

3.1 System Dynamics Tool: *STELLA* Version 8 Tutorial 1

*Introduction to Computational Science:
Modeling and Simulation for the Sciences*

Angela B. Shiflet and George W. Shiflet
Wofford College
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Introduction

We can use the software *STELLA*® from isee systems (<http://www.iseesystems.com/>) to model dynamic systems. **Dynamic systems** are usually very complex, having many components with involved relationships. For example, we can use *STELLA* to model the competition among different species for limited resources or the chemical reactions of enzyme kinetics.

To understand the material of this tutorial sufficiently, we recommend that you do everything that is requested. While working through the tutorial, answer Quick Review Questions in a separate document.

In the first tutorial on *STELLA*, we consider an example on unconstrained growth. In this example, the rate of change of the population is equal to 10% of the number of individuals in the population, and the initial population is 100 individuals. Thus, we have the following **differential equation**, or equation involving a derivative:

$$\frac{dP}{dt} = 0.1P, \quad P_0 = 100$$


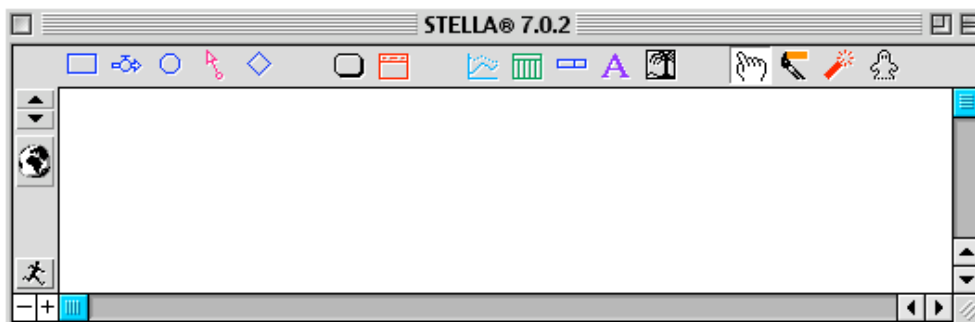
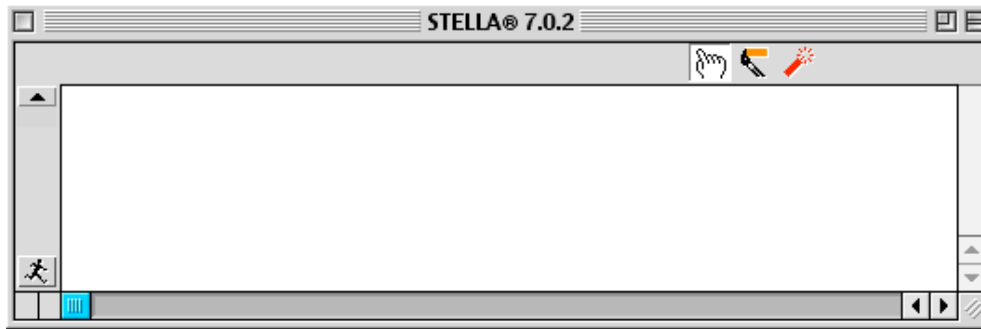
Start running the software, perhaps by double-clicking the *STELLA* icon (). A window in the **Map/Model Level** appears as in Figure 3.1.1.


Figure 3.1.1 Map/Model Level



Go to a deeper level by clicking the downward pointing triangle on the left. The new layer is the **Equation Level** (see Figure 3.1.2). Return to the Map/Model Level by clicking the upward pointing triangle on the left.





Figure 3.1.2 Equation Level



Click on the **earth icon** on the left of the window so that the **equation icon**  appears. In this mode, we can construct the diagram model with equations.

The most important icons for building a model appear on the top left of this level's window and are in Table 3.1.1. We describe the meaning of each of these building blocks in the following sections.

Table 3.1.1 Basic building blocks of *STELLA*

Building Block	Icon	Meaning
Stock		noun, something that accumulates
Flow		verb, activity that changes magnitude of stock
Converter		converts, stores equation or constant, does not accumulate
Connector		transmits inputs and information

Stock

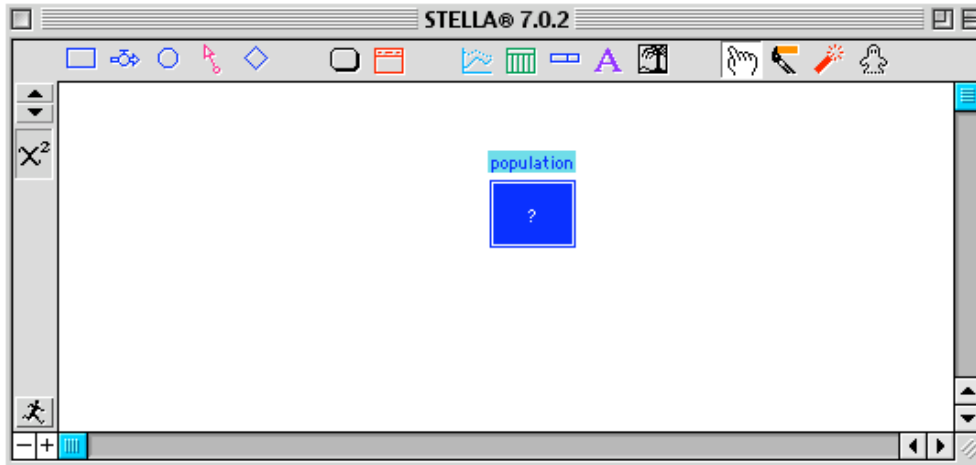
In *STELLA* terminology, a **stock** is a noun and represents something that accumulates. Some examples of stocks are population, radioactivity, enzyme concentration, self-esteem, and money. At any instant, the magnitudes of the stocks give us a snapshot of the system. The most common type of stock is a reservoir, which a plain rectangle represents.

Quick Review Question 1 In *STELLA*, click on the rectangular stock icon. Without holding down the mouse button, move the cursor towards the top-middle of the window. What is the shape of the cursor?

Click in the window to insert a stock object. Without clicking again, type the name of the stock, *population*. If the stock has become unselected, click once on the stock and

start typing to change the name. The contents of the window should be as in Figure 3.1.3.

Figure 3.1.3 Contents of window after insertion of stock called *population*



Quick Review Question 2 Click on the stock's name, *population*, and attempt to drag the name around the screen. Describe where the name can be dragged.

Under the *File* menu, select **Save** (or **ctrl-s** on a PC or **command-s** on a Macintosh) to save your work on a disk. Use a meaningful name for the file, such as *STELLATutorial1*. Save your work frequently. Thus, if there is a power interruption, you will not lose much of your work. Also, sometimes if you make a mistake, it is easier to close the file without saving and open the recently saved version.

Flow

While a stock is a noun in the language of *STELLA*, a **flow** is a verb. A flow is an activity that changes the magnitude of a stock. Some examples of such activities are births in a population, decay of radioactivity, formation of an enzyme, improvement of self-esteem, and growth of money. The flow icon represents a directed pipe with a spigot and flow regulator.

Click on the flow icon. Starting a couple of inches to the left of the stock, click and drag to the right over the stock until the rectangular stock icon becomes shaded. With the flow still selected, type its name, *growth*. The diagram should appear as in Figure 3.1.4.

Figure 3.1.4 Diagram after addition of *growth* flow



Quick Review Question 3 Drag the *population* stock around the right of the screen. What happens to the diagram?

If moving the *population* stock does not result in the flow arrow moving, too, but reveals another cloud, you need to attach the flow to the stock. Drag the stock over the cloud at the point of the arrowhead until the cloud becomes shaded. Perform the task of Quick Review Question 3 again.

Save your work.

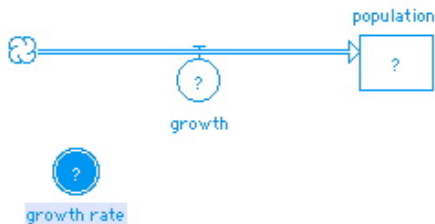
Converter

We can use a **converter** to modify an activity. A converter can store an equation or a constant. For example, with the population model, a converter might store the constant growth rate, say $10\% = 0.1$.

As an example for radioactive decay, radioactive substance bismuth-210 decays to radioactive substance polonium-210. With A representing the amount of bismuth-210 and B the amount of polonium-210, the ratio B/A is significant in the model of decay. A converter can store this ratio.

Select the converter icon, which is a circle. Click below and to the left of the flow name, *growth*. Name the converter *growth rate*. Blanks are permissible. The diagram should appear similar to Figure 3.1.5.

Figure 3.1.5 Diagram after insertion of converter *growth rate*



Action Connector

An **action connector** or **connector** transmits an input or an output. For example, in a population model, a connector can transmit the growth rate value from the growth rate converter to the growth flow.

In a radioactive decay model, connectors from the bismuth-210 (A) stock and from the polonium-210 (B) stock to a converter for the ratio of B over A transmit the respective amounts of radioactivity for use by the converter.

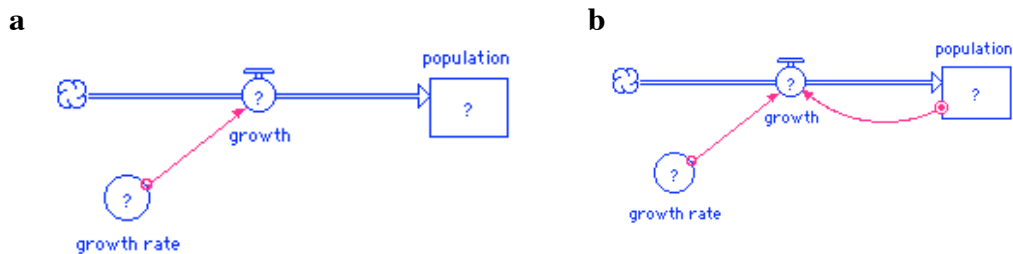
Because they transmit data, connectors do not have numerical values. Also, a flow can go into a stock but a connector cannot.

In the population model, both the growth rate and the current population affect the current growth. For example, if the growth rate is higher, so is the growth. Moreover, a larger population exhibits a greater change in population. We indicate these relationships by connecting the *growth rate* converter and the *population* stock to the flow *growth*.

Select the connector icon, click on the *growth rate* circle and drag until the *growth* flow

darkens before releasing. The resulting diagram is as in Figure 3.1.6a. To use the same tool again, hold down the **ALT** key on a PC and the **option** key on a Macintosh. Connect *population* to *growth* as in Figure 3.1.6b.

Figure 3.1.6 Connectors drawn to *growth* flow




Quick Review Question 4 For the connector from the stock to the flow, click on the small circle on the stock and drag it around. Where can you drag it?

Quick Review Question 5 What happens to the connector as you drag the stock *population* around the window?

Save your work.

Dynamite

To remove a component from the diagram, we use **dynamite** () . Using the delete key does not completely eliminate the item from the model. At the top of menu select the dynamite icon, which is the next-to-the-last icon.

Quick Review Question 6 Click the dynamite. Without clicking, move the dynamite cursor over the stock, flow, and converter. What happens to these components?

Quick Review Question 7 Does anything happen as you move the dynamite cursor over the connector's arrow edge and arrowhead?

Quick Review Question 8 What happens as you drag the dynamite over the small circle at the beginning of the connector's arrow?

Quick Review Question 9 With the dynamite shading *population*, click to remove the stock. What is eliminated?

When we remove an item with dynamite, the process eliminates the item and all connected connectors and flows. Restore the model to its previous form by closing the current document *without saving* and reopening the document. If a component is missing, recreate the model to appear as in Figure 3.1.6b.

Equations and Initial Values

We are now ready to enter equations and initial values. To begin defining an initial population, double-click the *population* stock and view a popup menu as in Figure 3.1.7. For an initial population of 100 bacteria, type 100. The value replaces the shaded text "(Place initial value here)".

Figure 3.1.7 Popup menu after double-clicking *population* stock

☐ population
☒ Reservoir ☐ Conveyor ☐ Queue ☐ Oven
☒ Non-negative
☐ Array

Allowable Inputs
 growth
 growth_rate

7 8 9 *
 4 5 6 /
 1 2 3 -
 0 . +
 «

☐ INITIAL(population) = ... Units...

{ Place initial value here... }

Document Message... Cancel OK

Notice in the top left corner, by default a checkbox labeled *Non-negative* is checked. Clearly, populations cannot be negative, so this default is appropriate. However, sometimes a stock can store a negative amount, such as money in the case of debt or velocity in the case of a falling object with up being positive. In such situations, we should uncheck the *Non-negative* checkbox.

Click *OK*.

Quick Review Question 10 To establish the growth rate as $10\% = 0.1$, first, double-click the converter. What name does *STELLA* give for the converter?

Type 0.1 in place of the shaded "{ Place right hand side of equation here... }", and then click *OK*. Notice that after entering a growth rate and an initial population, the question marks no longer appear in the circle and rectangle, respectively.

For equations, *STELLA* uses an underscore in place of a blank in a name. Thus, "growth rate" in a diagram (see Figure 3.1.6) becomes "*growth_rate*" in a *STELLA* equation (see Figure 3.1.7). We employ such replacement of blanks with underscores in the text and tutorials to avoid confusion with component names.

Unlike *growth_rate*, the flow *growth* is not a constant; but the growth in the population changes with time as the population changes. For our example, at any instant, the rate of change in the population, or *growth*, is 10% (*growth_rate*) of the current population (*population*). In calculus terminology, the instantaneous rate of change of population is the derivative of *population* with respect to time *t*, so that we have the following formula:

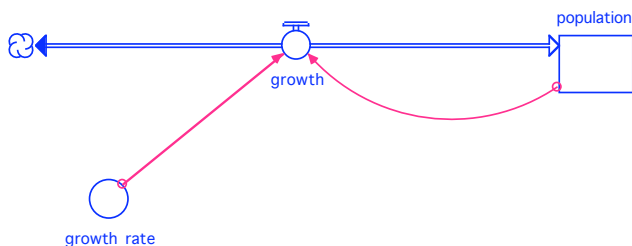
$$\begin{aligned}\frac{d(\text{population})}{dt} &= \text{growth_rate} \cdot \text{population} \\ &= 0.1 \cdot \text{population}\end{aligned}$$

Double-clicking on the *growth* faucet, we see a popup menu as in Figure 3.1.8.

Figure 3.1.8 Popup menu for *growth*

Quick Review Question 11 The submenu *Required Inputs* lists the items that have connectors to *growth*, namely *population* and *growth_rate*. We include these variables in the formula for *growth*. For our example, this instantaneous rate of change of population is 0.1 population bacteria per unit of time. Using * for multiplication and clicking on the appropriate variables in *Required Inputs*, enter the formula for growth. What is the resulting formula? Click *OK*.

As Figure 3.1.8 shows, the popup menu for a flow has two radio buttons, *UNIFLOW* and *BIFLOW* in the top left corner. The default is *UNIFLOW*, which indicates that growth can only flow in one direction, into the stock *population*. Should we wish to allow values to flow in both directions through the flow, we would check *BIFLOW*. In this case, the flow would appear as in Figure 3.1.9, with the open arrowhead indicating the primary direction into *population* and the darkened arrowhead representing the possibility of removal from the population.

Figure 3.1.9 Biflow

Clicking the down arrow on the top left of the *STELLA* window takes us to the **Equation Level** and reveals the resulting formulas, which Equation Set 1 displays. On

the model, we had established a value for *growth_rate* (0.1), an initial value for *population* (100), and the equation for *growth* (*growth_rate* * *population*). The variable ***dt***, which appears in the formula for *population(t)*, represents the **change in time** between time steps. The variable ***t*** represents **time**; and ***population(t)*** is the **population at time *t***; while ***population(t - dt)*** is the population at the previous time step, *t - dt*. As we discuss in detail in Module 3.2 on "Unconstrained Growth," the first equation indicates the population at one time step is the population at previous time step plus the change in population over that time interval:

$$\begin{aligned} (\text{new population}) &= (\text{old population}) + (\text{change in population}) \\ &= (\text{old population}) + \text{growth} * dt \\ &= (\text{old population}) + (\text{growth over 1 unit}) * (\text{length of time step}) \end{aligned}$$

Equation Set 1 Formulas

```
population(t) = population(t - dt) + (growth) * dt
INIT population = 100
growth = growth_rate * population
growth_rate = 0.1
```

Quick Review Question 12 For current time *t*, give the meaning of each of the following:

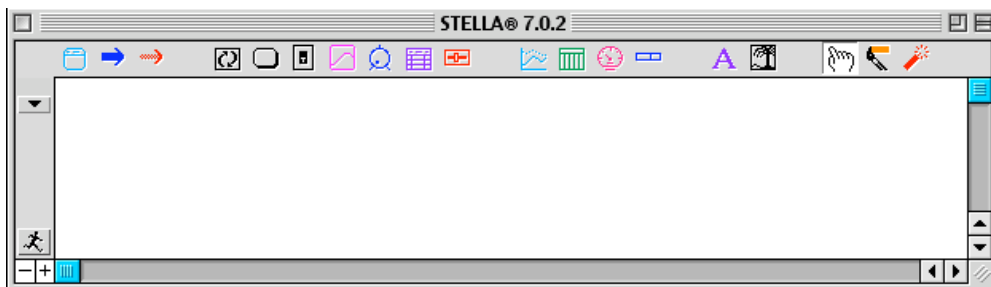
- $t - dt$
- $population(t - dt)$
- $growth * dt$

Save your work and continue saving frequently. Click the up arrow on the top left to return to the **Map/Model Level**.

Comments

Click again on the up arrow on the top left of the *STELLA* window to go to the **Interface Level**. Figure 3.1.10 displays the top part of the resulting layer.

Figure 3.1.10 Interface Level



Documenting our work is extremely important. We want other people to be able to understand the model as quickly as possible. Moreover, we can very easily forget what we intended just a few days or hours ago. We may have several very similar versions of the same model that we need to distinguish one from another. We do not want to waste our own or someone else's time by having to dig deeply into the different levels and equations to understand the model.


Quick Review Question 13 To enter a comment, click the **A** icon to get a **text box**. What is the shape of the resulting cursor?

Click towards the top middle of the window to insert the text box. Type "Unconstrained Growth Population Model" on one line and your name and date on the next. Type an explanation that the model is for growth of a population with no limiting factors.

Quick Review Question 14 Click on the outside lines of the text box. What appears?

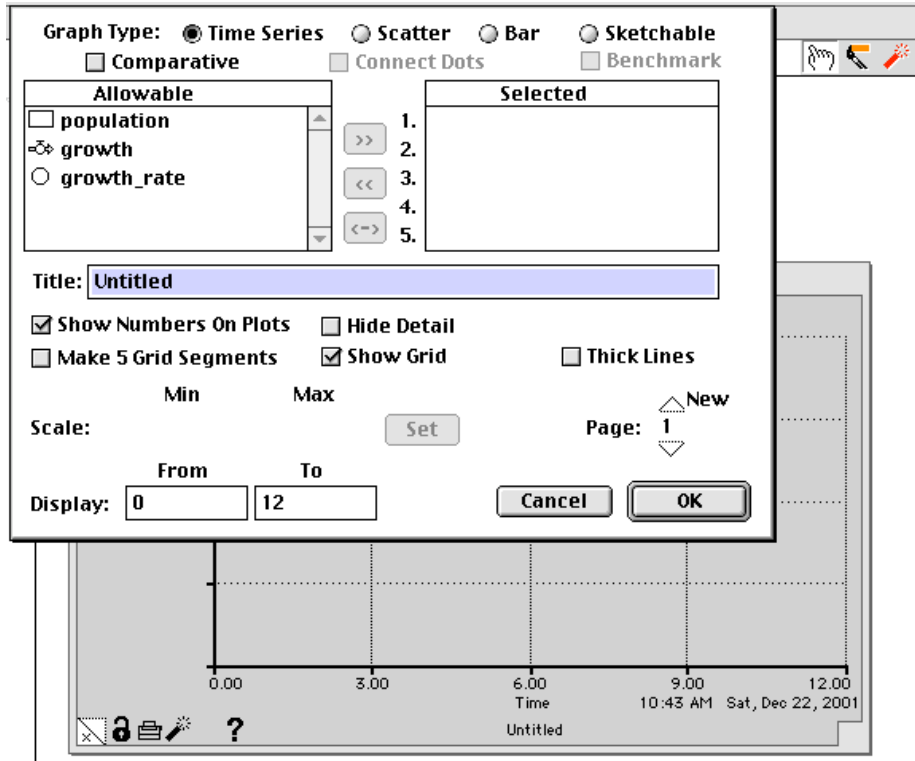
Drag on one of the small shaded rectangles, called **handles**, at a corner to resize or display all of the text. Drag on one of the box's lines to move the box without resizing.

Graphs

In the Interface level (Figure 3.1.10), the **graph pad** icon () appears as a picture of a small, blue graph in the middle of the sequence of icons. After clicking this icon, click towards the left of the window to place the graph object. A graph popup window appears immediately. Adjust the placement of the graph by dragging on its title bar.

Quick Review Question 15 Click outside of the graph popup window. What happens and what do you see?

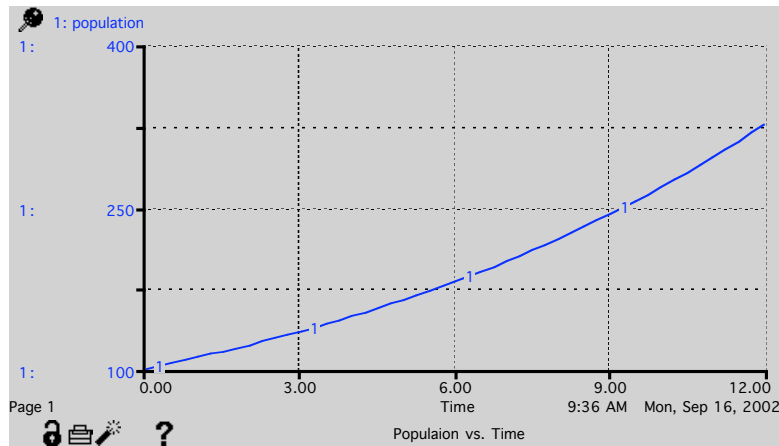
The "Graph 1" icon will remain in the window unless you destroy it with dynamite. Double-click on the "Graph 1" icon to redisplay the graph popup window. Move the graph towards the middle top of the screen and resize as you wish. To continue displaying the graph and to prevent accidentally moving it, click on the **thumb tack** icon on the top left of the graph window. Double-click inside the graph window to display the **Graph Definition Window** (see Figure 3.1.11).

Figure 3.1.11 Graph Definition Window with Graph Window in background

In the text box for *Title*: in the middle, type "Population vs. Time" so that the title appears on the graph's window. Leaving the graph type as the default *Time Series*, time will appear on the horizontal axis. To have *STELLA* graph the population with respect to time, we double-click *population* under *Allowable*. Alternatively, click once on the *population* line, and click ">>".

Quick Review Question 16 Double-click *growth* under *Allowables*. Give two ways to remove *growth* from the *Selected* items.

If you have not done so already, remove *growth* from the *Selected* items. Close the Graph Definition Window by clicking *OK*, and run the simulation by choosing **Run** (or **ctrl-r** on a PC or **command-r** on a Macintosh) from the *Run* menu to obtain the graph of Figure 3.1.12. Notice that the bottom left corner of the graph indicates an initial population (at time 0.0) of 100.

Figure 3.1.12 Graph of *Population vs. Time* using the default run specifications

Quick Review Question 17 How many time units does the simulation run?

Quick Review Question 18 About how many time units does it take for the initial population to double?

To change the default time specifications, from the *Run* menu choose **Run Specs...**, so that the popup menu as in Figure 3.1.13. Have the simulation run for 100 time units. If we are modeling the growth of a population of bacteria, the time unit would probably be an hour; while for a larger animal, the unit might be a month. Supposing the model is for a colony of bacteria, change the *Unit of Time* to *Hours*. Change *DT* to 0.1. Thus, calculations for the simulation will be every 0.1 hour instead of every 0.25 hour. Usually, a smaller *DT* generates more accurate results but causes the simulation to take longer. Although the computations take longer, we can also obtain better results with the Runge-Kutta 2 or the Runge-Kutta 4 integration method. For the time being, leave the Integration Method as the default, Euler's Method. Chapter 5 on "Simulation Techniques" discusses these methods.

Figure 3.1.13 *Run Specs* popup menu

RUN SPECS

Length of simulation:
 From:
 To:
 DT:
☐ DT as fraction
 Pause interval:

Unit of time:
☐ Hours
☐ Days
☐ Weeks
☐ Months
☐ Quarters
☐ Years
☒ Other

Interaction Mode:
☒ Normal
☐ Flight Sim

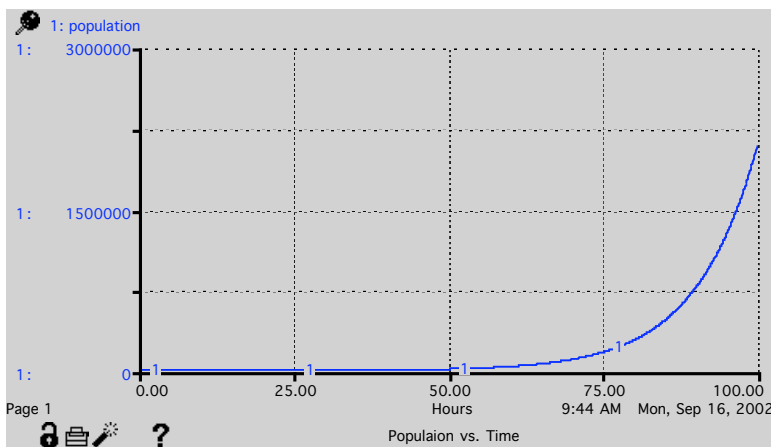
Integration Method:
☒ Euler's Method
☐ Runge-Kutta 2
☐ Runge-Kutta 4

Sim Speed:
 real secs = 1 unit time
 Min run length: 0 secs

☐ Analyze Mode: stores run results in memory (0.0 MB required)

Quick Review Question 19 After making the above changes, how many time steps (DT's) will be in the simulation?

Click *OK*, and run the simulation. Notice in Figure 3.1.14 that *STELLA* changes the range on the time axis to 0.00-100.00 and on the population axis to 0-3000000.

Figure 3.1.14 Graph of *Population vs. Time* using the *Run Specs* popup menu of Figure 3.1.13

To preserve this graph regardless of what other changes we make, click the **Lock** icon at the bottom left of the graph window (see Figure 3.1.14). Clicking the next icon would **print** the graph. Selection of **dynamite** on the graph window clears the graph. If we click the **Question Mark** icon, we can enter notes about the graph. If we have more than one page, we can click on the bottom left corner to page through the graphs.

Double-click the graph to display the Graph Definition Window once again (see Figure 3.1.11). To generate a new graph page, select the up arrow by the word *New* above *OK* on the bottom right of the window. For this page, make the proper specifications to plot *population* and *growth* from 0 to 5 hours on the same graph (see Figure 3.1.15). Run the simulation. Notice in Figure 3.1.16 that the graphs are numbered and colored with different scales on the vertical axis. The ranges are such that the graphs appear almost horizontal at 0.

Figure 3.1.15 *Run Specs* for graphs of *population* and *growth*

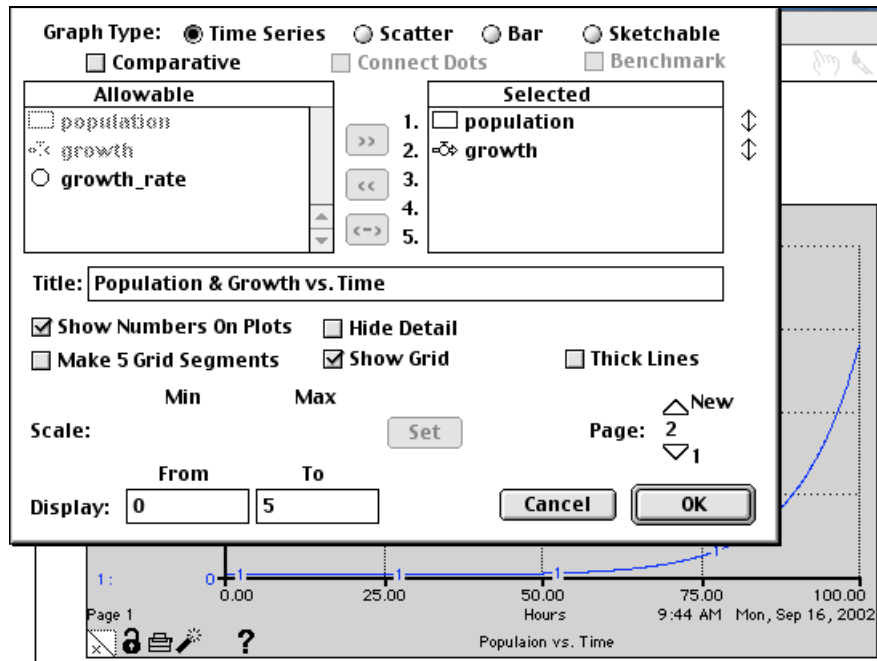
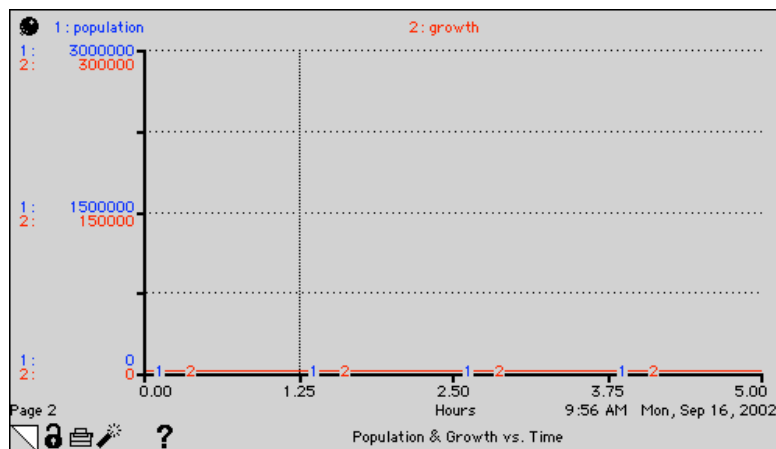


Figure 3.1.16 Graph of *Population & Growth vs. Time*

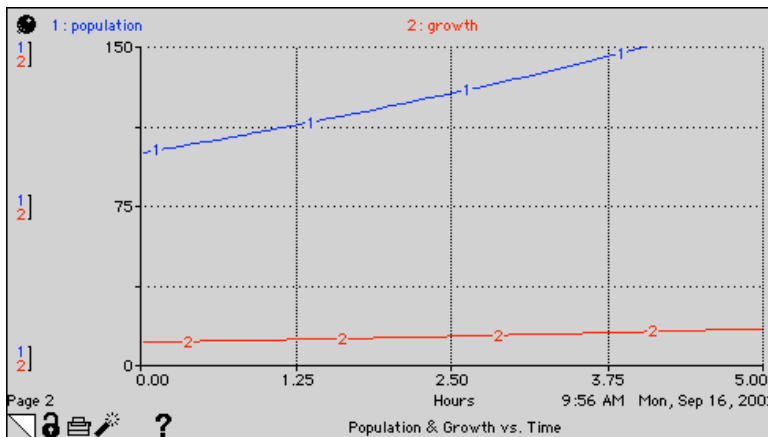


Double-clicking the graph, we can change the scales in the Graph Definition Window (see Figure 3.1.17). On the *Selected* submenu, click *population*. You may need

to click the up-down arrow to its right to display the minimum (*Min*) and maximum (*Max*) values on the *Scale* towards the bottom left. Change the range to from 0 to 150, and click *Set*. Similarly, set the scale for *growth* to from 0 to 150, and click *Set* and *OK*. Without re-running, the graph, which is in Figure 3.1.18, immediately reflects the scale changes.

Figure 3.1.17 Graph Definition Window to change scales

Figure 3.1.18 Graph of *Population & Growth vs. Time* for scales of 0 to 150 for *population* and *growth*



Quick Review Question 20 Notice that we still cannot see all of the *population* graph for the time period. What maximum to the nearest 10 (160, 170, 180 etc.) shows the entire graph from 0 to 5?

Change the range for *population* and *growth* to be the same and so that both graphs appear completely.

Tables

Besides a pictorial view, we may want a table of values from the simulation. The **Table Pad** icon appears to the right of the Graph icon on the window for the Interface Level (see Figure 3.1.10). Click this icon and place a table object below the graph object. Double-click the table to display the **Table Definition Window** as in Figure 3.1.19. Name the table "Population Changes," and move *growth* and *population* to the *Selected* submenu. Unselect *Every DT*, and change the reporting interval to 10. Thus, although the simulation will perform the calculations as before, the table will display the results for every 10 hours. Figure 3.1.20 displays the revised Table Definition Window. Run the simulation.

Figure 3.1.19 Table Definition Window

The 'Table Definition Window' is a dialog box with the following components:

- Allowable** list: Blank Line, ☐ population, ☒ growth, ☐ growth_rate.
- Selected** list: (Empty)
- Table Type:** ☐ Comparative
- Orientation:** ☒ Vertical
- Report:** ☒ Beginning balances, ☐ Ending balances
- Report flow values:** ☒ Instantaneous, ☐ Summed
- Report interval:** ☒ Every DT
- Title:** (Empty text field)
- Buttons:** Cancel, OK

Figure 3.1.20 Revised Table Definition Window

The 'Revised Table Definition Window' shows the following changes from Figure 3.1.19:

- Selected** list: ☒ growth, ☐ population.
- Report interval:** 10
- Report flow values:** ☒ Instantaneous, ☐ Summed
- Report interval:** ☐ Every DT
- Title:** Population Changes

Quick Review Question 21 How many rows of values appear in the table?

Drag the vertical line separating the *Hours* and *growth* columns to the left to adjust the spacing. To display the larger *population* values, drag another vertical line to the right.

It is more appropriate to have the growth and population in whole numbers. To change the format of the population values, double-click the *population* column heading.


Quick Review Question 22 What do we do to display the population in whole numbers?

Change the precision of each column to 0, and click *OK* and view the result.

Input/Output Tools

We can change initial values and constants in the model by going to the Map/Model Level, double-clicking the stock or converter, and changing the value. In running our model for several situations, this process is tedious. Moreover, we cannot detect the values immediately by looking at the screen or printout. However, *STELLA* has a variety of tools for input and output values that can help us perform an assortment of simulations quickly and view the results readily.

One of the most useful such tools, is the **List Input Device** for defining constants

and initial values. Click its icon () , which appears in purple, two items to the left of the graph icon on the Interface Level Window (see Figure 3.1.10). After placing a List Input Device on the window, double-click in a blank area of the list (not on the drop-down menu or scroll bar) and specify the *List Title* as "Values." For the list, select (initial) *population* and *growth_rate*, choosing appropriate minimum and maximum values, such 1-2000 and 0-0.9, respectively. Click *OK*. Unlock any locked tables or graphs. Change the initial population to 15 and the growth rate to 0.2. Run the simulation. If a graph does not display properly, double-click the graph and change the scale.

Quick Review Question 23 What happens when you click "U" on the input list?

The **Knob** and the **Slider Input Device** icons are immediately to the left and right of the List Input Device icon, respectively. Remove *growth_rate* from the input list by double-clicking a blank area towards the top of the list and double-clicking *growth_rate*. Place a Knob Input Device for input of *growth_rate* in the window. Change the value of *growth_rate* by rotating the knob and then by typing a value in the small display above the knob. Use dynamite to destroy the knob.

Quick Review Question 24 Insert a Slider Input Device for *growth_rate*. Give two ways to designate the growth rate with this device.

We can use the **Numeric Display** to show one value. The Numeric Display icon appears to the left of the Text Box icon, "A". Insert a Numeric Display object on the window, and have it display *population* with no decimal point.

Quick Review Question 25 In the popup window for the Numeric Display, what do we specify to have the output value for *population* be a whole number?

Print the Interface, Map/Model, and Equations Level Windows. Save and Quit *STELLA*.

Reference

Getting Started with the STELLA Software, A Hands-On Experience, 2004. isee systems
<http://www.iseesystems.com/>