3.1 System Dynamics Tool:

Berkeley Madonna Tutorial 1

Introduction to Computational Science:
Modeling and Simulation for the Sciences

Angela B. Shiflet and George W. Shiflet
Wofford College

Introduction

We can use the software *Berkeley Madonna*® (http://www.berkeleymadonna.com/), developed by Robert Macey and George Oster of the University of California at Berkeley, to model dynamic systems. **Dynamic systems** are usually very complex, having many components with involved relationships. For example, we can use *Berkeley Madonna* to model the competition among different species for limited resources or the chemical reactions of enzyme kinetics.

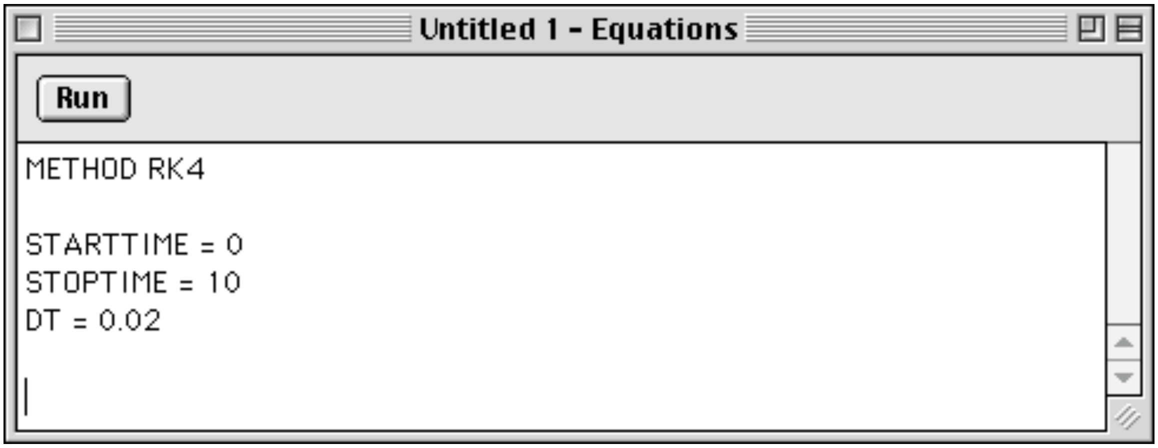
To understand the material of this tutorial sufficiently, we recommend that you do everything that is requested. While working through the tutorial, answer Quick Review Questions in a separate document.

In the first tutorial on *Berkeley Madonna*, 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:

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

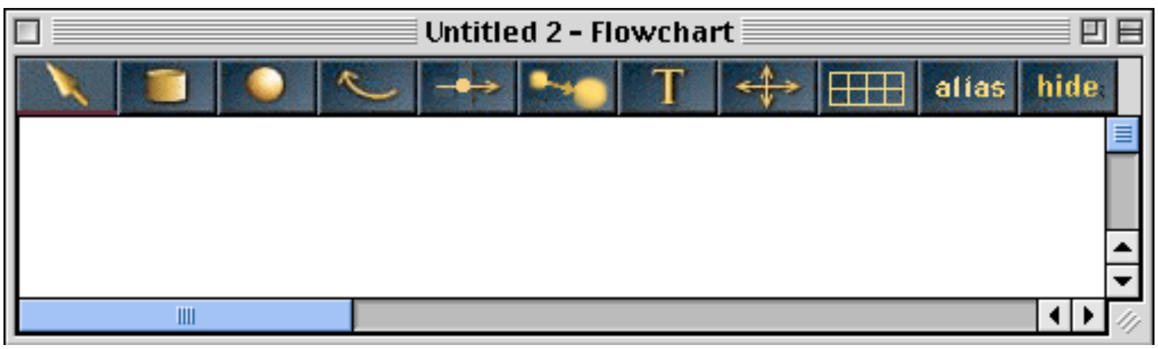
Start running the software, perhaps by double-clicking the *Berkeley Madonna* icon ( ). An **equations window** appears as in Figure 3.1.1.

Figure 3.1.1 Equations window



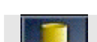
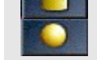
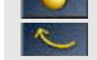
From the *File* menu select ***New Flowchart*** to obtain a **flowchart window** (see Figure 3.1.2). With this window, we can construct a diagram model with equations.

Figure 3.1.2 Flowchart window



The most important icons for building a model appear on the top left of this window after the **selector** () 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 *Berkeley Madonna*

Building Block	Icon	Meaning
Reservoir		noun, something that accumulates
Formula		converts, stores equation or constant, does not accumulate
Arc		transmits inputs and information
Flow		verb, activity that changes magnitude of reservoir

Reservoir

In *Berkeley Madonna* terminology, a **reservoir**, which the text and some other system dynamics software tools call a **stock** or **box variable**, is a noun and represents something that accumulates. Some examples of reservoirs are population, radioactivity, enzyme concentration, self-esteem, and money. At any instant, the magnitudes of the reservoirs give us a snapshot of the system. A cylinder or drum represents a reservoir.

Quick Review Question 1 In *Berkeley Madonna*, select the cylindrical reservoir icon. Holding down the mouse button, drag the cursor towards the top-middle of the window. What is the shape of the cursor?

Without clicking again, type the name of the reservoir, *population*, which replaces the default name *R1*. If the reservoir has become unselected, click once on the reservoir and start typing to change the name. Because a selected object is red, the contents of the window should be as in Figure 3.1.3.

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

Quick Review Question 2 Click on the reservoir'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 *BerkeleyTutorial1*. 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.

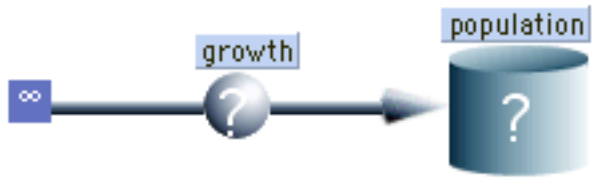
Flow

While a reservoir is a noun in the language of *Berkeley Madonna*, a **flow** is a verb. A flow is an activity that changes magnitude of a reservoir. 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 reservoir, click and drag to the right over the reservoir until a rectangular surrounds the reservoir icon.

With the flow still selected, type its name, *growth*. After clicking elsewhere, 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* reservoir around the right of the screen. What happens to the diagram?

If moving the *population* reservoir does not result in the flow arrow moving, too, you need to attach the flow to the reservoir. Drag the infinity symbol at the arrowhead over the reservoir until a rectangle surrounds the reservoir. Perform the task of Quick Review Question 3 again.

Save your work.

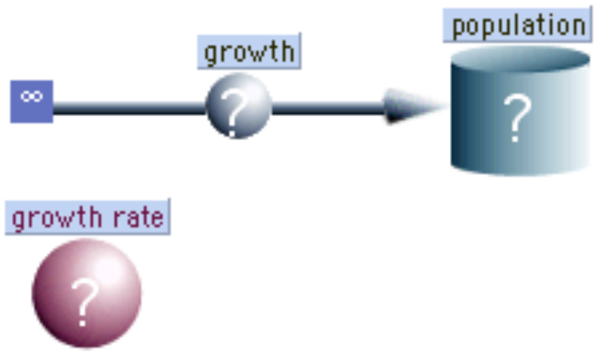
Formula

We can use a **formula**, which the text and some system dynamics tools call a **converter** or **variable**, to modify an activity. A formula can store an equation or a constant. For example, with the population model, a formula 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 formula diagram component can store this ratio.

Drag the formula icon, which is a sphere, below and to the left of the flow *growth*. Alternatively, select the formula icon and then click on the desired location in the flowchart window. Name the formula *growth rate*. Blanks are permissible. The diagram should appear similar to Figure 3.1.5.

Figure 3.1.5 Diagram after insertion of formula *growth rate*



Arc

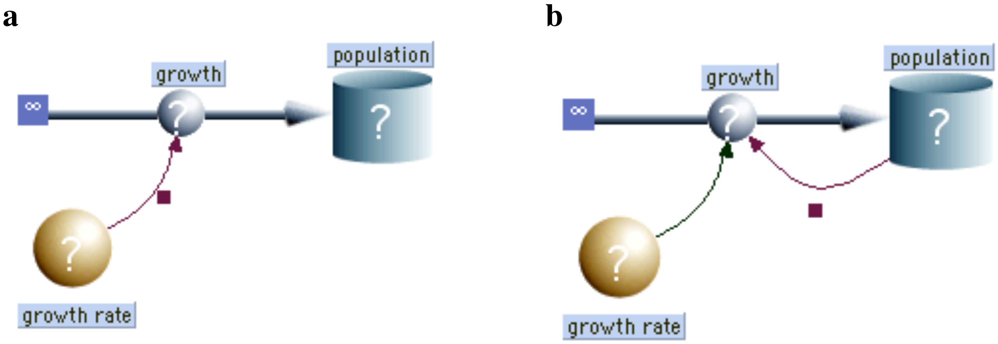
An **arc**, which we call a **connector** or **arrow** in the text, transmits an input or an output. For example, in a population model, an arc can transmit the growth rate value from the growth rate constant to the growth flow.

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

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* formula and the *population* reservoir to the flow *growth*. Select the arc icon, click on the *growth rate* sphere and drag until the sphere on the *growth* flow has a surrounding rectangle. A **control point** appears as a small square at the tail of the arc. Drag this control point out and to the side to obtain a curved arc as in Figure 3.1.6a. Using the same tool, connect *population* to *growth* as in Figure 3.1.6b.

Figure 3.1.6 Arcs drawn to *growth* flow

a **b**



Quick Review Question 4 What happens to the arc as you drag around the reservoir or the small sphere on the flow?

Save your work.

Removing a Component

To remove a component from the diagram, we use ***Clear*** or ***Cut*** from the *File* menu. Using the delete key on a reservoir or formula removes the component's name but does not eliminate the item from the model.

Quick Review Question 5 Click the *population* reservoir, and use *Clear* or *Cut* from the *File* menu to remove it. What happens to the diagram?

Quick Review Question 6 Click the arc from *growth rate* to *growth*. What happens if you press the delete key?

Quick Review Question 7 How do you delete this arc?

Quick Review Question 8 Select the *growth* flow, and press the delete key. What happens?

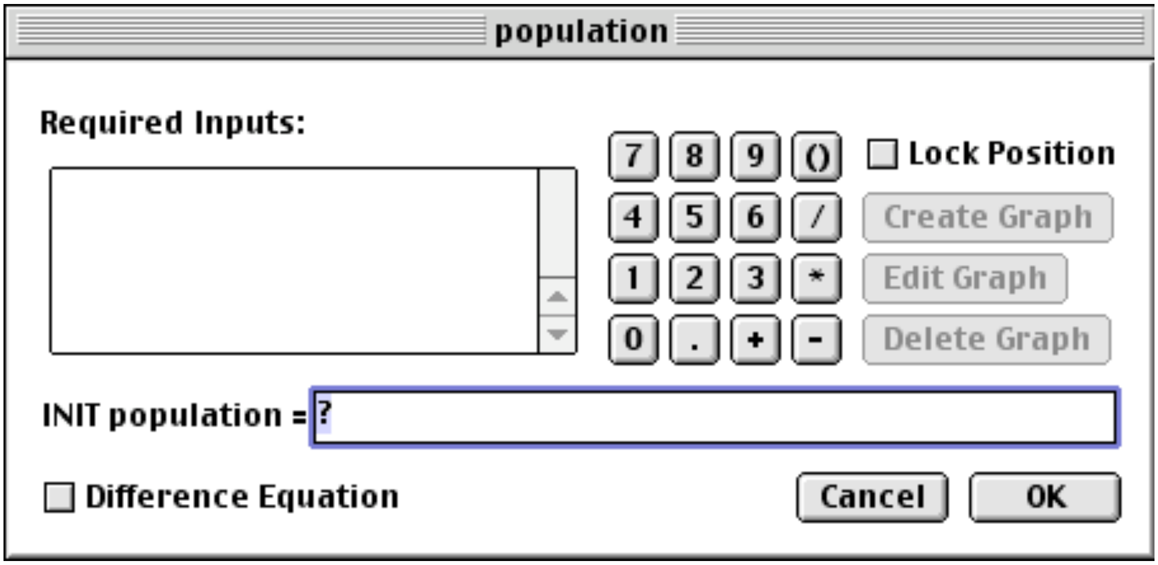
When we remove a component, the process eliminates the item and all connected arcs and flows. Restore the model to its previous form by closing the current document *without saving* and reopening the document. If a component is missing, recreate the model to appear as in Figure 3.1.6b.

Equations and Initial Values

We are now ready to enter equations and initial values. To begin defining an initial population, double-click the *population* reservoir and view a popup menu as in Figure 3.1.7. For an initial population of 100 bacteria, type 100. The value replaces the question mark after "INIT population." Click *OK*.

Quick Review Question 9 How does the appearance of *population* change on the diagram?

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

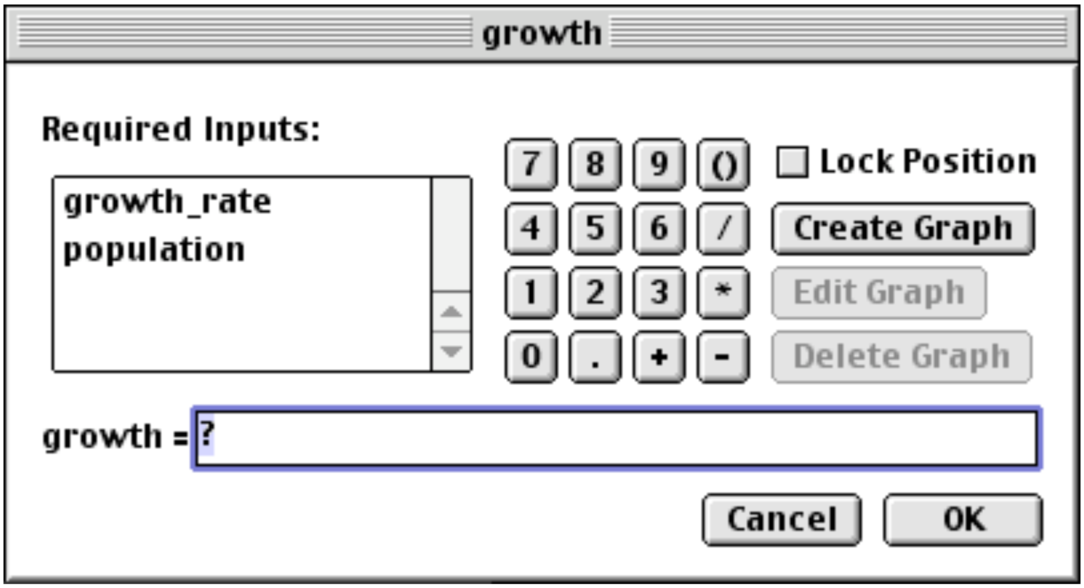


Quick Review Question 10 To establish the growth rate as 10% = 0.1, first, double-click the formula *growth rate*. What name does *Berkeley Madonna* give for the formula?

Type 0.1 in place of the question mark after "growth_rate =", and then click *OK*. Notice that after entering a growth rate and an initial population, the question marks no longer appear in the sphere and cylinder, respectively.

For equations, *Berkeley Madonna* 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 *Berkeley Madonna* equation (see *Required Inputs* of Figure 3.1.8). We employ such replacement of blanks with underscores in the text and tutorials to avoid confusion with component names.

Figure 3.1.8 Popup menu for *growth*



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:

$$\frac{d(population)}{dt} = growth\_rate \cdot population$$
$$= 0.1 \cdot population$$

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

Quick Review Question 11 The submenu *Required Inputs* lists the items that have arcs 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 double-clicking on the appropriate variables in *Required Inputs*, enter the formula for growth. What is the resulting formula? Click *OK*.

The flow *growth* is a **biflow**, which indicates that values can go in both directions through the flow, into and out of *population*. Moreover, *Berkeley Madonna* allows *population* to take on positive, negative, or zero values.

From the ***Model*** **menu**, selecting ***Equations*** or using the indicated shortcut opens the equations window 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 ***t*** indicates **time**, and "d/dt (population)" is the symbol for the derivative of *population* or the instantaneous rate of change of *population* with respect to time *t*. Thus, according to the formula, the rate of change of *population* with respect to time is *growth*. As we discuss in detail in Module 3.2 on "Unconstrained Growth," this equation indicates the population at one time step is the population at previous time step plus the change in population over the **time interval for one step**, ***DT***:

(new population) = (old population) + (change in population)
= (old population) + *growth* * *DT*
= (old population) + (growth over 1 unit) * (length of time step)

Equation Set 1 Formulas

```
{Top model}

   {Reservoirs}
   d/dt (population) = + growth
      INIT population = 100

   {Flows}
   growth = growth_rate * population

   {Functions}
   growth_rate = 0.1
```

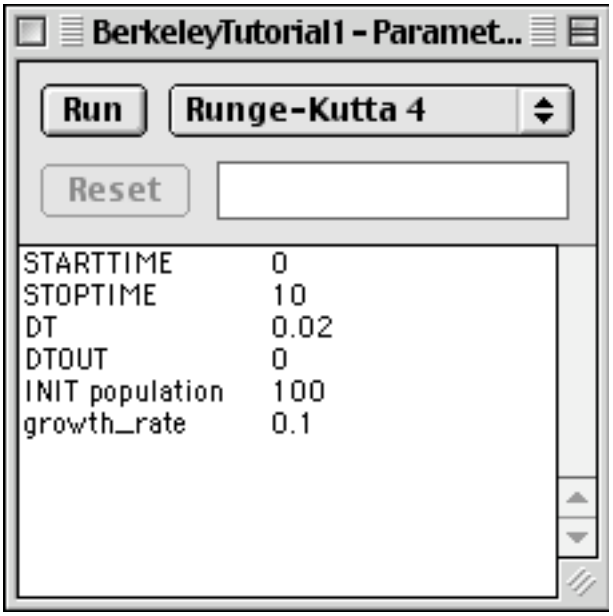
Save your work and continue saving frequently.

Parameters

From the ***Parameters*** menu, select ***Parameters Window*** to obtain a popup menu as in Figure 3.1.9. Have the simulation run for 100 time units by clicking once on the ***STOPTIME*** line and typing 100 in the text window.

Quick Review Question 12 What symbol now appears by the value of *STOPTIME*?

Figure 3.1.9 Parameters window



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 with an understood unit of time of one hour (hr). Change *DT* to 0.1. Thus, calculations for the simulation will be every 0.1 hr instead of every 0.02 hr. 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, choose the integration method to be Euler's Method from the dropdown menu. Chapter 5 on "Simulation Techniques" discusses these methods.

Comments

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 windows and equations to understand the model. To enter a one-line comment in a flowchart, click the **T icon** to get a **text box**. Click towards the top middle of the window to insert the text box. Type "Growth Population Model" on one line. The delete key and insertion work as expected.

Quick Review Question 13 Press *RETURN*. Does the text box continue to a new line?

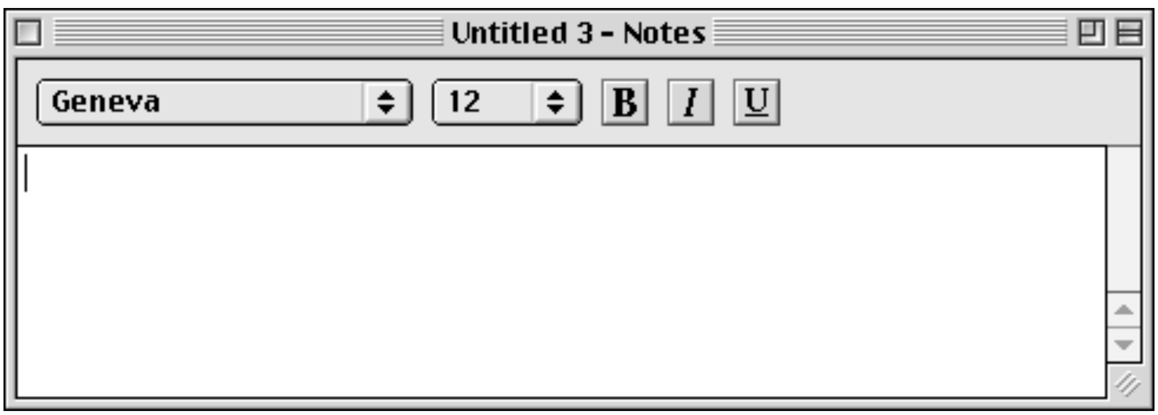
Type your name and date in new text boxes below your title.

Quick Review Question 14 Move the cursor over the title text box. Give the shape of the cursor.

Still using the text feature, click at the first of the title text box and insert "Unconstrained " so that the box now reads "Unconstrained Growth Population Model". We can also use the T icon to edit a component's name. To leave the text mode, we choose another icon, such as select on the far left.

For longer comments, from the *Model* menu, select ***Notes*** or use the indicated shortcut. Type your name and an explanation that the model is for growth of a population with no limiting factors in the **notes window** (see Figure 3.1.10). Drag the bottom right corner to resize the window, and drag on the title bar to move the box without resizing. Close this and other windows by clicking on the square on the top left of the window's title bar. To reopen the notes window, we can again select *Notes* from the *Model* menu or us the indicated shortcut.

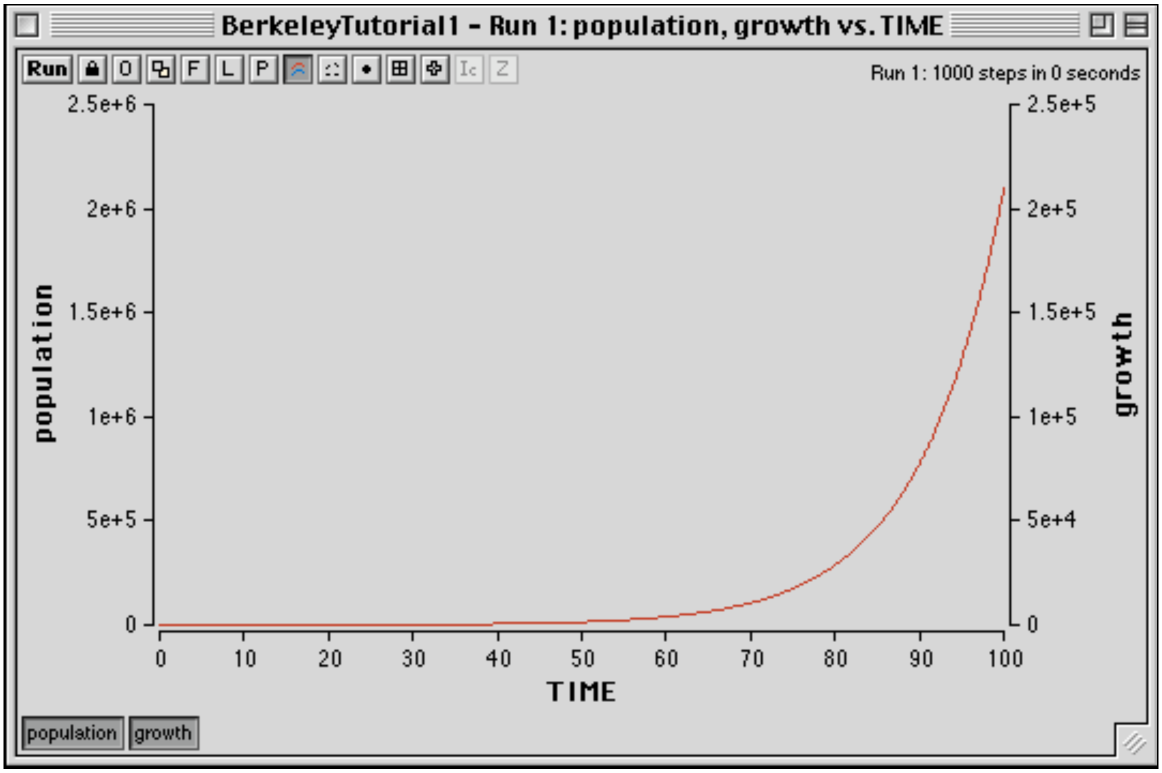
Figure 3.1.10 Notes window



Graphs

We can now run the simulation in several ways, such as clicking the ***Run*** button on the parameters window or selecting ***Run*** from the *Model* or *Compute* menu. A graph popup window as in Figure 3.1.11 appears immediately. Adjust the placement of the graph by dragging on its title bar.

Figure 3.1.11 Plot of *population* and *growth* versus time using the default run specifications



The title bar indicates the name of the model's file, the run, and the variables that are possible to plot. Note that the scale for *population* appears along the left axis while that for *growth* is along the right. By default, *TIME* appears on the horizontal axis. Because these particular graphs have identical shapes, one appears on top of the other. Click the **labels icon** (L) beneath the title bar to display a label on the graph.

Quick Review Question 15 Which graph (*population* versus *TIME* or *growth* versus *TIME*) did *Berkeley Madonna* plot first and what is its color? Because the two graphs have the same shape, the second graph hides the plot of this first graph.

Quick Review Question 16 How many time steps (*DT*'s) does the simulation run?

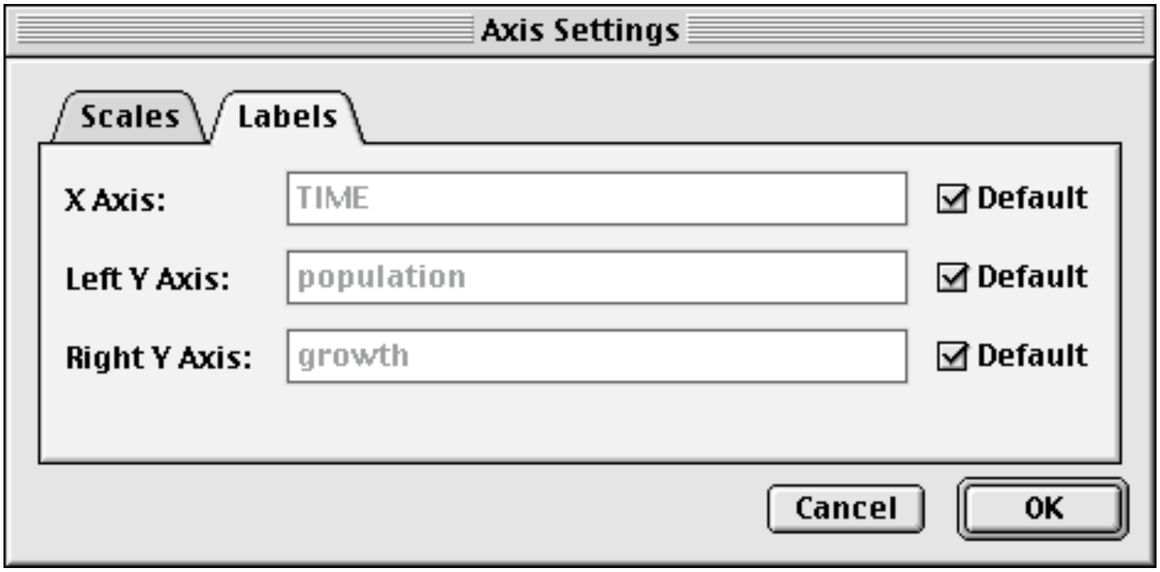
For documentation, click the **parameters icon** (P) to the right of the labels icon. *Berkeley Madonna* places the parameter list on the graph. We can drag the parameter and label lists to desired locations on the graph.

For printing on a black-and-white printer, deselect the colored graph icon ( ) and click the dotted graph icon ( ) on the graph window.

We can specify axes scales and labels in one of two ways: by selecting ***Axis Settings...*** from the *Graph* menu or by double-clicking in the graph's margin. In the **axis-**

settings window, if necessary, click the *Labels* tab to view a display as in Figure 3.1.12, Uncheck the *Default* checkbox. After "TIME", type your name in parentheses so that the graph will have your name at the bottom. Click *OK*.

Figure 3.1.12 Axis-settings window, *Labels* tab, for graphs of *population* and *growth*



Print the graph by selecting ***Print Graph...*** from the *File* menu. From the *File* menu, also, select ***Save Graph As...***, and save the graph under the name "BerkeleyTutorial1 Graph1."

To preserve this graph regardless of what other changes we make, click the **Lock icon** to the right of *Run* at the top left of the graph window (see Figure 3.1.11). Run the simulation again to generate another graph. To have *Berkeley Madonna* graph only population with respect to time, click the *growth* button on the bottom left of the graph window of Figure 3.1.11.

Quick Review Question 17 Describe changes to the graph.

Click the labels icon L to remove the unnecessary label. Easily restore the graph to its original form by clicking the *growth* button on the bottom left and clicking the labels icon L.

Double-click in the middle of the graph to once more reveal the axis-settings window. Select the *Scales* tab so that the window appears as in Figure 3.1.13. Uncheck the *Auto* checkbox for the *X Axis* and change the specifications to plot *population* and *growth* from 0 to 5 hours. Click *OK*. The ranges in the resulting graph in Figure 3.1.14 are such that the graphs appear almost horizontal at 0.

Figure 3.1.13 Axis-settings window, *Scales* tab, for graphs of *population* and *growth*

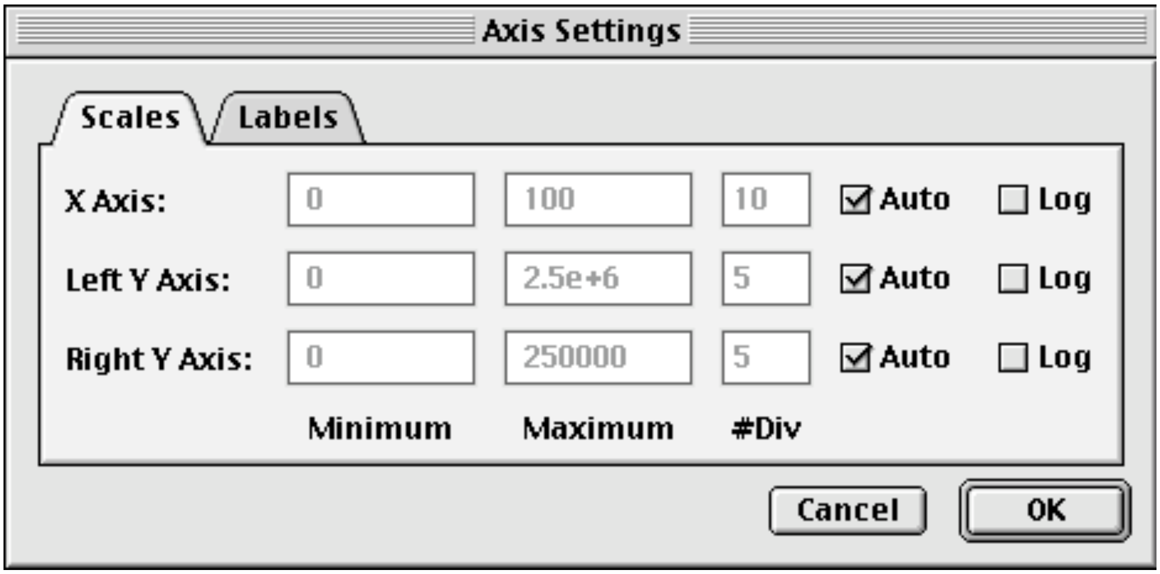
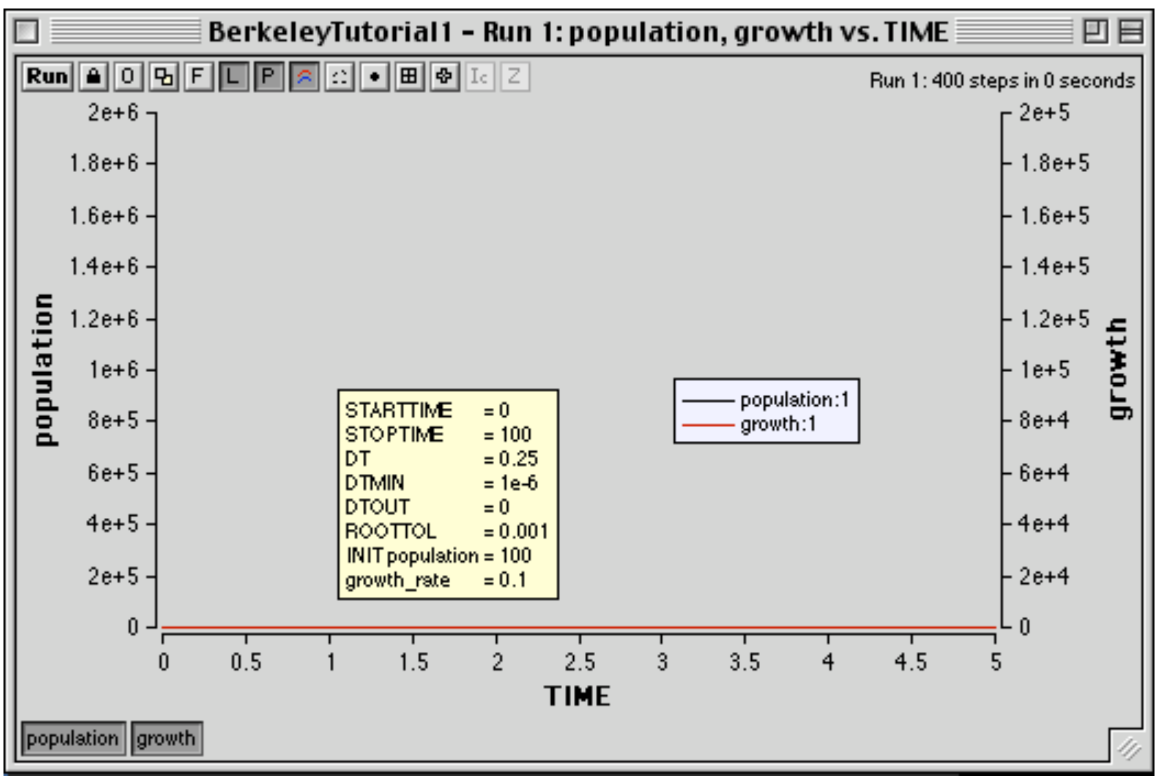


Figure 3.1.14 Graph of *population* and *growth* versus *TIME*



Quick Review Question 18 Describe how to change the scale for *population* to be from 0 to 150.

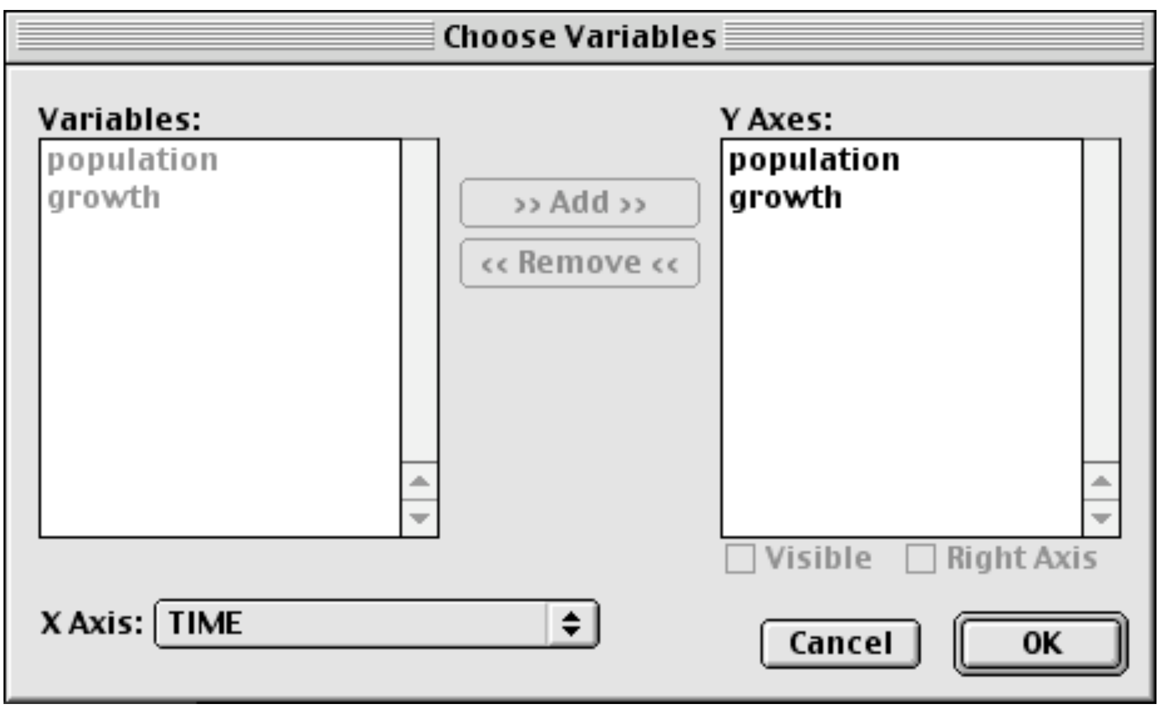
Change the range of *population* to be from 0 to 150 and for *growth* to be from 0 to 19. Without re-running, the graph immediately reflects the scale changes.

Quick Review Question 19 Notice that we still cannot see the entire *population* graph for the time period. What maximum to the nearest 10 (160, 170, 180 etc.) shows the entire graph from 0 to 5?

Quick Review Question 20 Describe the effect of unselecting the graph icon that has two rows and two columns of rectangles ( ).

Previously, we employed the buttons at the bottom of a graph window to designate the plots to display. For greater control of the associated axes, select ***Choose Variables...*** from the ***Graph*** menu or double-click in the middle of the graph. Suppose we wish to display only the graph of *growth* versus time with the scale for *growth* along the left vertical axis. In the choose-variables popup menu (Figure 3.1.15), double-click *population* from the *Y Axes* list. Alternatively, click once on the *population* line, and click <<*Remove*<<.

Figure 3.1.15 Choose-variables popup menu



Quick Review Question 21 After removing *population* from the *Y Axes* list, describe change to the *Variables* list on the left.

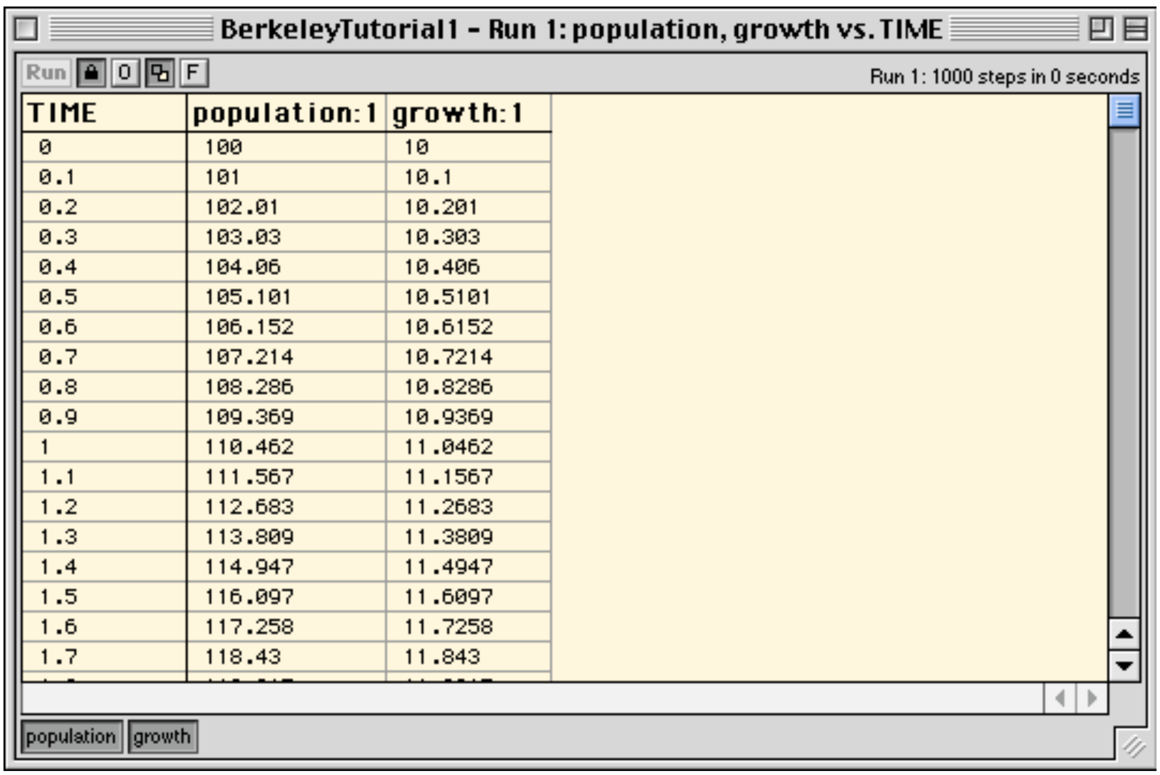
Select *growth* and uncheck its *Right Axis* checkbox, and click *OK*. Remove the label.

Quick Review Question 22 Describe the graph including placement of the *growth* axis.

Tables

Besides a pictorial view, we may want a table of values from the simulation. Make a copy of the first graph window, which contains the plots of *population* and *growth*, by selecting ***Duplicate Graph*** under the *Graph* menu. On the new graph window, click the **Table** icon ( ). The resulting table appears as in Table 3.1.2.

Table 3.1.2 Table window



TIME	population:1	growth:1
0	100	10
0.1	101	10.1
0.2	102.01	10.201
0.3	103.03	10.303
0.4	104.06	10.406
0.5	105.101	10.5101
0.6	106.152	10.6152
0.7	107.214	10.7214
0.8	108.286	10.8286
0.9	109.369	10.9369
1	110.462	11.0462
1.1	111.567	11.1567
1.2	112.683	11.2683
1.3	113.809	11.3809
1.4	114.947	11.4947
1.5	116.097	11.6097
1.6	117.258	11.7258
1.7	118.43	11.843

Quick Review Question 23 About how many hours does it take for the initial population to double?

In the case of a large table where *DT* is small, we may not want a list of values at every step of the simulation. For example, to display values every 10 simulation hours, we set ***DTOUT*** to 10 in the parameter window. Run the simulation using this setting.

Quick Review Question 24 How many rows of values appear in the table?

From the *File* menu select ***Save Table As...***, and save the table using a name such as "BerkeleyTutorial1 Table1." Because *Berkeley Madonna* saves the table as "Tab Delimited Text" or as "Comma Separated Values," you can open the file with spreadsheet or word processing software. Do so; type your name at the top; and print and close the resulting file. After printing, select *DTOUT* in *Berkeley Madonna*'s parameters window; and press *Reset* to reestablish the default value of 0, which indicates output should occur at every time step.

Sliders

We can change initial values and constants in the model by using the parameters window. In running our model for several situations, this process is tedious. However, **sliders** can help us perform an assortment of simulations quickly and view the results readily. A slider allows us to drag a slider bar to change a variable's value or click to increment or decrement by a designated amount. From the *Parameters* menu, select ***Define Sliders*** to obtain the popup menu of Figure 3.1.16.

Quick Review Question 25 In the define-sliders popup menu, give two ways to move *growth_rate* to the list of sliders.

Figure 3.1.16 Define-sliders popup menu

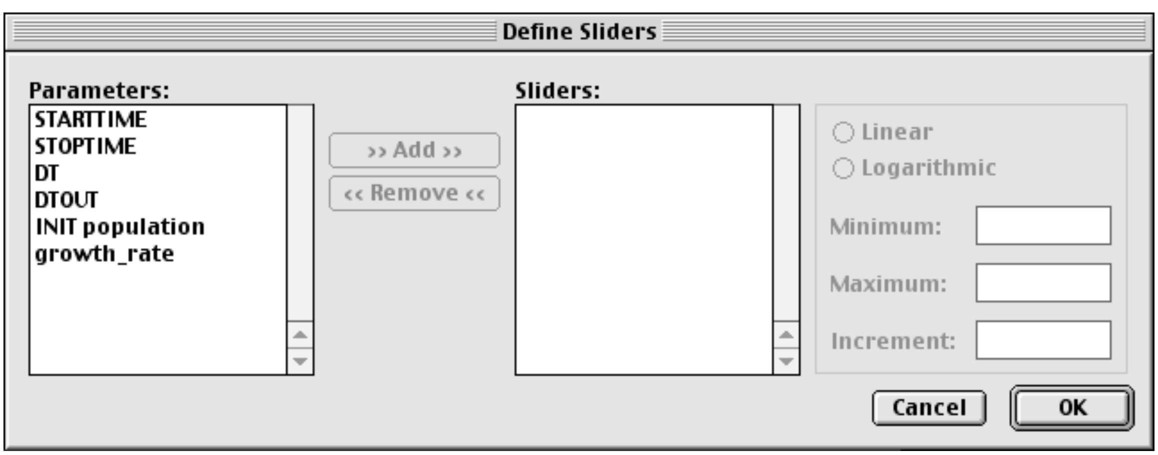


Figure 3.1.17 shows the window after designating that the slider bar for *growth_rate* has a minimum of 0, maximum of 0.3, and changes in increments/decrements of 0.01. Fill in the values and click *OK*. Your systems now should display a slider as in Figure 3.1.18. With the graph of *population* versus time visible, drag the slider bar and observe the impact on the graph.

Figure 3.1.17 Defining a *growth_rate* slider

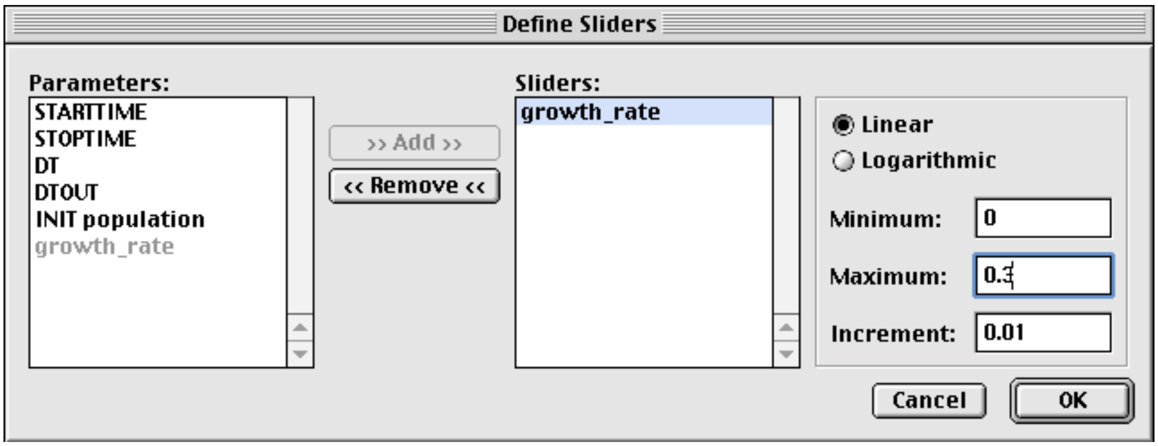


Figure 3.1.18 Slider for *growth_rate*

Quick Review Question 26 Click the arrows to the left of the slider bar to change the value of *growth_rate* to 0.03. Give the approximate population at 100 hr.

Print the flowchart, equations, and notes windows. You should have already saved and printed a graph *population* and *growth* versus *TIME* for *growth_rate* = 0.1 and a table of values for *population* and *growth* with *DTOUT* = 10. Save and quit *Berkeley Madonna*.

Reference

Macey, Robert, George Oster, and Tim Zahnley, 2000. *Berkeley Madonna User's Guide*, Version 5.0, University of California. http://www.berkeleymadonna.com