

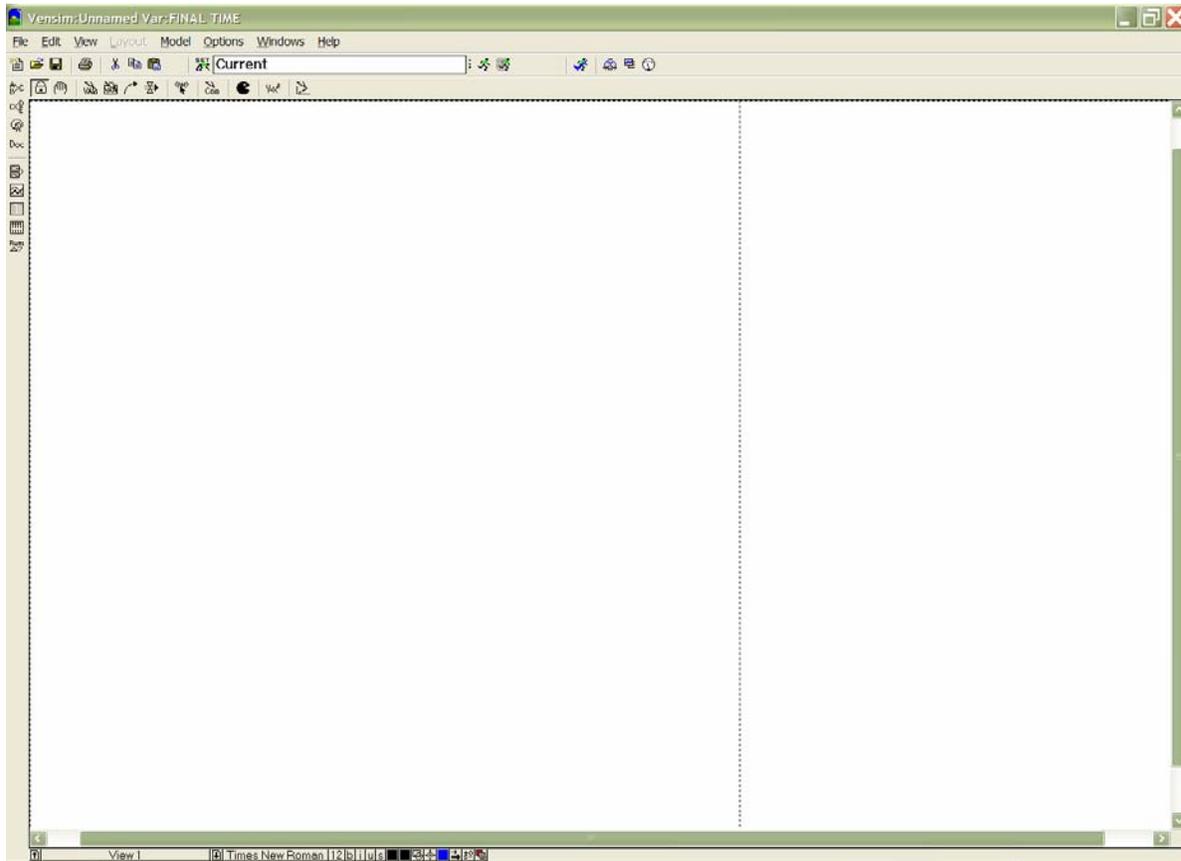
Tutorial

Formulating Models of Simple Systems Using VENSIM PLE

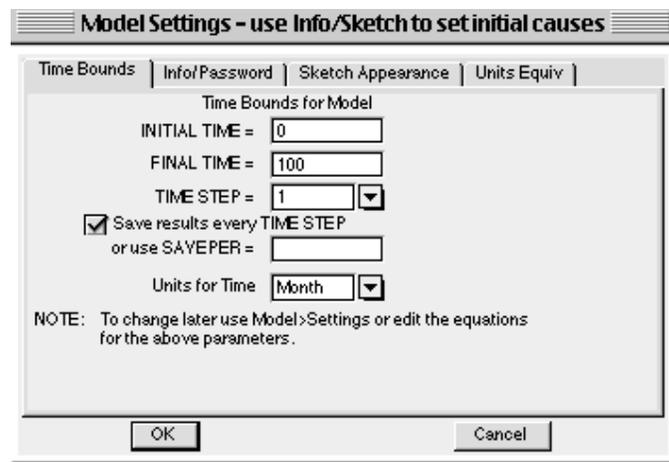
**System Dynamics Group
MIT Sloan School of Management
Cambridge, MA 02142**

I. Introduction and Getting Started

The purpose of this workshop is to help you develop some familiarity with building and analyzing system dynamics models using the VENSIM PLE software. To do this you are going to build a simple model of the federal deficit. To begin you need to get VENSIM PLE ready for modeling. When you first open VENSIM PLE on your computer, the screen should look like this:



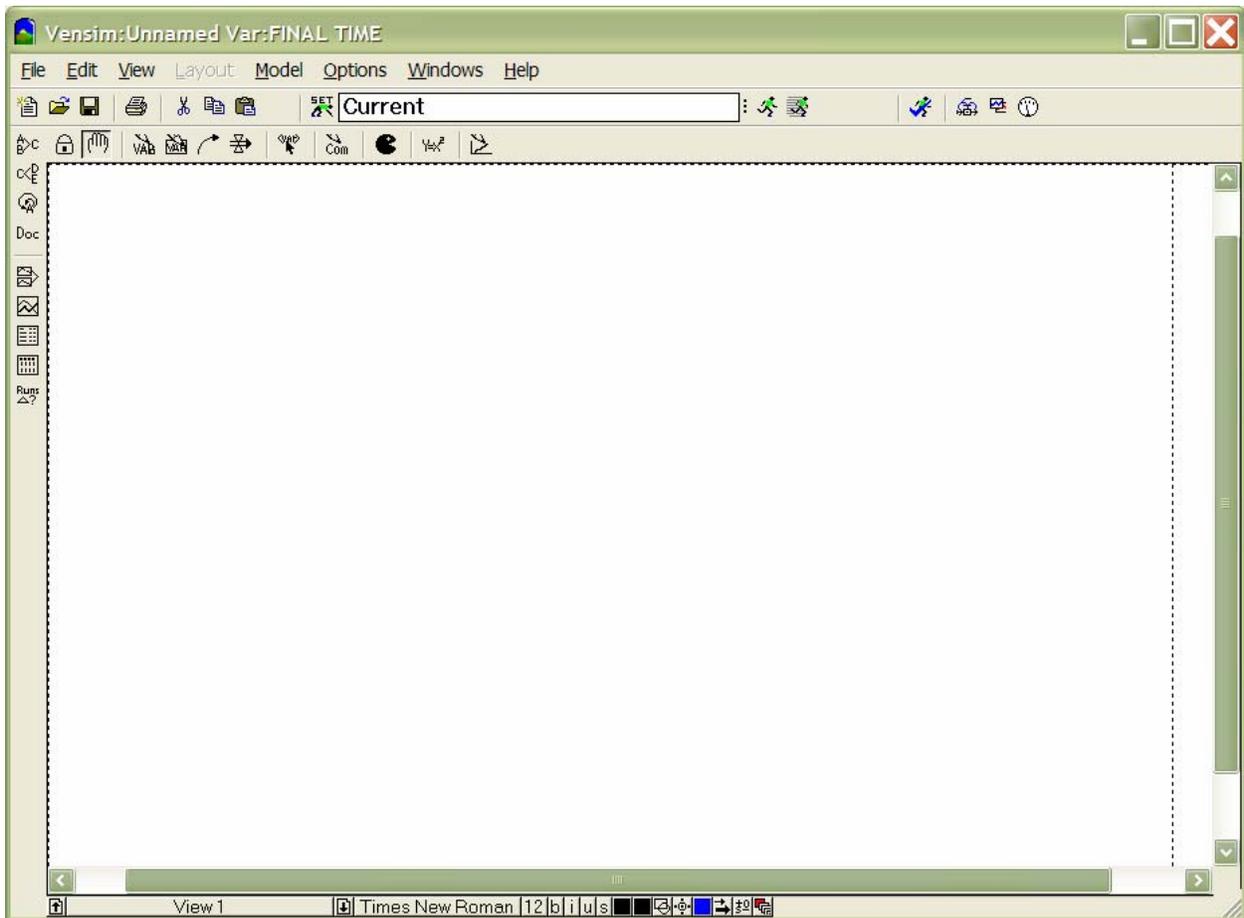
To start working on a new model go to the **File** menu and select **New Model**. VENSIM PLE will return the following dialog box:



You must choose the time horizon of your model (when your simulation will start and finish), the appropriate time step (how accurately you wish to simulate your model), and the units of time. Start your model of the deficit in 1988 (enter 1988 in the **INITIAL TIME** box) and simulate it through the year 2010. Select a time step of 0.25 years. Check the box saying “Save results every time step.” Finally, change the units of time from **Month** to **Year**.

Click on **OK** or hit return. To give your model a name, choose the **Save As...** command from the **File** menu and enter the desired name in the text field and click on OK. (VENSIM PLE will automatically supply the **.mdl** extension. If you are working with a different version of VENSIM and see a *Show all of type* option on the right side of the dialog box, make sure that the **.mdl Fmt Models** extension is selected. This allows VENSIM PLE to save the model in a format that can be used by both Macintosh and IBM-compatible computers.)*

Your screen should now look like this:



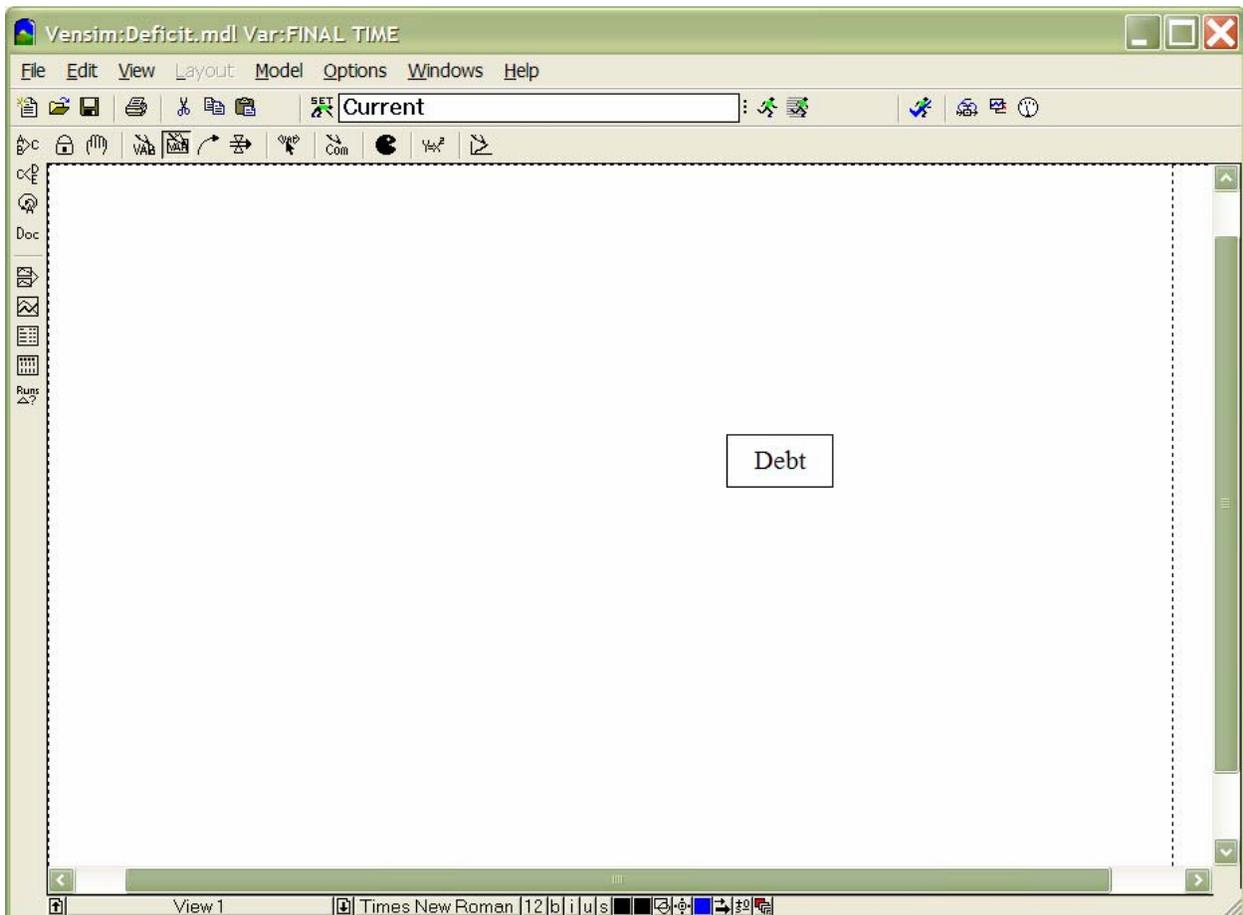
You are ready to start building your model.

* VENSIM saves every simulation run and custom graph you produce as a separate file. It supplies a **.vdf** extension for simulation runs and a **.vgd** extension for custom graphs. These files cannot be opened from outside the VENSIM application; they can be opened from inside VENSIM through the **Control Panel**.

II. Developing the Stock, Flow, and Feedback Structure

The VENSIM PLE software is designed using the metaphor of a “work bench.” The large blank area in the middle of the screen is your work area, where you actually develop and analyze your model. The different buttons on the border of the work area represent the different “tools” available as you work on your model. The tools on the top horizontal row are for building your model. The tools on the left vertical row are for model analysis. The tools on the bottom horizontal row allow you to change the formatting of the model diagram. You will become familiar with many of these tools as you build the deficit model.

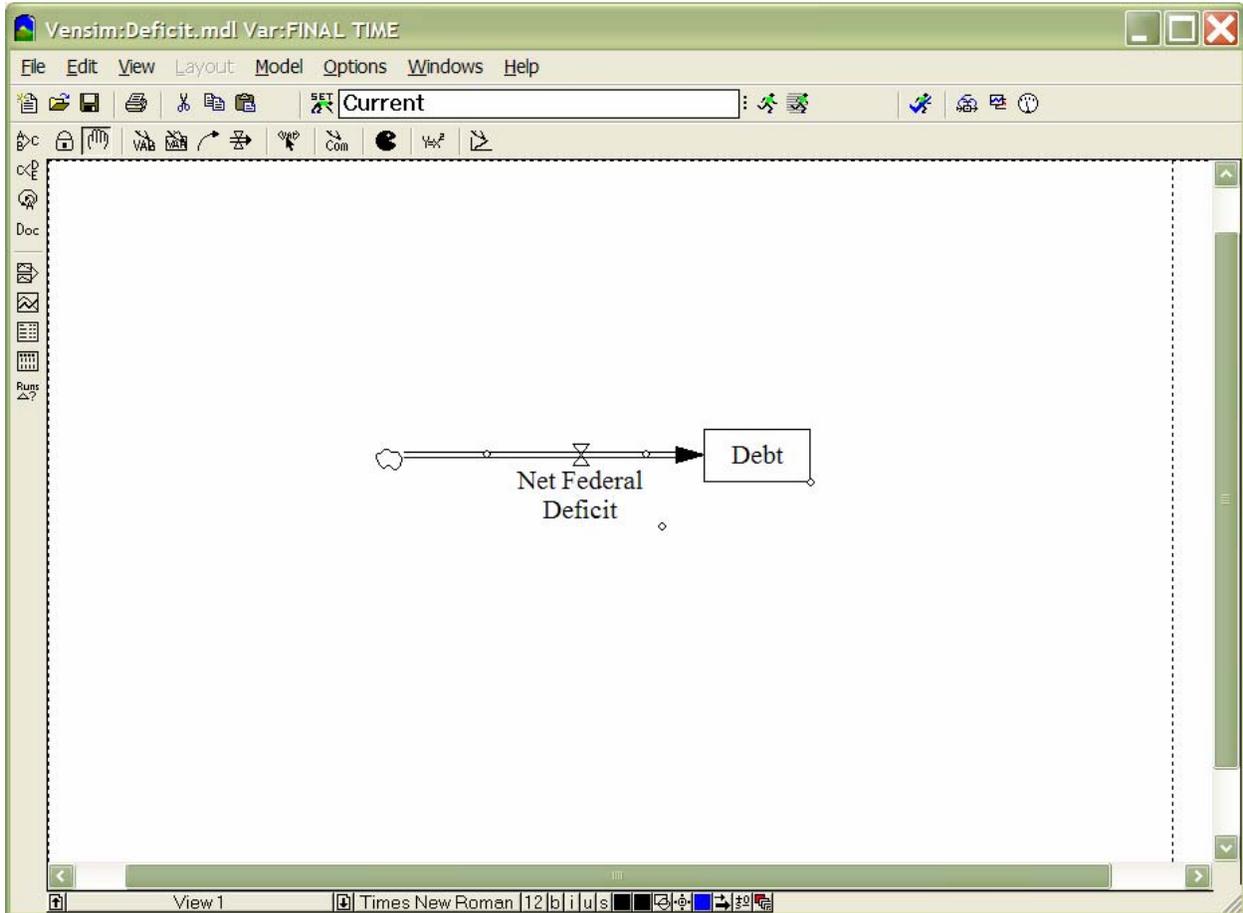
To begin, add a stock representing the outstanding federal debt to your model. To do this click on the  button (the one with the box in it) on the top horizontal toolbar and then click in the right center of the screen. You use this tool whenever you want to add a stock or level variable to your model. VENSIM PLE then returns an empty text box and a blinking cursor. Type the word **Debt** and then hit the return key. Your screen should now look like this:



You have just created the first variable in your model, the stock of money that constitutes the federal debt.

Now add the inflow to the stock of debt. Click on the  button in the top horizontal tool menu. Now, click and release once to the left of the Debt stock, move the cursor so that it sits *inside* the Debt stock, and click and release again. VENSIM PLE then gives you an empty text box and a blinking cursor. Type **Net Federal Deficit** and hit the return key.

Your screen should now look like this:



Note: The  icon (which is supposed to resemble a cloud) represents the boundary of your model. In this case the “cloud” on the left side of the flow signifies that you do not, at the moment, care about where the deficit comes from--you are not keeping track of the stock that is being drained by the deficit flow. You do care, however, where the deficit goes: hence you are accumulating it in the Debt stock. If your deficit flow has “clouds” on both ends, then you haven’t hooked the flow to the stock correctly. To fix this, click on the  tool and then click on the flow valve. This action will remove the flow from the model and let you start over again.

You have now created the flow, **Net Federal Deficit**, which increases the stock of **Debt**. At this point you may wish to change the name of the stock variable from **Debt** to **Federal Debt**. To do this, click on the  button (the one without the box in it) on the top horizontal toolbar and then click on the **Debt** stock. VENSIM PLE gives you a text box with **Debt** already

written. You can now edit the text in any way you choose. Click in front of the **D**, add the word **Federal**, and press the return key.

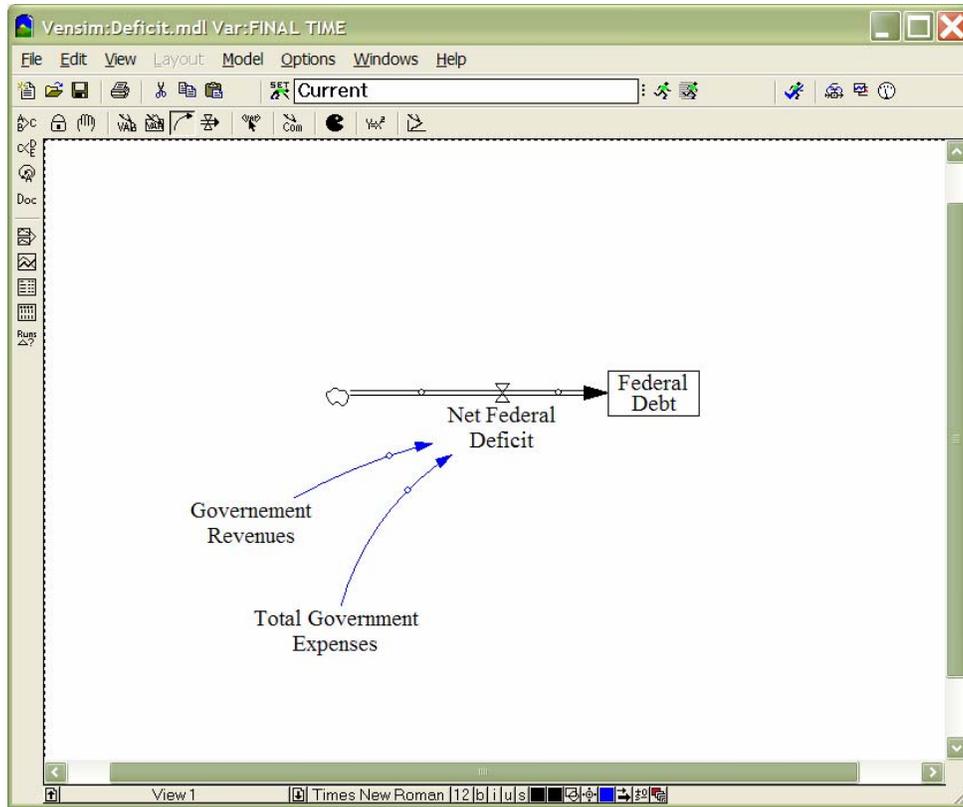
Now you need to create the variables needed to determine the **Net Federal Deficit**. Assume the **Net Federal Deficit** is determined by two variables, **Government Revenues** and **Total**

Government Expenses. Click on the  button again and add these two variables to your diagram (click and release on the work area, type the variable name, hit return, and then click and release again, on a different part of the work area, to add the next variable). Unlike the previous two variables--**Federal Debt**, which was a stock, and **Net Federal Deficit**, which was a flow

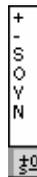
--the new variables are not attached to a valve or a box. These are called *auxiliary variables*.

To show pictorially that the **Net Federal Deficit** is determined by **Government Revenues** and **Total Government Expenses**, we connect them with causal arrows. First click on the  button to select the causal arrow tool. Now, click and release on the variable **Government Revenue** and then click and release again on **Net Federal Deficit**. Do the same for **Total Government Expenses**. Make sure your causal arrows actually end on the words **Net Federal Deficit**. They should *not* be attached to the cloud, the stock, or directly to the valve. You can delete arrows using the  tool.

Clicking on the  button allows you to select the variables you have created and move them to different places on the screen. To do this, place the arrow cursor over the variable you wish to move, hold down the mouse button, move the variable to the desired place, and then release the mouse button. You can also select the “handles” of the causal arrows (the small circles in the middle of the arrow) and change the curvature of the arrow. Arrange your variables and arrows so that your diagram looks approximately like this:



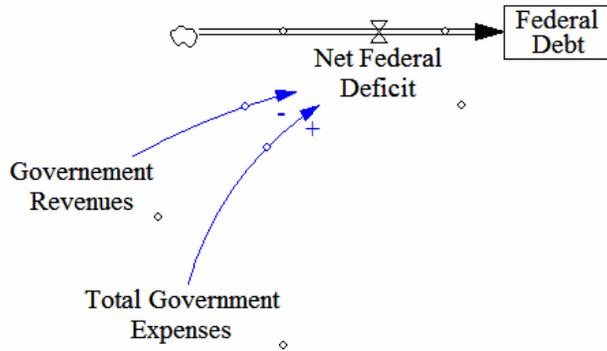
Now, you may want to update your diagram by labeling the arrows to show that **Government Revenue** and **Total Government Expense** affect the **Net Federal Deficit** in different ways. Specifically, an *increase* in revenue causes the deficit to *decrease*, while an *increase* in expenses causes the deficit to *increase*. To do this, first click on the  button. Then select the “handle” of the arrow you wish to label by clicking and releasing on the small circle in the middle of the arrow (the handle darkens when selected). Now, with the handle selected, click and release the  button on the bottom horizontal toolbar. You then see a pop-up menu that looks like this:



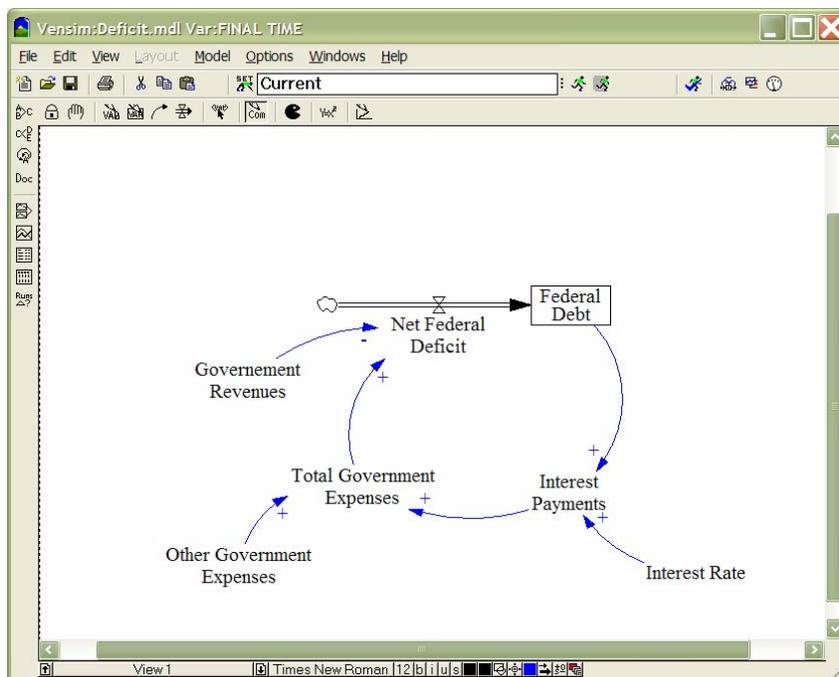
Click and release on the desired label, and it will show up in the diagram.

As a side note, to indicate a delay in a causal arrow, right click it with the “hand” selected. You can click on “Delay marking” to show a delay in an arrow. You also have the ability to move the polarity mark to the inside or outside of the arrowhead, which may make it easier to see when there are many links coming in to a single variable.

Label your two causal arrows so your diagram looks like this:

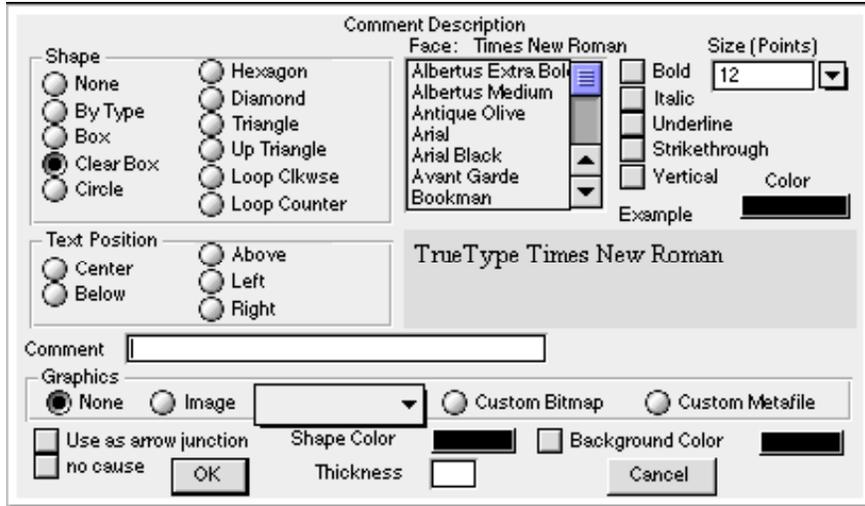


Now, using the same steps discussed above, complete the stock, flow and feedback so your diagram looks like this:

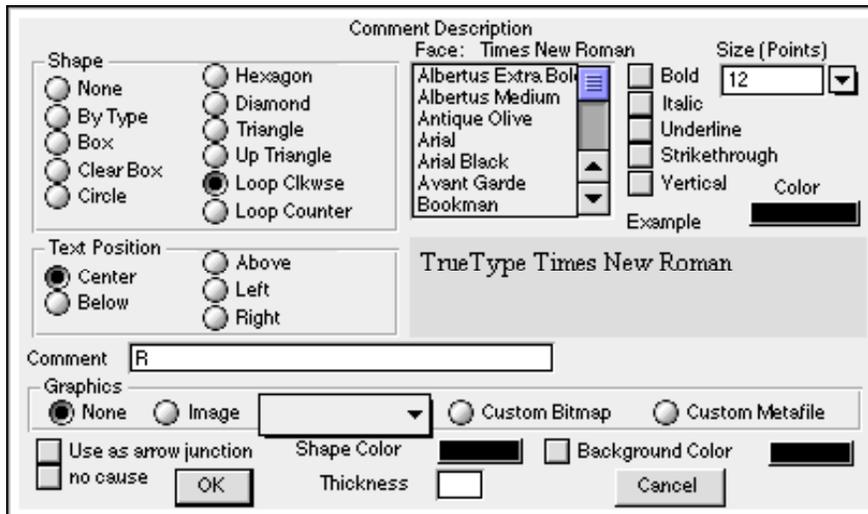


You may want to slide the handle of each arrow close to its arrowhead, so each label is clearly associated with its causal arrow.

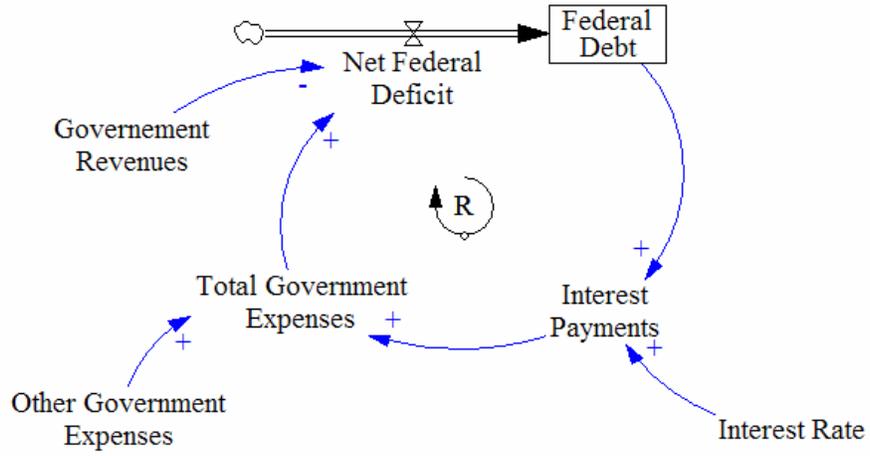
Finally, you may wish to label the positive feedback loop you have just created. To do this, click on the  button and then click in the center of the feedback loop. You can use this tool to create comments that, while having no structural use, can greatly help someone else understand your model diagram. After clicking in the center of the loop, you should see the following dialog box:



Click on the **Loop Clkwise** button in the **Shape** box; click on **Center** in the **Word Position** box; and type **R** in the **Comment Type** box. Your screen should now look like this:



Click on the **OK** button or hit return. Your screen should now appear as:

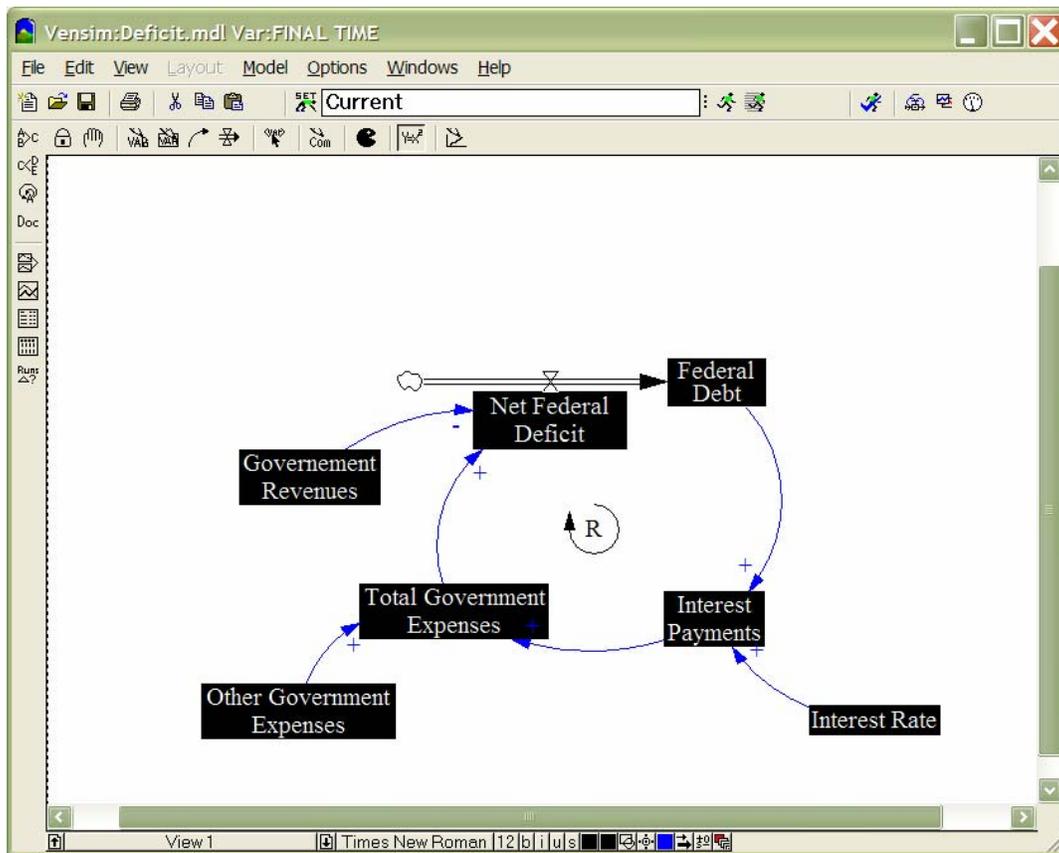


Use the comment tool again to add a name to your loop by clicking underneath the “R” and adding a name such as “Compounding Interest”.

III. Specifying Equations for Your Model

Now that you have developed a complete stock, flow, and feedback representation of the deficit, you need to write equations for each of the variables. Equation formulation is a critical step in the process of model building and is a key part of the process of developing a rigorous understanding of the problem at hand.

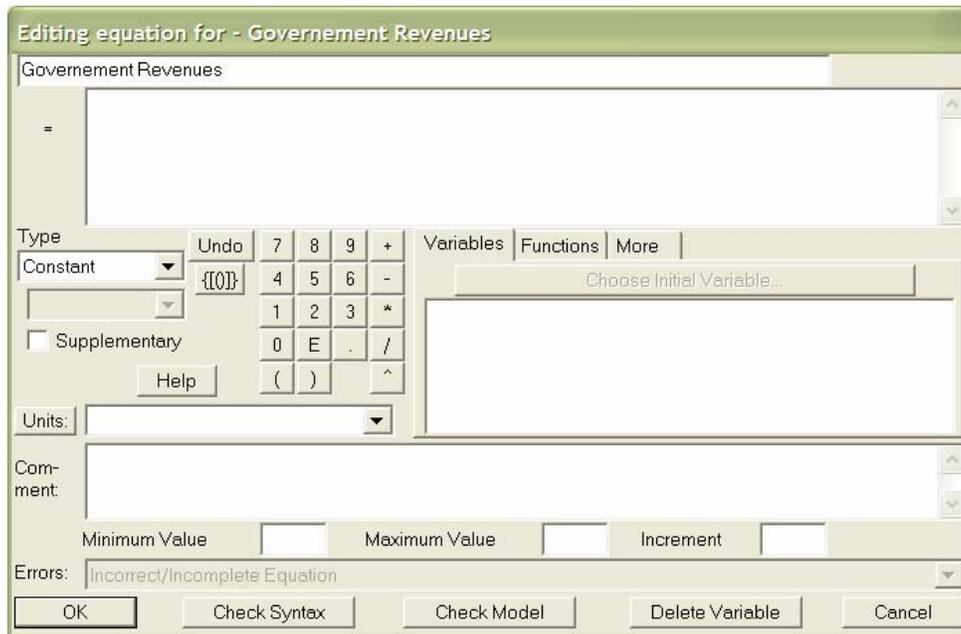
To begin writing equations, click on the  button on the *top horizontal toolbar*. The variables in your diagram become highlighted.



A highlighted variable indicates that the equation for that variable is incomplete.

Variables in system dynamics models are classified as either exogenous or endogenous. Exogenous variables are those that are not part of a feedback loop, while endogenous variables are members of at least one feedback loop. Your deficit model has three exogenous variables--**Government Revenue**, **Other Government Expense**, and the **Interest Rate**--and four endogenous variables--**Interest Payments**, **Total Government Expense**, **Net Federal Deficit**, and the **Federal Debt**.

Start by writing the equations for the exogenous variables. To begin, click on the highlighted variable **Government Revenue**. You then see the following dialog box:



Good modeling practice requires that each equation in a model have three elements, the equation itself, specified units of measure, and complete documentation. You enter the equation in the box to the right of the = sign. You enter the unit of measure in the text field to the right of the word **Units**. Equation documentation or “comment” is entered in the box to the right of the word **Comment**.

To write an equation for Government Revenue, click in the box to the right of the = sign. Assume that government revenue is constant, so that all you need to do is enter the appropriate number for government revenue.

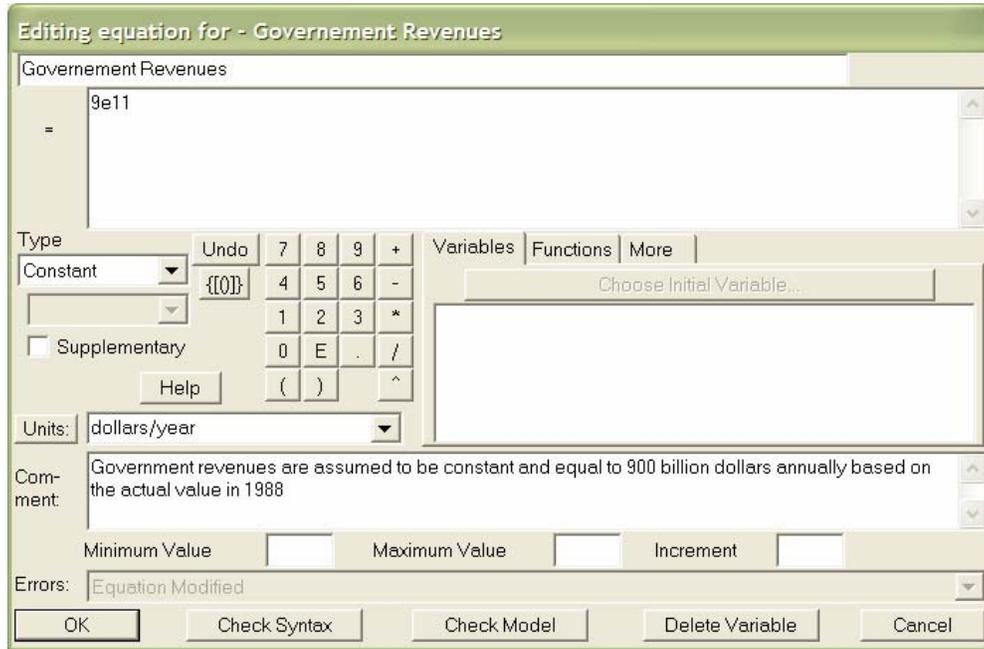
Government revenue was about 900 billion dollars annually in 1988, so type 900000000000 in the box. Alternatively you can write 9e11 which is VENSIM PLE shorthand for 9×10^{11} .

Now fill in the units. Revenue is a flow variable, so the appropriate unit of measure for this equation is dollars/time unit. Since you already chose to run the model in time steps of 1 year, the appropriate unit is dollars/year. Type **dollars/year** in the units field. (The next time you specify the units for a variable in this model, dollars/year will appear in the units pull-down menu. You can click on the arrowhead to the right of the units field to see units already specified for other variables in the model, and then use the mouse to select from that list when appropriate.)

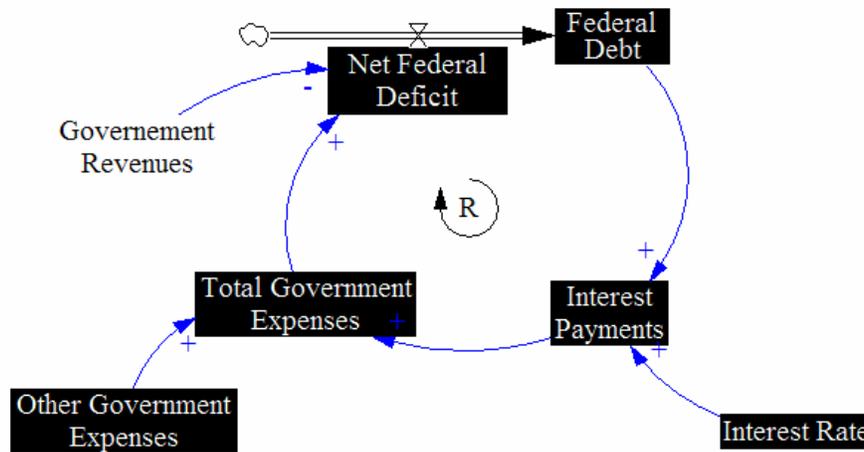
Finally, provide a description of this equation in the comment field. A good comment will be brief but also give the reader some sense of the logic behind the equation as well as state the key assumptions. For example, one might write for this equation:

Government revenues are assumed to be constant and equal to 900 billion dollars annually based on the actual value in 1988.

Your dialog box should now look like this:



Click on **OK** or hit return and your diagram will look like this:



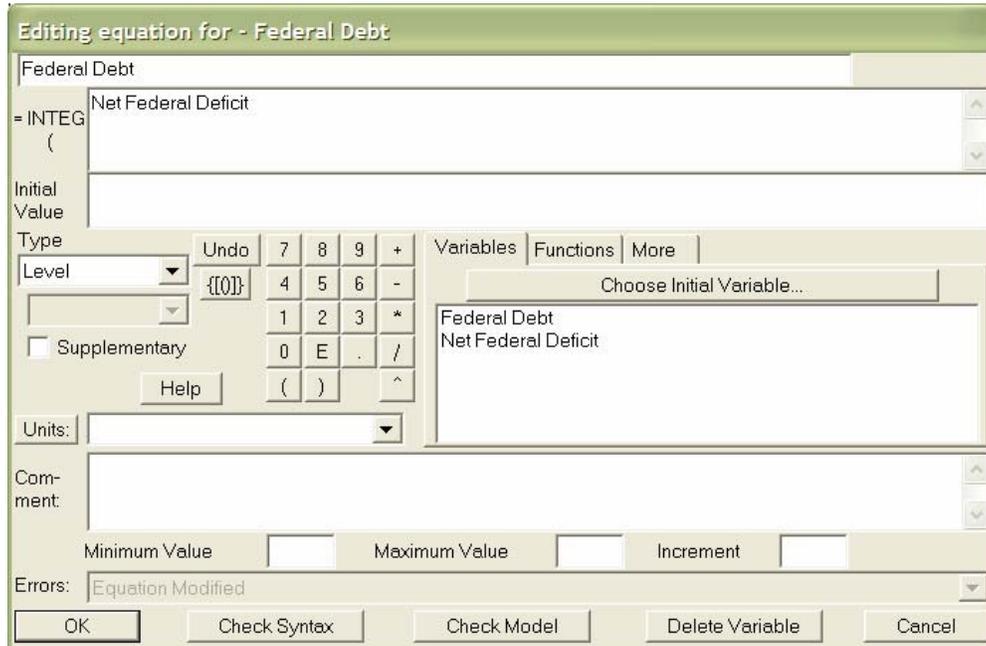
Government Revenues is no longer highlighted, since you have just specified its equation.

Following the process above, write equations for the two other exogenous variables, **Interest Rate** and **Other Government Expense**. Use the following information:

- Government expenses, excluding interest on the debt, were approximately 900 billion dollars in 1988.
- The interest rate paid on the national debt in 1988 was around 7%/year.

With the equations formulated for the exogenous variables, now turn your attention to the endogenous variables. Writing equations for the stocks and the flows is a little different, so let's do an example of each. First we formulate the equation for the stock, **Federal Debt**.

Again, click on the  button in the top horizontal toolbar and then click on **Federal Debt**, which displays the following dialog box:



Unlike flows and constants, a stock requires an additional element specified for its formulation. After you specify the equation, you need to select an initial or starting value.

You enter the equation for the stock in the box to the right of the word **Integ**. **Integ** stands for “integrate” and simply means that the stock at any moment in time is equal to the sum of all the inflows minus the sum of all the outflows plus the initial value.

When you created the stock, flow, and feedback diagram, you connected the flow **Net Federal Deficit** to the stock **Federal Debt**. VENSIM PLE captures this stock-flow dependency by providing a list of the required **Inputs** to the stock **Federal Debt** on the left side of the equation dialog box. (The variable we are formulating, Federal Debt, itself also appears in the **Inputs** box, but we focus on the input **Net Federal Deficit**. In general, you will never want to have the same variable on both the left and right sides of an equation.)

Because the model diagram shows the flow **Net Federal Deficit** feeding into the stock **Federal Debt**, VENSIM has anticipated that the flow is an input to the stock equation and placed the **Net Federal Deficit** variable name in the box to the right of **Integ**. If this is not the case in your version of VENSIM PLE, then your model diagram is incorrect and needs to be changed—make sure the flow is attached to the stock).

The **Integ** box should now look like this:



Below **Integ** box is the **Initial Value** box. Here you enter the initial condition or starting point for the stock. The outstanding federal debt was approximately 2.5 trillion dollars in 1988, so enter 2500000000000 in the initial value box (alternatively you can write 2.5e12 which is VENSIM PLE shorthand for 2.5×10^{12}). The **Initial Value** box should look like this:

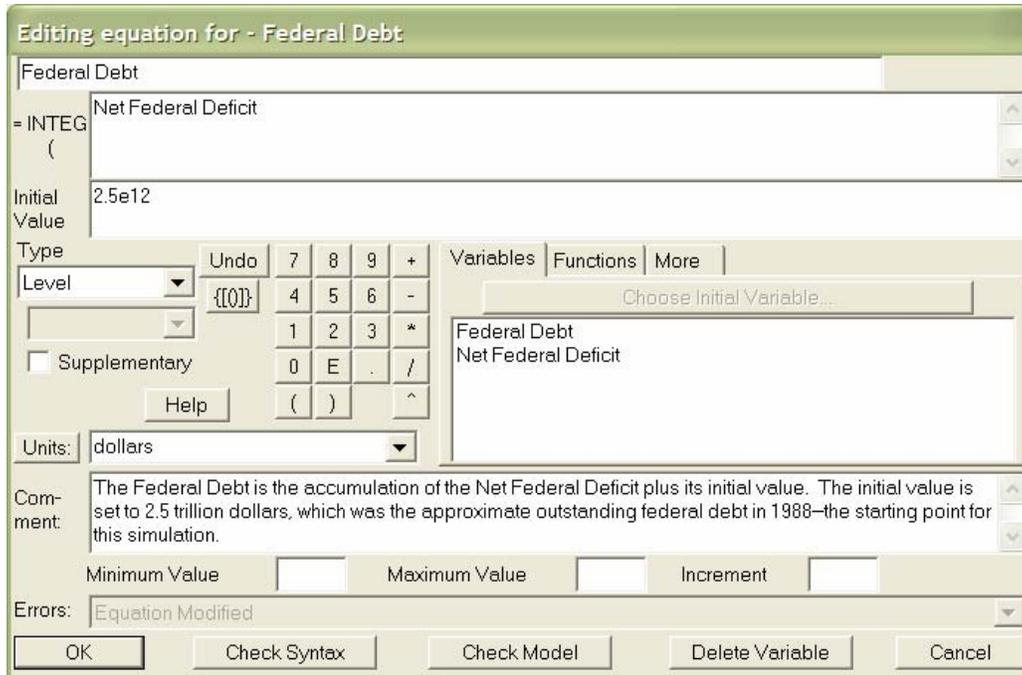


Now the equation specification for the **Federal Debt** stock is complete. Your equation indicates that the federal debt is simply the accumulation of the **Net Federal Deficit** since 1988 added to the initial value.

You still need to specify the unit of measure, however, and document your equation in the comment field. The units should be fairly straightforward. The **Federal Debt** is a stock and its units are dollars. Useful comments briefly explain the structure of the equation and highlight the key assumptions made. A sample comment for **Federal Debt** is:

The Federal Debt is the accumulation of the Net Federal Deficit plus its initial value. The initial value is set to 2.5 trillion dollars, which was the approximate outstanding federal debt in 1988--the starting point for this simulation.

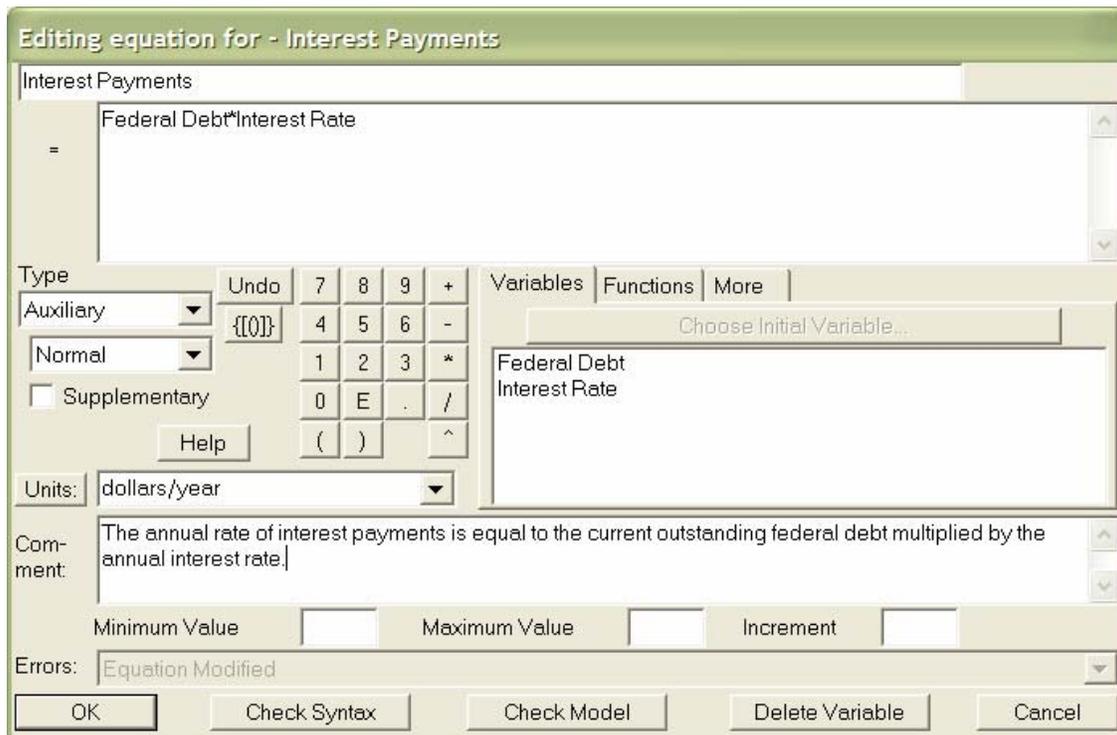
Your dialog box should now look like this:



Click on **OK** or press return.

Now you need to specify the equations for the flow and the auxiliary variables.

Again using the  tool on the top horizontal toolbar, click on the **Interest Payments** variable. You should see a dialog box that looks like this:



This box is identical to those used to specify the exogenous variables, but there are two other variables in the required **Inputs** box. When you developed the stock, flow, and feedback diagram, you drew causal arrows connecting the variable **Federal Debt** and constant **Interest Rate** to the variable **Interest Payments**. VENSIM PLE has conveniently recognized this and provided a list of the required inputs to your equation based on the picture you have already created. In fact, if you try to write your equation without using the two required inputs, VENSIM PLE will give you an error message.

The rate of interest payment is simply equal to current debt level multiplied by the interest rate. To enter this equation first click on the **Federal Debt** variable in the **Inputs** box. It now appears in the equation box. Now type * (alternatively you can click on the  button), and then click on the **Interest Rate** variable in the **Inputs** box. Your equation box should now look like this:



To complete the equation, you need to specify the units and document your equation in the comment field. An appropriate comment might look like the following:

The annual rate of interest payments is equal to the current outstanding federal debt multiplied by the annual interest rate.

The dialog box for the variable **Interest Payments** should now look like this:

Editing equation for - Interest Payments

Interest Payments

= Federal Debt*Interest Rate

Type: Auxiliary (Normal) Supplementary Help

Units: dollars/year

Comment: The annual rate of interest payments is equal to the current outstanding federal debt multiplied by the annual interest rate.

Minimum Value: Maximum Value: Increment:

Errors: Equation Modified

Buttons: OK, Check Syntax, Check Model, Delete Variable, Cancel

Calculator interface showing: Variables (Federal Debt, Interest Rate), Functions, More, Choose Initial Variable...

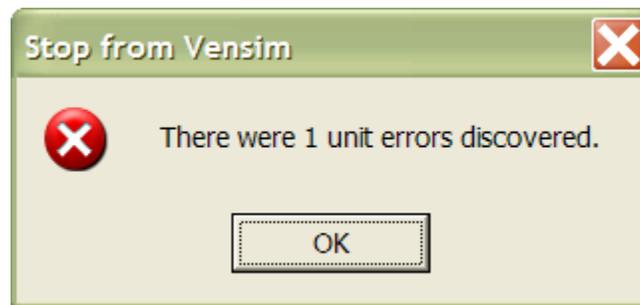
Following a similar process to the one outlined above, you should now be able to complete your model.

IV. Using the Model Structure Analysis Tools

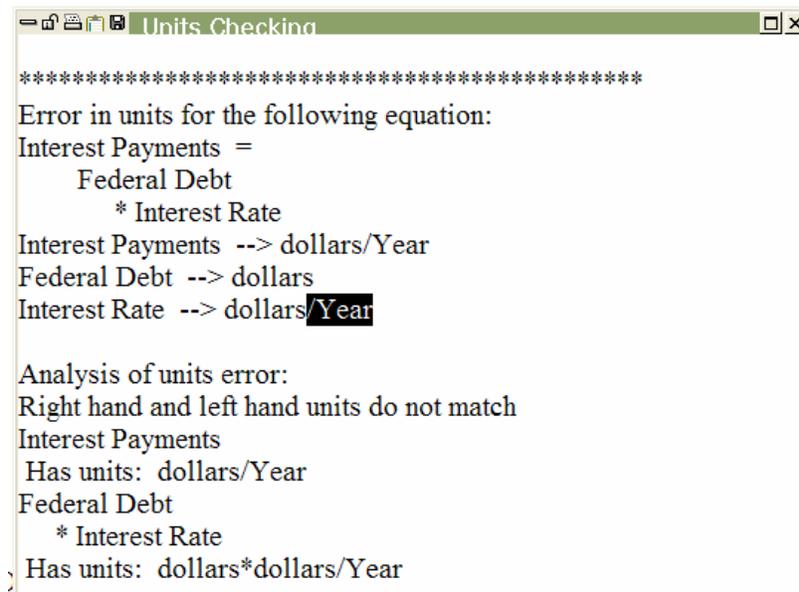
VENSIM PLE provides five tools for analyzing and understanding the structure of your model. The tools are represented by the top five buttons on the vertical toolbar on the left edge of the screen.

By far the most important of these is the unit-checking function. To access this tool, go to the **Model** menu and select **Units Check**.

An important feature of any system dynamics equation is *dimensional consistency*. This is just a fancy way of saying that the units of measure must be the same on both the left and right sides of the equation. As an example, suppose you had chosen the units of the **Federal Debt** stock to be dollars and the units of the **Interest Rate** to be dollars/year. If this were the case, then a units check would yield the following message:



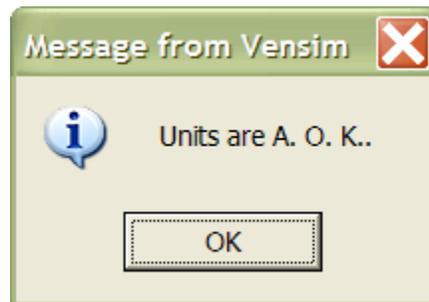
Followed by:



The problem is that, in this example, the equation for **Interest Payments** is not dimensionally consistent: The right and left sides of the equation have different units. The flow **Interest**

Payments is measured in dollars per year. The **Federal Debt**, because it is a stock, is measured in dollars. Multiplying this by something with units in dollars/year results in a quantity that has units in dollars²/year--hence the error.

The cause of the problem is that unit of measure for **Interest Rate** is incorrect. The interest rate is not measured in dollars per year. An easy way to see this is to recognize that the interest rate really has nothing to do with the dollars. It could easily apply to any other currency or any other type of measurement unit. The interest rate is really the ratio of the interest payment you must make each time period to the amount you owe. As a result, the appropriate unit of measure for **Interest Rate** is (\$/year)/\$ or 1/year. If you enter 1/year into the unit field of the interest rate variable--run the units check, you should get:



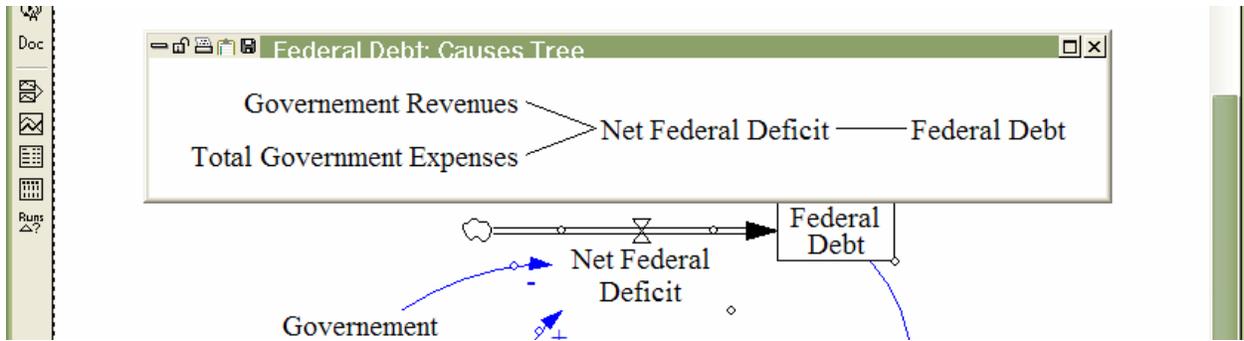
The units in your model now balance.

In this example, the unit-checking tool identified an incorrect assumption in a common mental model of the interest rate. Dimensional consistency is an essential requirement in all models, and VENSIM PLE's unit-checking feature often helps you identify serious flaws in both your understanding of the system under consideration and your resulting model formulations. Always make sure that the units in your model balance!

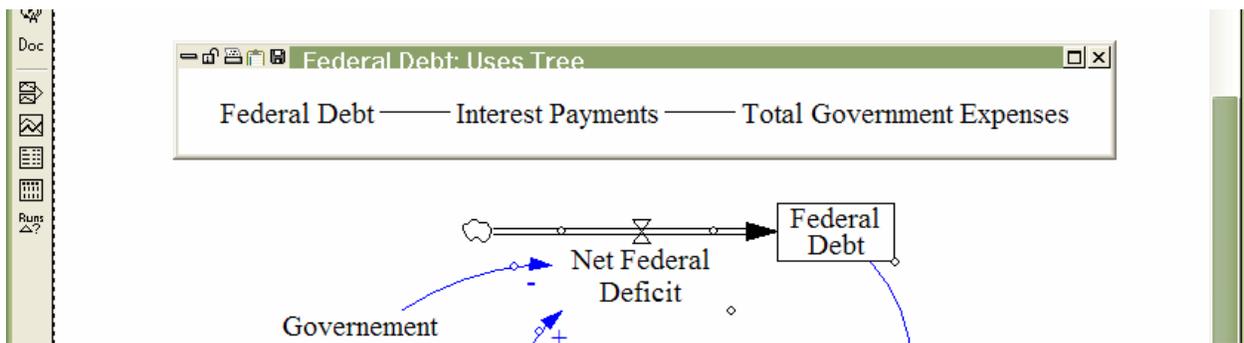
The other tools can also be useful. The  and the  buttons create "causes" and "uses" trees for the selected variable. To use these tools, you need to first "select" a variable. Do this by first clicking on the  button and then double-clicking on the variable you wish to select. You can tell which variable is selected by looking at the top border of the VENSIM PLE window. If you select the variable **Federal Debt**, the top border will look like this:



Having selected **Federal Debt**, clicking on the two "causes" and "uses" buttons in sequence gives you:



and



The  tool identifies all the feedback loops in which the selected variable is a member, and the  button creates a documented listing of the equations in your model.

V. Simulating Your Model

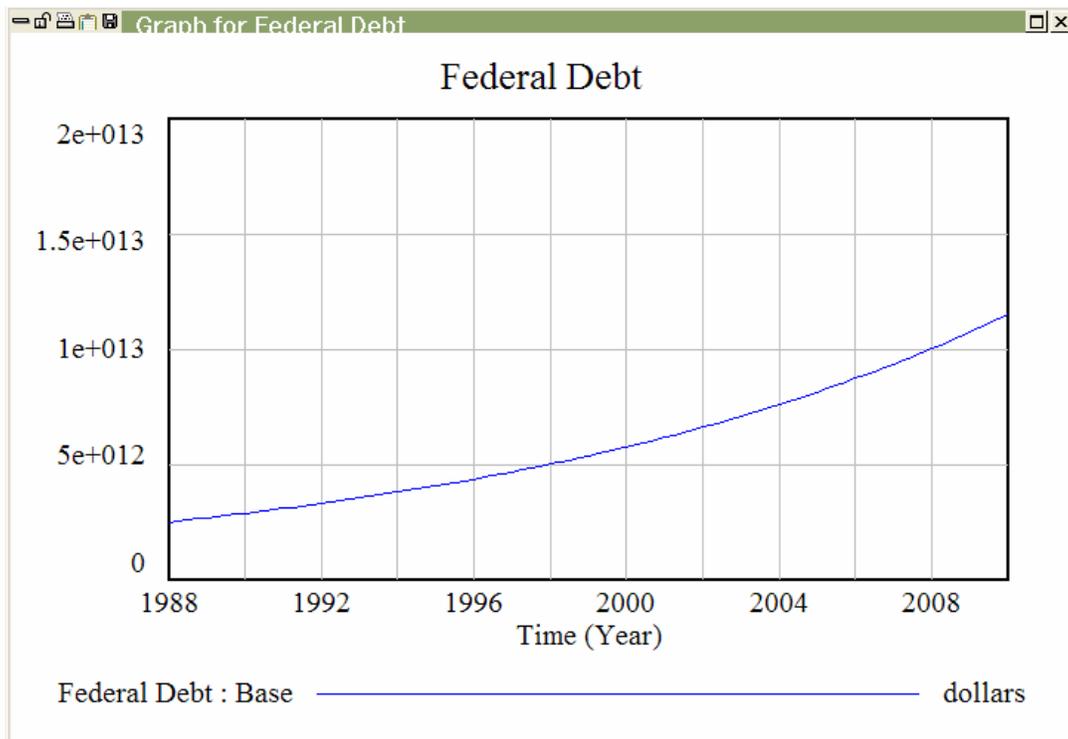
VENSIM PLE also has tools to help you analyze the behavior of your model. Before doing this, however, you must actually simulate the model so you have some behavior to analyze.

To run a simulation, you first need to choose a name for this particular model run. It is helpful to choose names that suggest some idea of what is being tested rather than simply using name like SIM1, SIM2, etc. Since this is the base case run for your model, you might choose to call the run **BASE**.^{*} The name of the simulation is entered in the white box in the analysis tool bar. The default name for any simulation run is **Current**. Change this to **Base**.

To run a simulation, click the  button and your model will start simulating.

Once the simulation run is completed, you can look at the results of your simulation. VENSIM PLE provides many tools with which to view simulation output. The most basic, and often most useful, of these is the strip graph. To create a graph of the **Federal Debt**, first click on the  tool and then double-click on the stock to select the variable **Federal Debt**.

To get see a strip graph, click on the  button in the left toolbar. You then see:

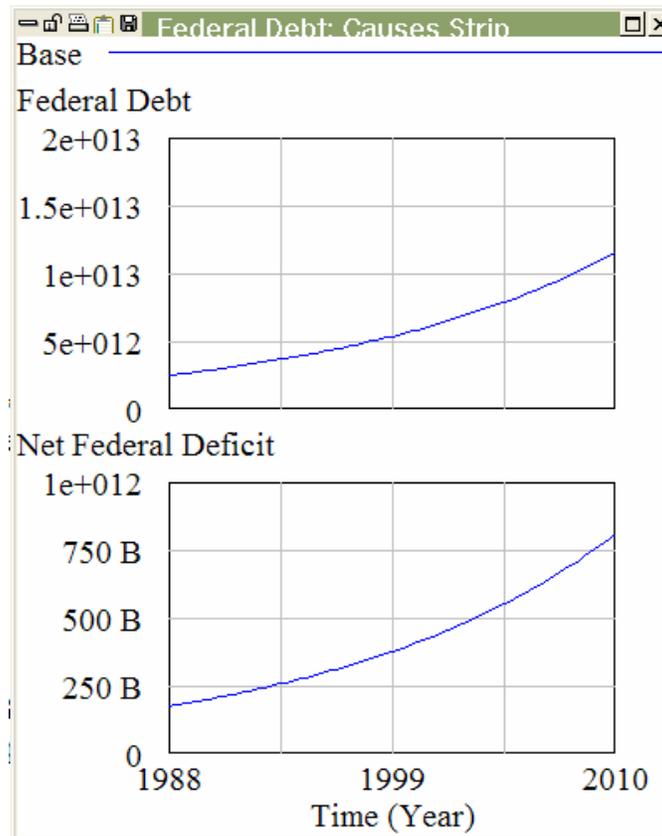


^{*} Advanced Tip: VENSIM PLE also offers you the choice of two numerical integration methods, Euler and Runge-Kutta 4. Runge-Kutta 4 is a more accurate simulation method, but it is also more computationally intensive. Generally it is better to use the Euler method and change only if you believe you are seeing integration error. Read *Business Dynamics*, Appendix A, for further details.

Given the current assumptions in the model, by the year 2010, the federal debt grows to more 10 trillion dollars, four times its value in 1988.

Besides the strip graph, VENSIM PLE provides many other ways to examine simulation output.

The  button displays a strip graph of the currently selected variable, along with graphs of all the variables that determine the selected variable (the causes). Clicking this button gives you:



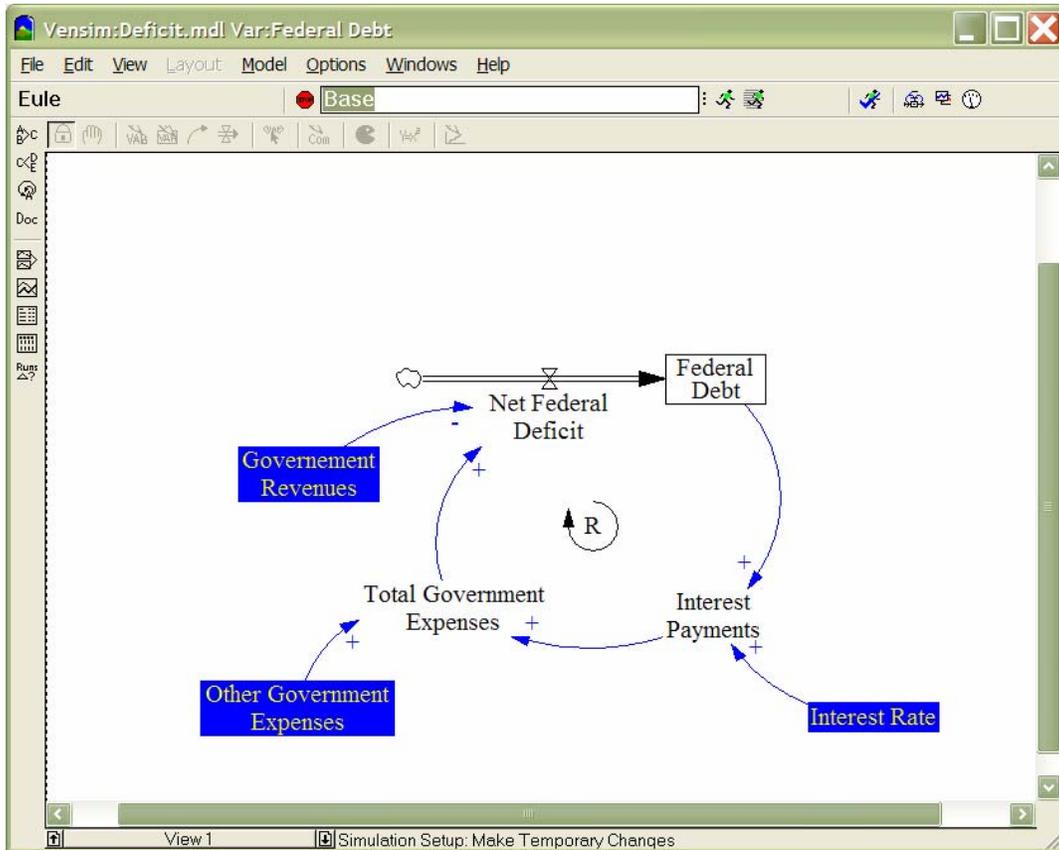
VENSIM PLE also can present the output in the form of a table rather than a graph. To see a table simply click on the  button.

Having analyzed all this simulation, you may wish to run additional simulations under different assumptions. For example, what might happen if the prevailing interest rate were 3.5% rather than 7%?

One way to do this is simply to change the model equation in the variable's equation box. This is time-consuming and error-prone, however, since you must remember to go back and change the parameter back to its original value before testing another assumption. If you change a variable's formulation in its equation box, it remains as you specify until you change it again. So, if you want to alter a variable's value only once, to observe its effect on the simulation, and then have the variable revert to its original value, you can use the Parameter Changes button,

accessible on the analysis tool bar. Test the effect of the interest rate on the federal debt by doing the following.

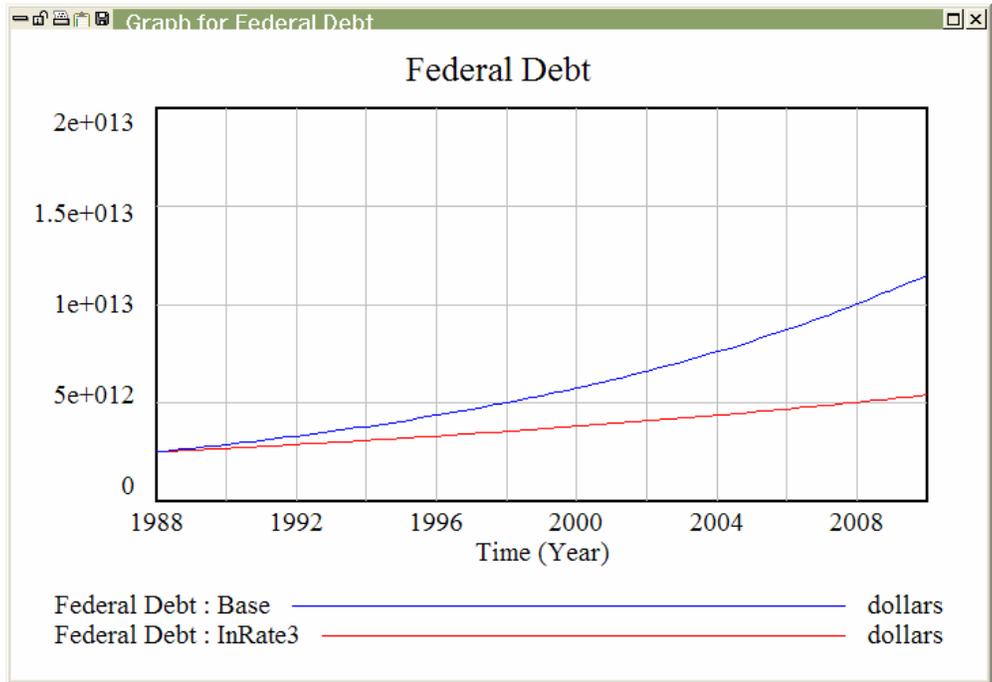
Click the  button. Your screen should now look like this:



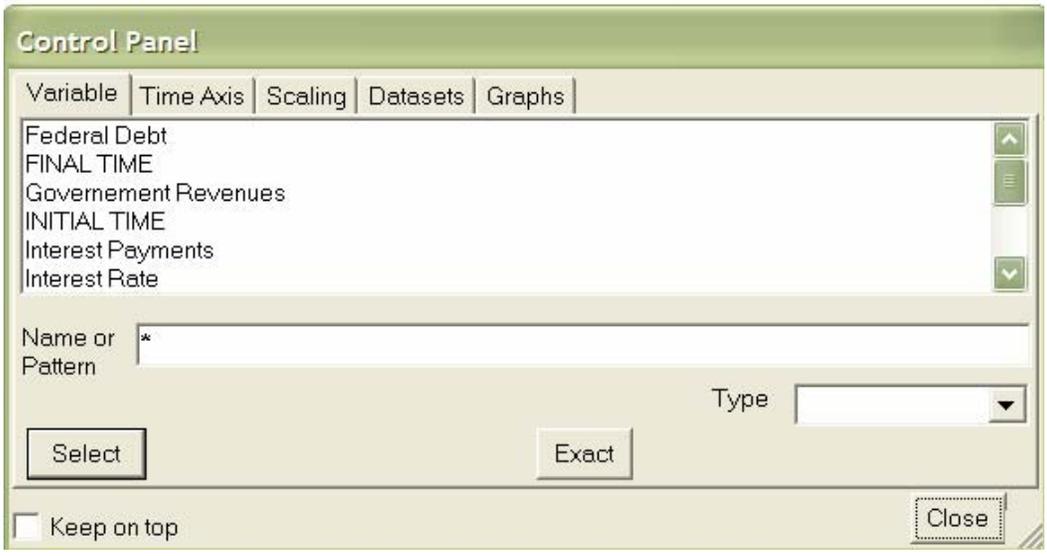
To change the interest rate for this simulation, click on **Interest Rate** and its current value, .07, will appear in a box. Change that value to .035 and hit **return**. Before simulating, make sure you the name of the simulation so that you can compare the two different runs.

Now the simulation will run with the new assumption for the interest rate. Now to run the simulation just click on the  button.

Now when you select any of the model output tools, they show the results from both simulations. The strip graph tool displays:



If you do not wish to see the previous (base) run displayed with the new simulation run, then click on the  button and the following dialog box will appear:

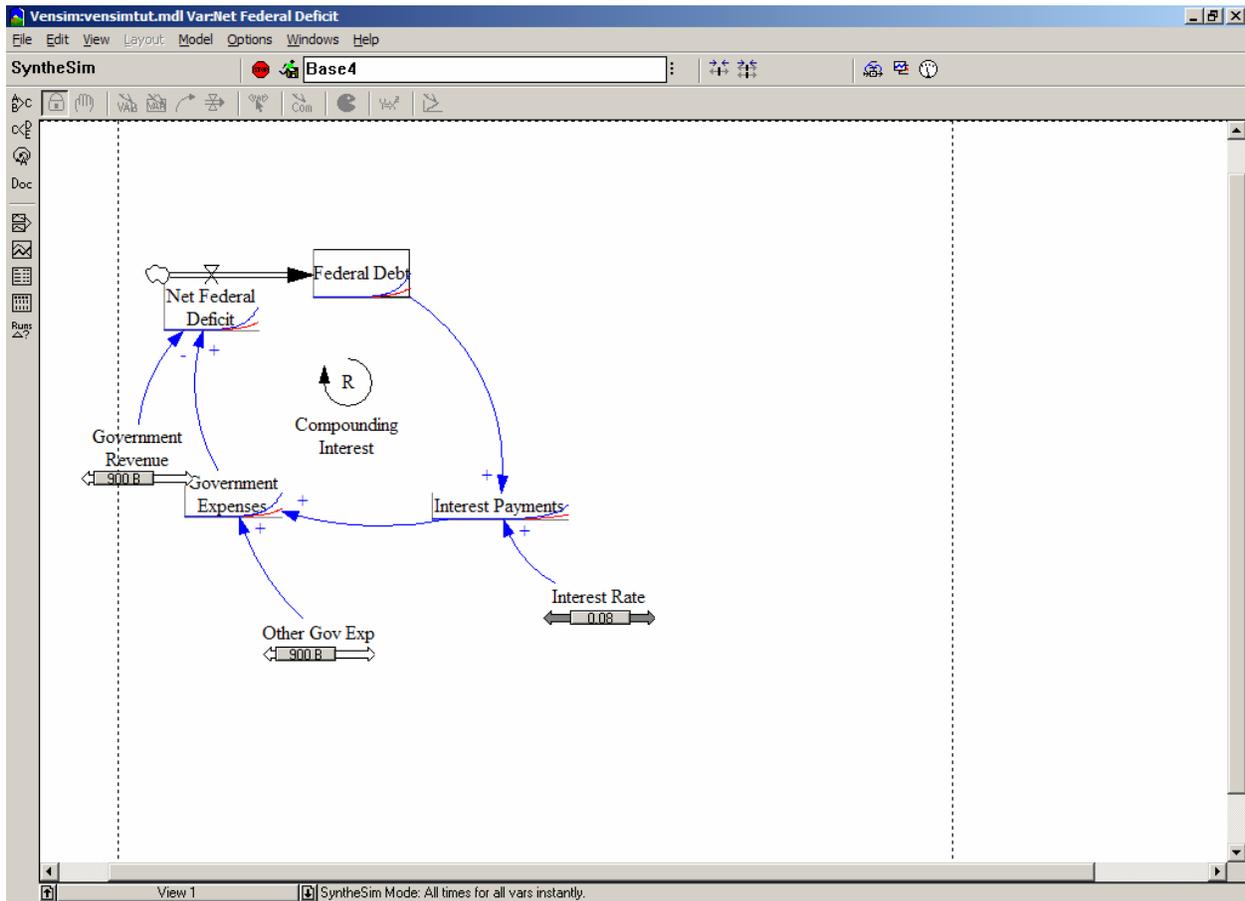


This is the **Control Panel**. Click on the **Datasets** button and the dialog box will display the two data sets you have created so far. To eliminate the first run, simply click on it twice.

This panel will also allow you to select a given variable (choose the **Variable** option). Modify the horizontal axis of your graphs, and create custom graphs. See the help menu for more information on all of these features.

SyntheSim Mode:

Another way to create multiple trial runs with different variables is to select the **Model** menu and choose “**Start SyntheSim**”. Each exogenous variable will have a slider that can be moved either way by clicking and dragging. As you move the slide, you’ll see the results of your new simulation run in mini-graphs next to each endogenous variable. If you click either end of a slider, you can type in the new value for that variable.



When you’d like to save a set of results, click the “**Save Results to...**” button next to the stop sign in the toolbar and then enter a new dataset name. Click the **Stop** button to go back into regular mode.