accurate and provides students an exposure to the dynamics of body metabolism that would be beyond their reach if analysis required the use of equations at second year algebra level.

Assessment at level 2: Assessment at this level could involve writing an explanation, given a scenario similar in structure to one studied in class. For example, students would describe limiting factors on population growth. Or students could be given a population model structure and be asked to select an important resource structure and draw the resource structure, connecting it correctly to the population structure. They might be asked to explain their reasoning for the final structure. This could be a paper and pencil assessment.

An assessment for the pharmacokinetic model used in algebra could require the students to describe factors that affect blood alcohol level (BAC). Students could be given a BAC situation not included in their packet, but related, and be asked to sketch a comparative graph if a key parameter were changed, explaining why they thought the graph would be accurate. Alternately, a scenario could be described, such as, a police officer stops a motorist who is believed to have been drinking. A breathalyzer test is given and the person registers above the legal limit for driving. The person argues that he just left the bar, he only had 6 beers over the past two hours, and so his BAC level is dropping quickly. What facts should the police officer consider when writing his report to fully describe the intoxication level of the driver in this incident?

In the second level lessons emphasis is on interaction of characters and understanding how and why behavior is altered due to the interaction. Assessment then would concentrate on explanations of the interactions.

Level 3 Lessons: A third level of lesson is one where students have had enough experience with simple first and second level behavior patterns that they can, when given a scenario, create a simple model to explore the dynamics of the interactions. There are not many secondary school classrooms where this level is evident. One way to operate at this level is to have the course

²Thanks go to Dr. Ed Gallaher for his work designing pharmacokinetic models using STELLA for his drug research and instruction to medical students at Oregon Health Sciences University in Portland, Oregon. Dr. Gallaher has work with the CC-STADUS and CC-SUSTAIN NSF grant participants to teach high school teachers to build and use simple pharmacokinetic models. The models used with the second year algebra students were developed based on his information.

content taught hand in hand with modeling throughout the class. Schools that have had system dynamics modeling courses have students who are capable of learning at this level when entering a more traditional class. Classes where level 3 lessons occur usually focus on some "few" foundation concepts over the course of a year (or semester) and explore those concepts in more detail. Examples of classes of this type are the Environmental Science class, taught by Ron Zaraza, and the Science, Technology, and Society class, taught by Scott Guthrie, at Wilson High School in Portland, Oregon.

Although having a course taught as described above is a desirable way to reach this level, it is not the only way. If students have had experience via level one and level two lessons, or have had a year of system dynamics modeling, it is possible to provide projects for students to do outside of class. Those projects would require the building of system dynamics models and analysis of behavior and interactions involved in the project scenario. Such lessons would describe a scenario in enough detail that the student can reasonable build and analyze the model in a few weeks working outside of class. It is not possible to provide the needed time for this level of lesson within the class period (in most classes).

Some examples of this type of lesson would be: (in math) bank account (checking with savings) models, bank account and loan models, predator/prey models, epidemic models, and supply/demand models; (in biology) predator/prey models; (in physics) skydiver models.

What follows is the beginning of a bank account scenario.

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The making (earning/investing) and spending of money is of interest to almost everyone. We like to figure out ways to make our money grow as quickly as possible over time. We often want to determine if the money we earn will allow us to purchase the necessities of life and still allow us to have some left over for a few luxuries. Creating computer models about the rise and fall of the money in our bank accounts can give us the information we need to make good decisions about how we manage our finances.

Problem 1: Creating a Basic Money Model

You are young but very conscious about saving your money. You have a miniature computer shaped bank, a gift from your eccentric aunt Gertrude when you were born, in which you save all of your money. You have received \$100 in gifts every birthday since you were born. When you were 12 you started mowing lawns, earning \$40 per month for 6 months out of each year. Also, when you were 12 you started baby-sitting your younger brother and sister and earned \$20 per month. Assume you are now ready to turn 15 years old (but you haven't had your 15th birthday yet) and have spent none of the money that you have earned or that has been given to you as birthday gifts.

Create a STELLA model that will calculate how much money you have in your computer bank. (Hint; use the pulse command for the birthday gifts, and the step command for the baby-sitting and lawn mowing money.) Use only one inflow. Label the inflow "deposits." To make the problem a little easier, let's assume the lawn mowing money is spread out over the whole year at \$20 per month. Let the time units be months. Set the $DT = 1$. Use Euler method of integration. How many months should you run this simulation? _____. Create a table that contains the money in your bank, the birthday money, the lawn mowing money, and the baby-sitting money. Run the simulation.

How much money have you saved just before your 15th birthday? _____ Look at each of the three methods you had to increase your money saved. Explain, using the table, how you

know that you created the STELLA model correctly, by the way the values are represented in the table.

birthday money:

baby-sitting money:

lawn mowing money:

Problem 2: Putting the Money in the Bank

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Problem 3: Establishing a Savings Account

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Problem 4: Setting up a College Fund

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Problem 5: Taking out a Loan to Buy a Car, and a Loan to Finish Paying for College.

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Extra Credit) Problem 6: Improving Your Results

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Level 4 Lessons: The fourth, and final level of lessons involves the ability to summon a (non-trivial) generic structure, when a discussion of certain behavior patterns appear, regardless of context in which it is presented. In this type of lesson a student would be requested to create scenarios and structures that would reasonably replicate the (non-trivial) behavior of a given type and explain why it should work that way. In class, students might be asked to read an article pertinent to course content and be asked to create a model structure on the spot that might serve to produce the behavior demonstrated. This would mean that the student has internalized the modeling process enough to use it as a ready tool for analysis. The student would start with the creation of some reference behavior graph and, perhaps from discussions with other students, formulate a structure that would be a reasonable core model. Typically the structure would emanate from a group of generic structures the student has studied. This type of lesson could reasonably be part of a social studies, political issues or environmental studies class. It would not be likely to occur in any mathematics class at the secondary school level. Students in some first and more second year system dynamics modeling courses experience lessons at this level. To reach this lesson level in other, more traditional classes, a more system dynamics saturated curriculum across disciplines would be required.

Shown below is an example of an assignment given to second year modeling students. It could easily be given in a social studies class where students have had adequate exposure to modeling throughout the curriculum.

Assignment: During this semester you will need to find 5 newspaper/news magazine articles (one must be from a course you are taking) that explain a problem that could be modeled as a system. Write a 1-2 page summary containing the following information:

1. Briefly explain the problem/system described in the article.
2. Create a reference graph for the behavior that is of interest.

3. Identify the stock(s) in the system, the flows, and some of the converters. Draw or design a rough STELLA model of the core part of the system diagram (no numbers or equations are required). Pay attention to units. A model will not make sense unless the units are consistent. Flows always have units that are the stock units per time unit (increase or decrease).

4. Identify any feedback either mentioned in the article or, after analyzing the diagram and explaining the system from the article, describe what you think would represent feedback in the system. Hypothesize about whether the system represents positive feedback (a continuing process of increase or decrease) or negative feedback (a balancing process that tries to bring the system into some kind of equilibrium). If you have negative feedback what do you think causes the system to come back into balance?

5. Submit the article or a photocopy of the article, including the date and source, paper-clipped to the summary you wrote.

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Not every subject would start with level one lessons. Mathematics would. Environmental science might. Physics might. Social studies probably would start with level two lessons. System dynamics is inherently multi-disciplinary. One needs to enter a traditional curriculum at the highest leverage points, those points were SD strategies and tools fit most naturally and produce the most significant, short term results. The long term results will take care of themselves as long as there are continual exposure points.

A final note: There is a growing need to conduct analysis, using accepted research strategies, comparing student retention and depth of understanding of core subject concepts using new tools, like system dynamics models, and more successful traditional instruction. This would be the task, perhaps, of some doctoral candidates. At this point those of us who have incorporated such techniques and tools into our instruction DO see a difference, but currently do NOT have the data that will convince the general community of secondary educators.