Formulating Models of Simple Systems

using

Vensim PLE
version 3.0B

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I. Introduction and Getting Started

The purpose of this tutorial is to help you develop some familiarity with building and analyzing system dynamics models using the Vensim PLE software. In order to become familiar with Vensim PLE, you are going to build a simple model of the federal deficit.

To begin you need to get Vensim PLE ready for modeling. This tutorial makes use of the Macintosh version on Vensim PLE; the IBM-Compatible version should work similarly, but some of the screens may look different. 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:
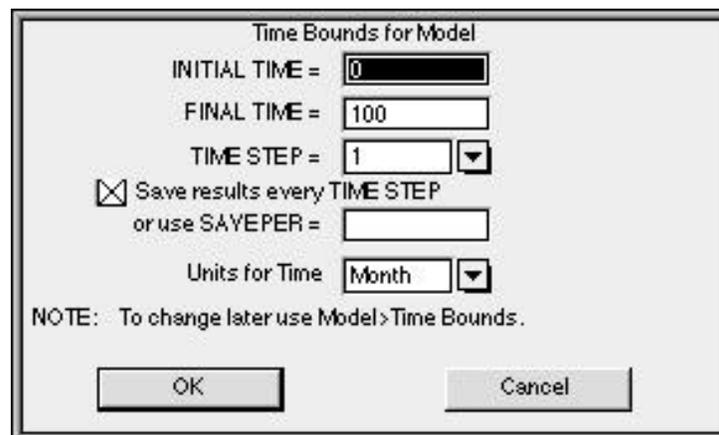
To begin your effort you must choose the time horizon of your model (when your simulation will start and finish), the appropriate time step (how accurately you wish to simulate your model), and the units of time. Start your model of the deficit in 1988 (enter 1988 in the **INITIAL TIME** box) and simulate it through the year 2010. Select a **time step** of 0.25 years. Finally, change the **units of time** from **Month** to **Year**. Your dialog box should now look like this:

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 should 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.)

Vensim saves every simulation run and custom graph you produce as a separate file. It supplies a **.vdf** extension for simulation runs. These files cannot be opened from outside the Vensim application; they can be opened from inside Vensim through the **Datasets / Simulate Model...** and **Control / Custom Graphs** dialog boxes.

Your screen should now look like this:
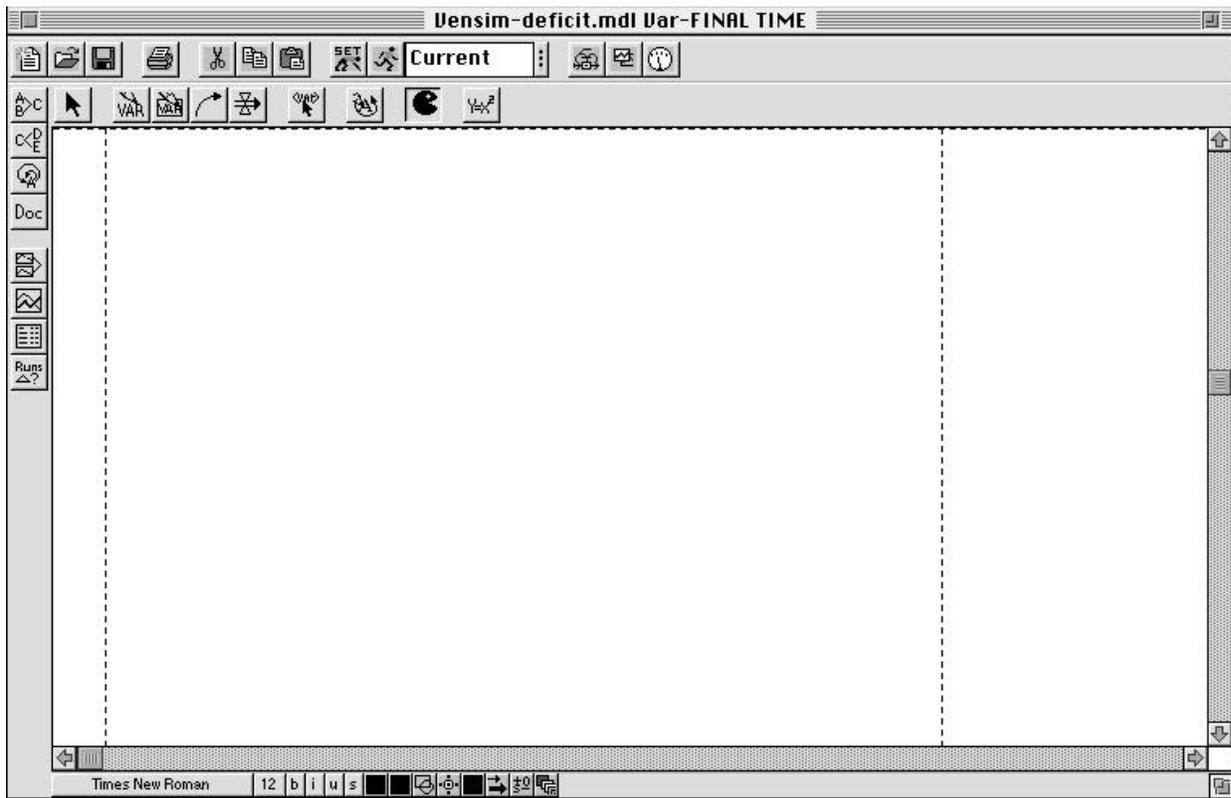
You are ready to start building your model.

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 upper toolbar consists of the Title Bar, a Menu, a Main Toolbar, and Sketch Tools. The Main Toolbar comprises two sets of tools: file operation tools that control standard file functions—opening, closing and saving files, printing, cutting, copying, and pasting—as well as simulation and graphing tools that will allow you to set up and run simulations, and set up display graphs. The sketch tools allow you to build in model components. The tools on the Status Bar (the bottom of the window) allow you to change the formatting of the diagram. The Analysis Tools on the left on the window are tools that you will use to analyze your model to understand its behavior. 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. Click on the button (the one with the box in it) on the sketch tools bar and then click in the right center of the screen. You use this tool whenever you want to add a stock (also known as a 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:
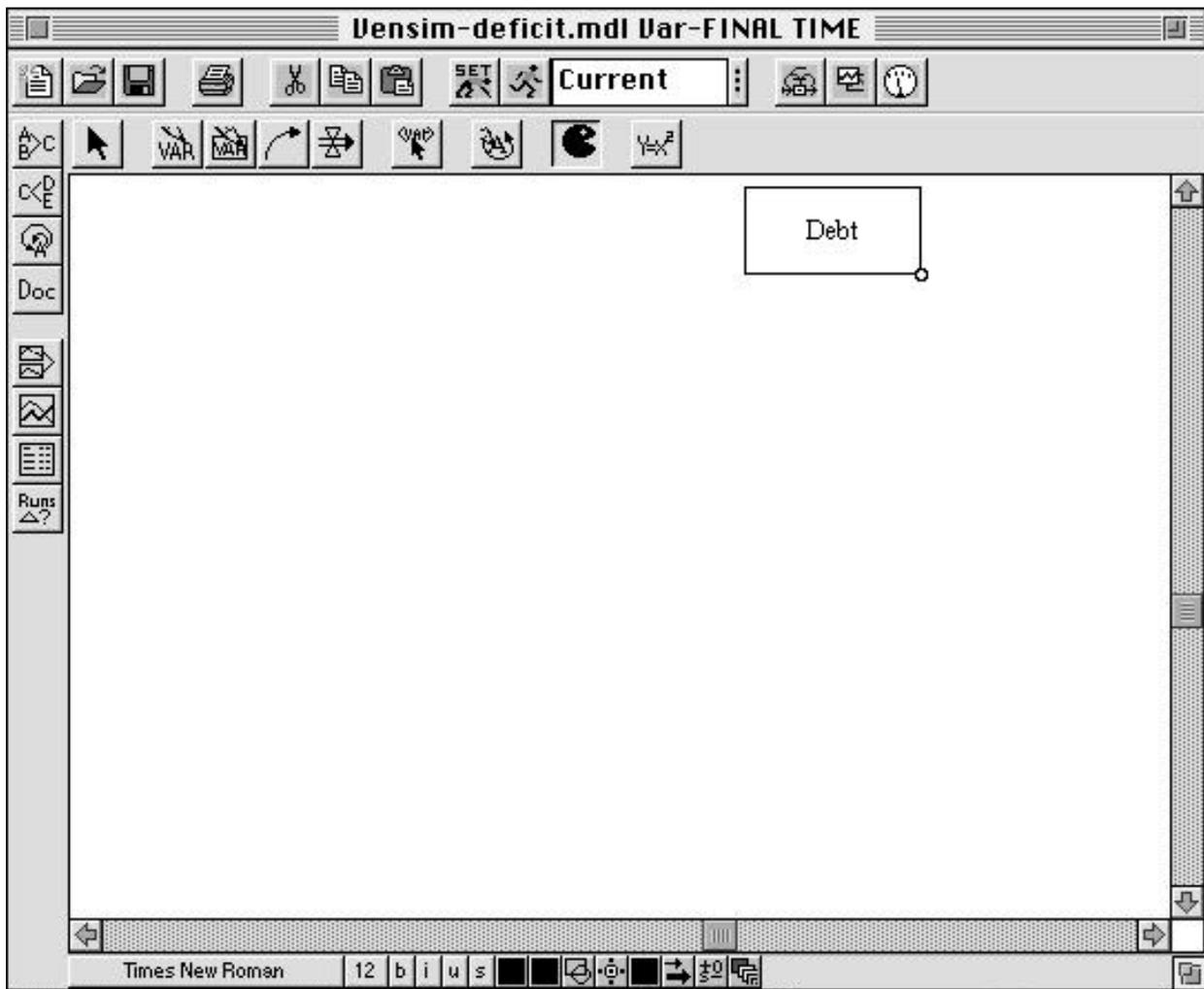
You have just created the first variable in your model, the stock of money that constitutes the federal debt.

Now, add the inflow to the stock of **Debt**. Click on the ⬇ button on the sketch tools bar. Now, click and release once to the left of the **Debt** stock, move the cursor so that it sits *inside* the **Debt** stock, (the stock should "blacken" if you do this correctly) 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:
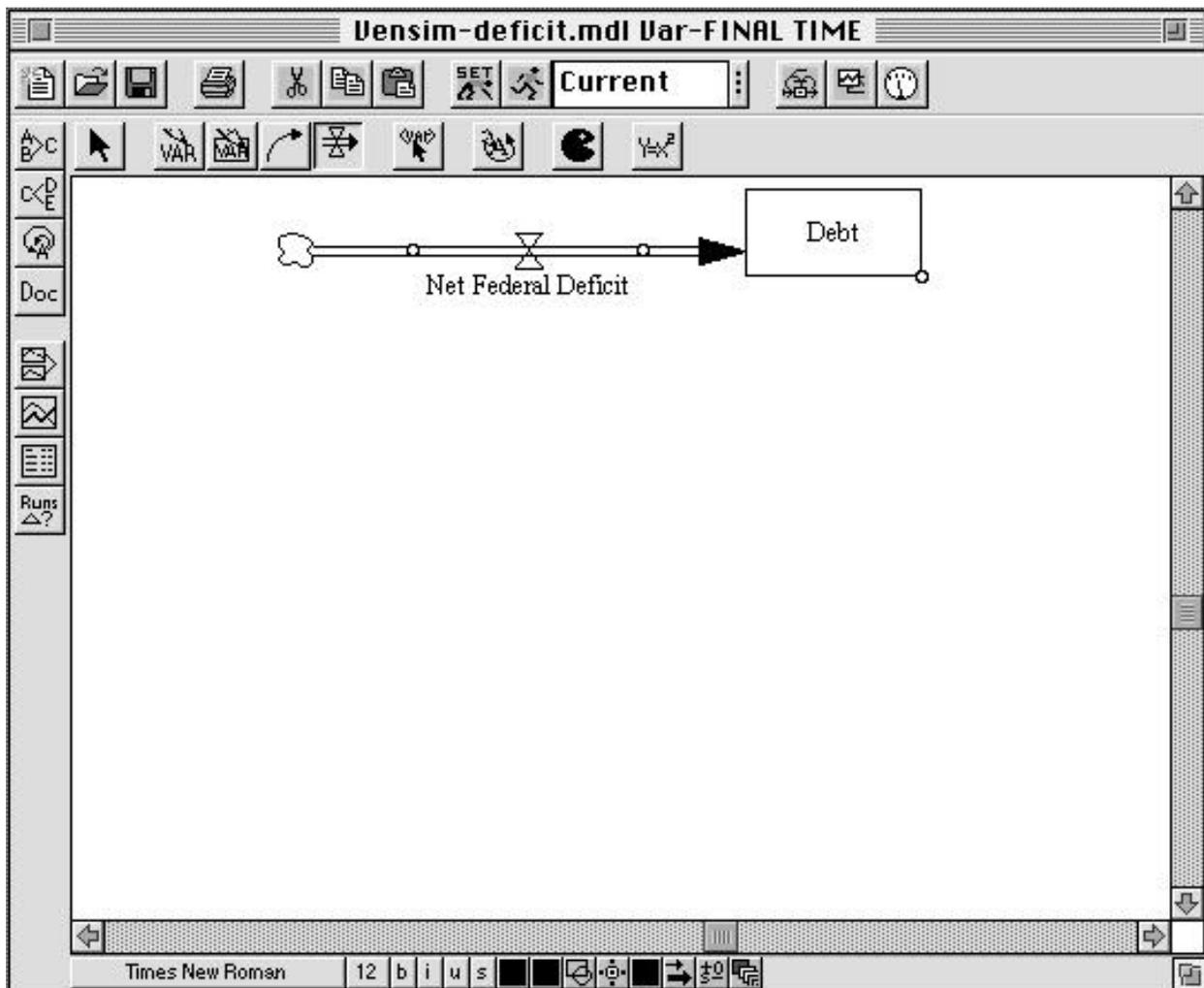
Note: The ☁ icon (which is supposed to resemble a cloud) represents the boundary of your model. In this case the "cloud" on the left side of the flow signifies that you do not, at the moment, care about where the deficit comes from — you are not keeping track of the stock that is being drained by the deficit flow. You do care, however, where the deficit goes: hence, you are accumulating the deficit in the **Debt** stock. If your deficit flow has "clouds" on both ends, then

you have not hooked the flow to the stock correctly. To fix this problem, 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 you wish to change the name of the stock variable from **Debt** to **Federal**

Debt. Click on the 🖉 button (the one without the box in it) on the sketch tool bar 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 hit 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 ![VAR] 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**, a stock, and **Net Federal Deficit**, a flow — the new variables are not attached to a valve or a box. These variables 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 ![arrow] 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 ![pacman] tool.

Clicking on the ![button] button allows you to select the variables you have created and move them to different places on the screen. To move variables, 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:
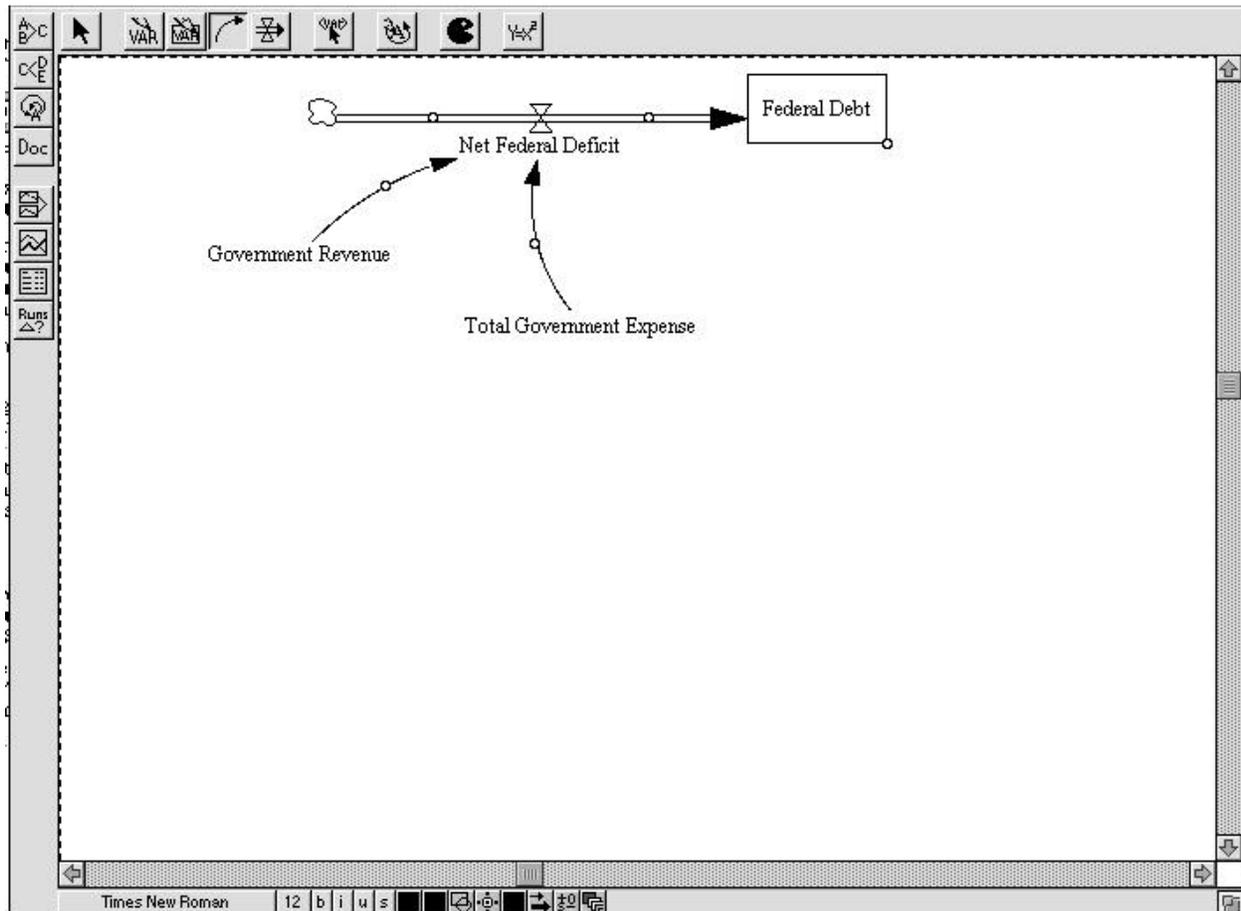

Now, you may want to update your diagram by labeling the arrows to show that **Government Revenue** and **Total Government Expense** affect the **Net Federal Deficit** in different ways. Specifically, an *increase* in revenue causes the deficit to *decrease,* while an *increase* in expenses causes the deficit to *increase.* To do this, first click on the ![button] 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] 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. Label your two causal arrows so your diagram looks like this:
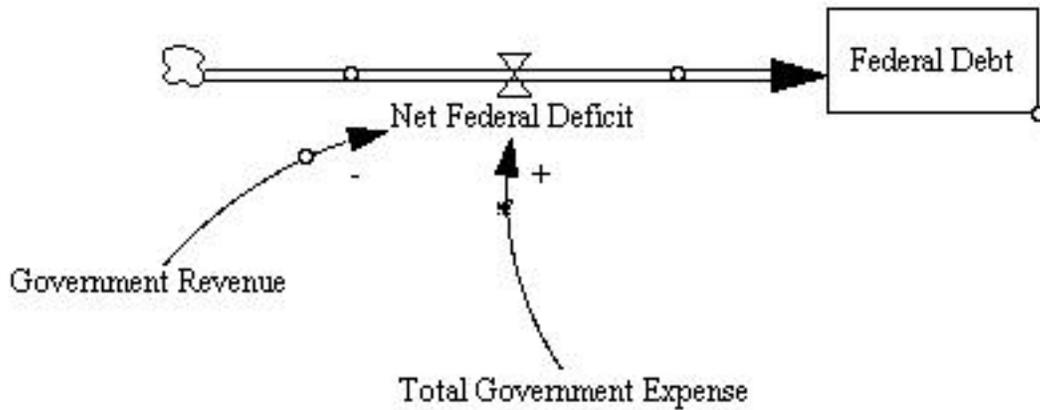
Now, using the same steps discussed above, complete the stock, flow and feedback so your diagram looks like this:
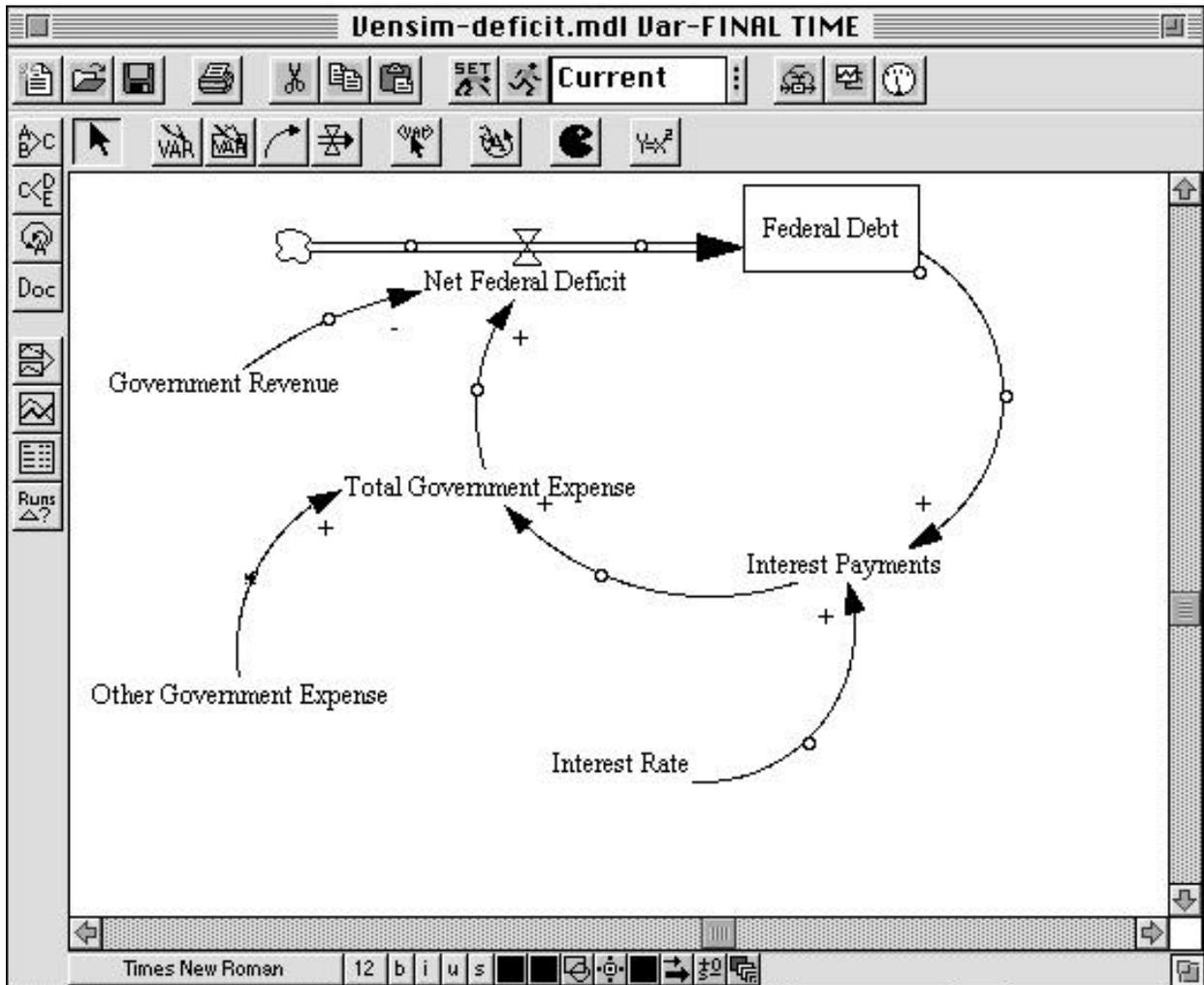
You may want to slide the handle of each arrow close to its arrowhead, so each label is clearly associated with its causal arrow.

Finally, you may wish to label the positive feedback loop you have just created. Click on the ![button] 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 to understand your model diagram. After clicking in the center of the loop, you should see the following dialog box:
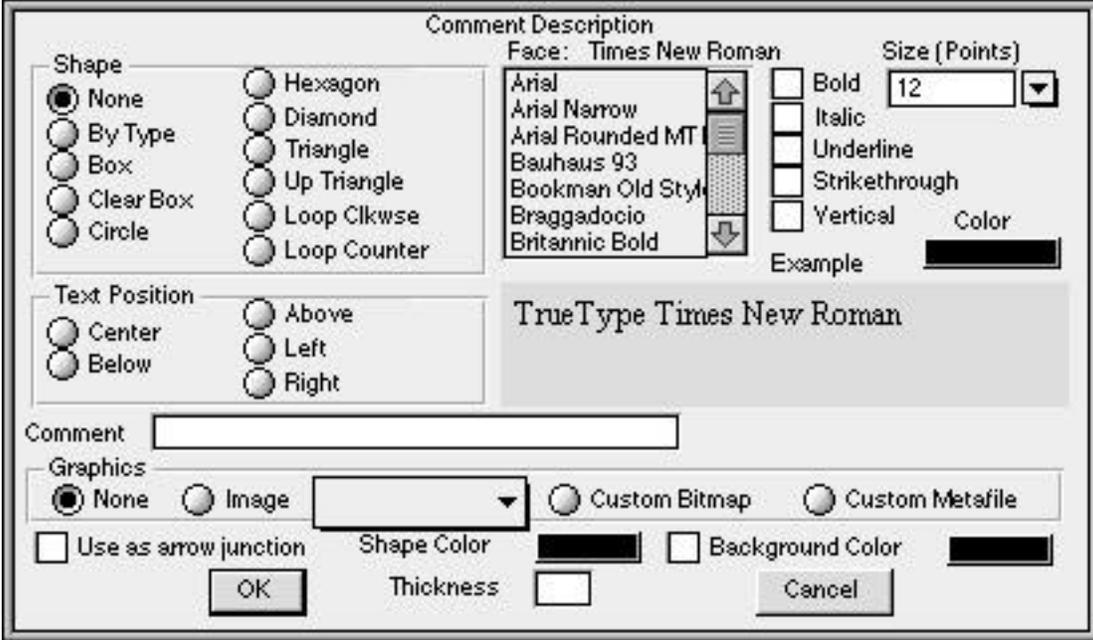
Click on the **Loop Clkwse** button in the **Shape** box; click on **Center** in the **Text Position** box; and type **R**, for **reinforcing**, in the **Comment** box. You may also type + or **P** to denote a positive feedback, also known as a reinforcing, loop. Your screen should now look like this:
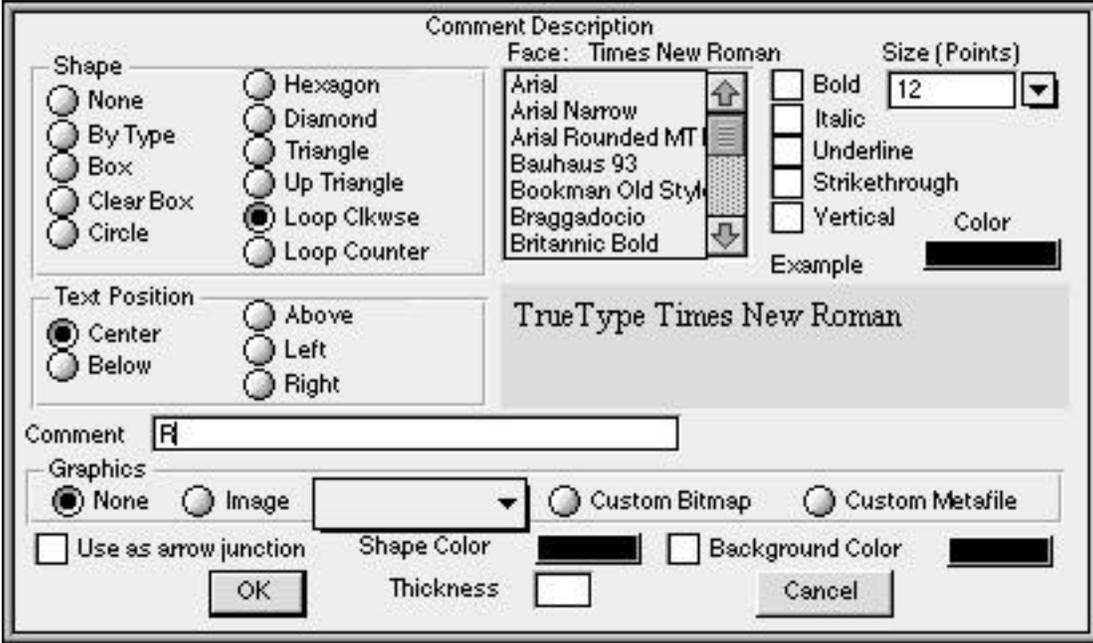
Click on the **OK** button or hit return.

Your screen should now appear as:
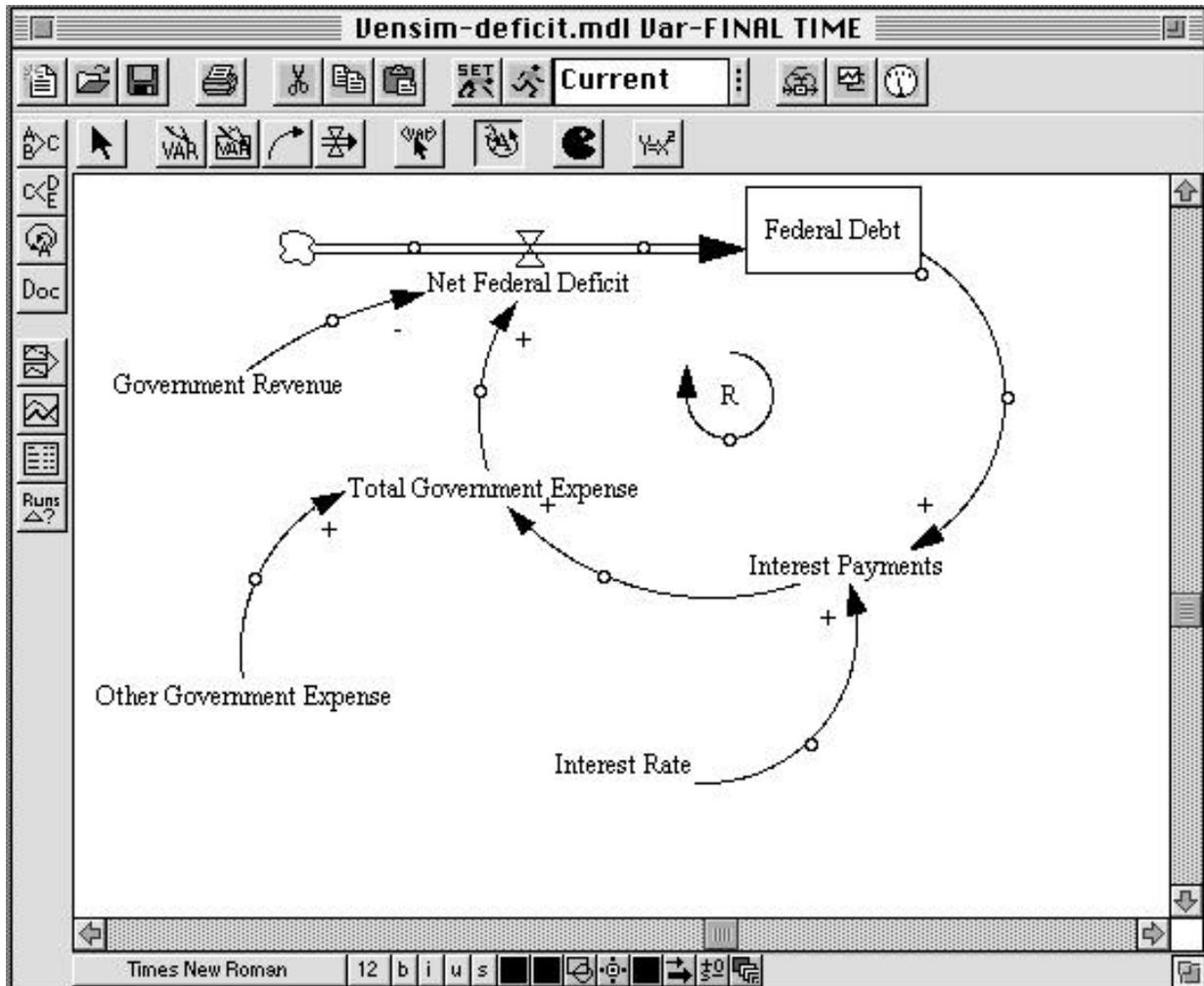
III. Specifying Equations for Your Model

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 [y=x²] button on the sketch tool bar. The variables in your diagram become highlighted.
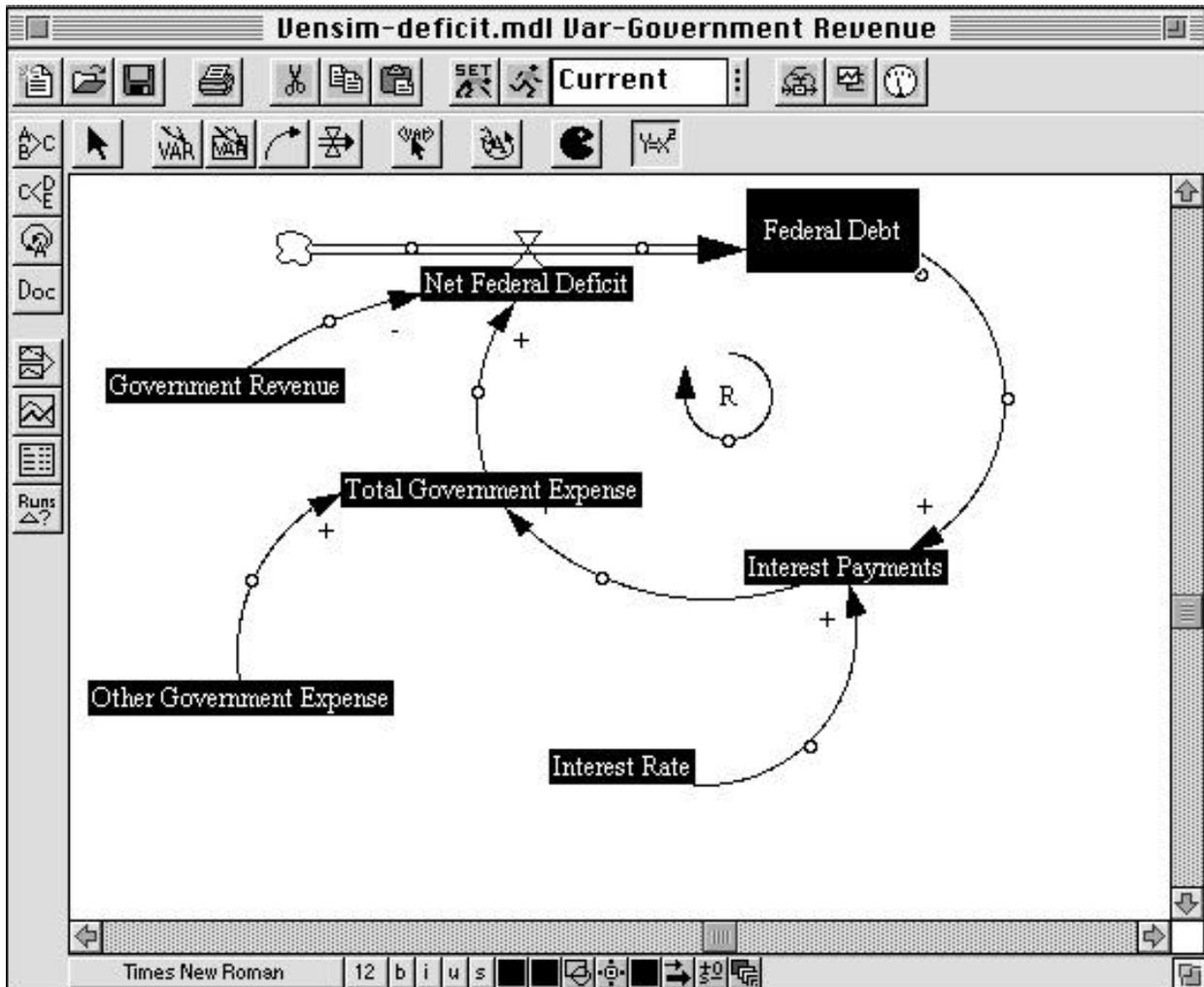
A highlighted variable indicates that the equation for that variable is incomplete.

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 Expenses**, 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:
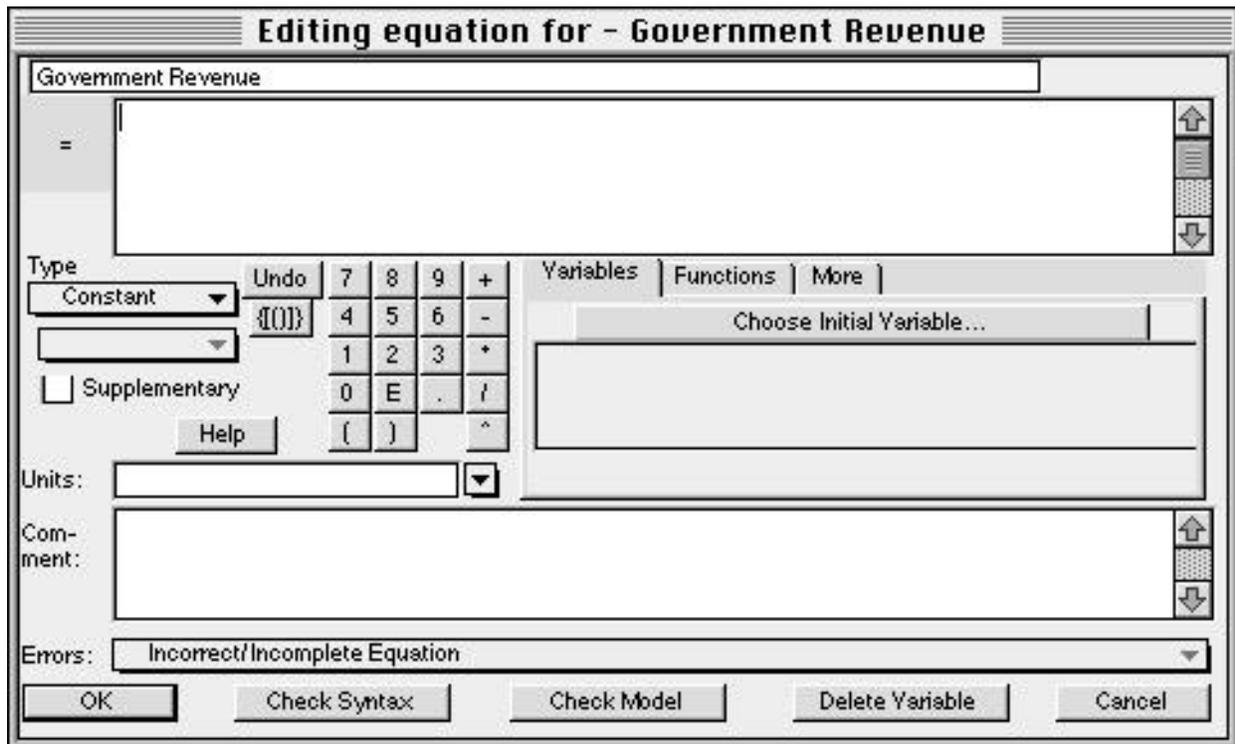
Good modeling practice requires that each equation in a model have three elements: the equation itself, specified units of measure, and complete documentation. You enter the equation in the box to the right of the **=** sign. You enter the unit of measure in the text field to the right of the word **Units**. 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. In 1988, government revenue was about 900 billion dollars annually, 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. Because 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 the units from that list when appropriate.)

Finally, provide a description of this equation in the comment field. A good comment will be brief, but it will also give the reader 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:
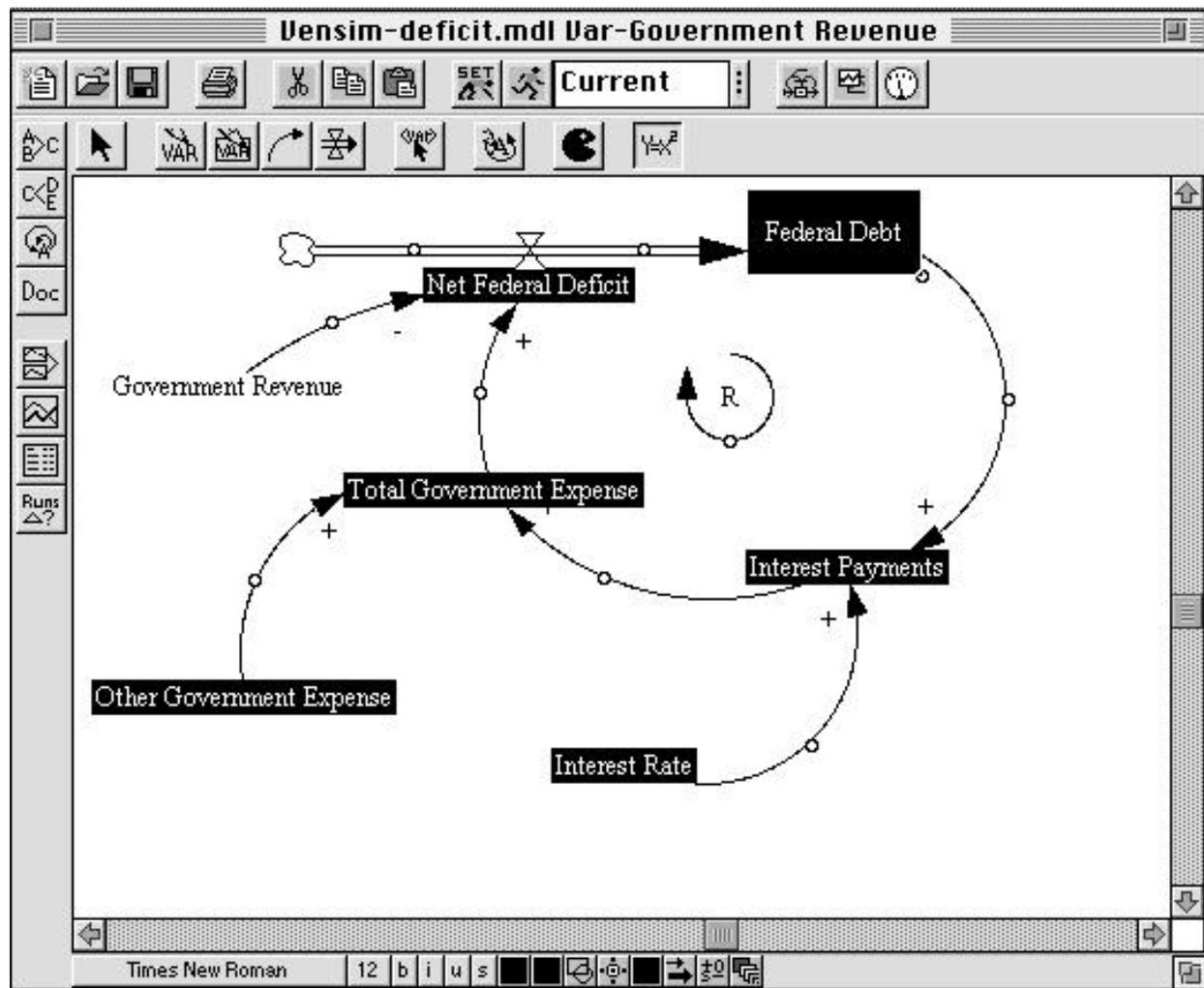
Government Revenue is no longer highlighted because you have just specified its equation.

Following the process above, write equations for the two other exogenous variables, **Interest Rate** and **Other Government Expenses**. 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.

Now that the equations for the exogenous variables are formulated, 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 [Y=X²] button on the sketch tool bar and then click on the stock, **Federal Debt**.

The following dialog box will be displayed:
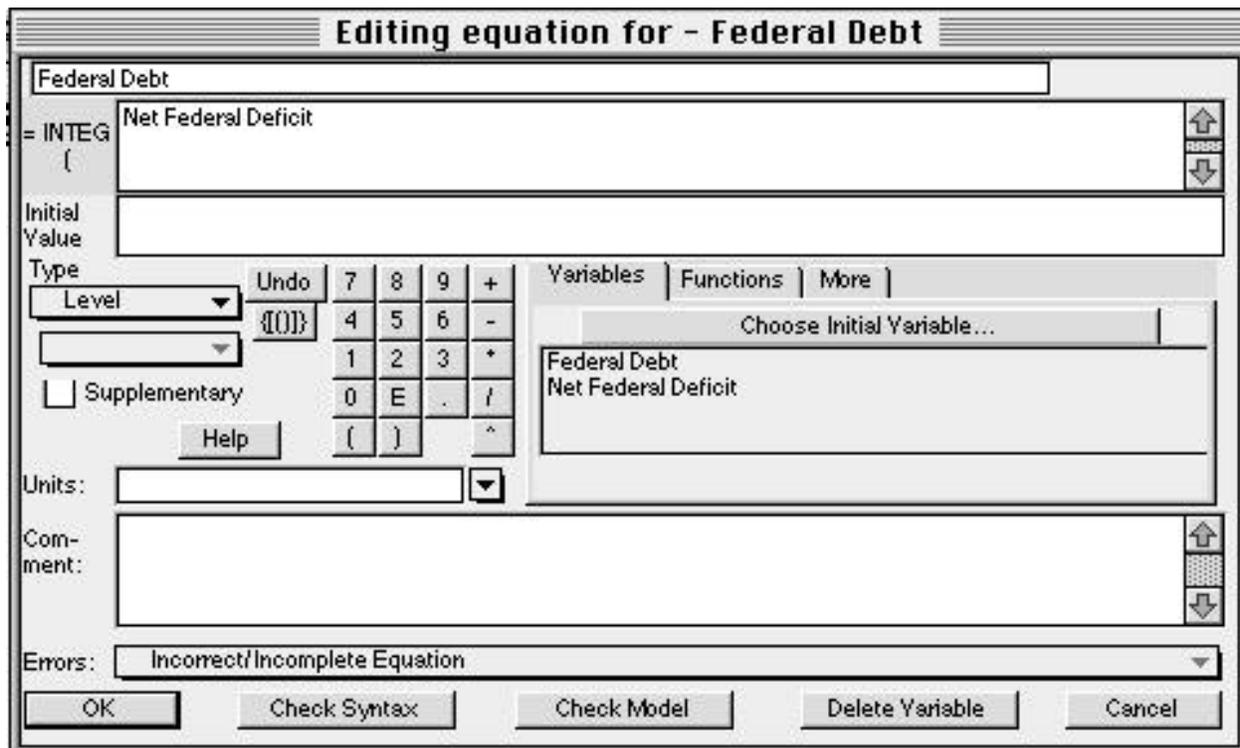
Unlike flows and constants, a stock requires that an additional element be specified in its formulation; after you specify the equation, you need to select an initial or starting value.

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 **Variables** to the stock **Federal Debt** on the right side of the equation dialog box. (The variable we are formulating, **Federal Debt**, itself also appears in the **Variables** 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 has 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 simply click in the box to the right of the **Integ** and then click on the variable **Net Federal Deficit** in the **Variables** box to write the equation for the change in **Federal Debt**. (Note: If **Net Federal Deficit** is *not* in the **Variables** box, 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:

Federal Debt
= INTEG Net Federal Deficit (

Below the **Integ** box is the **Initial Value** box. Here you enter the initial condition or starting point for the stock. In 1988, the outstanding federal debt was approximately 2.5 trillion dollars, 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:

Initial Value	2.5e12

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 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 the initial value of the debt. 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:
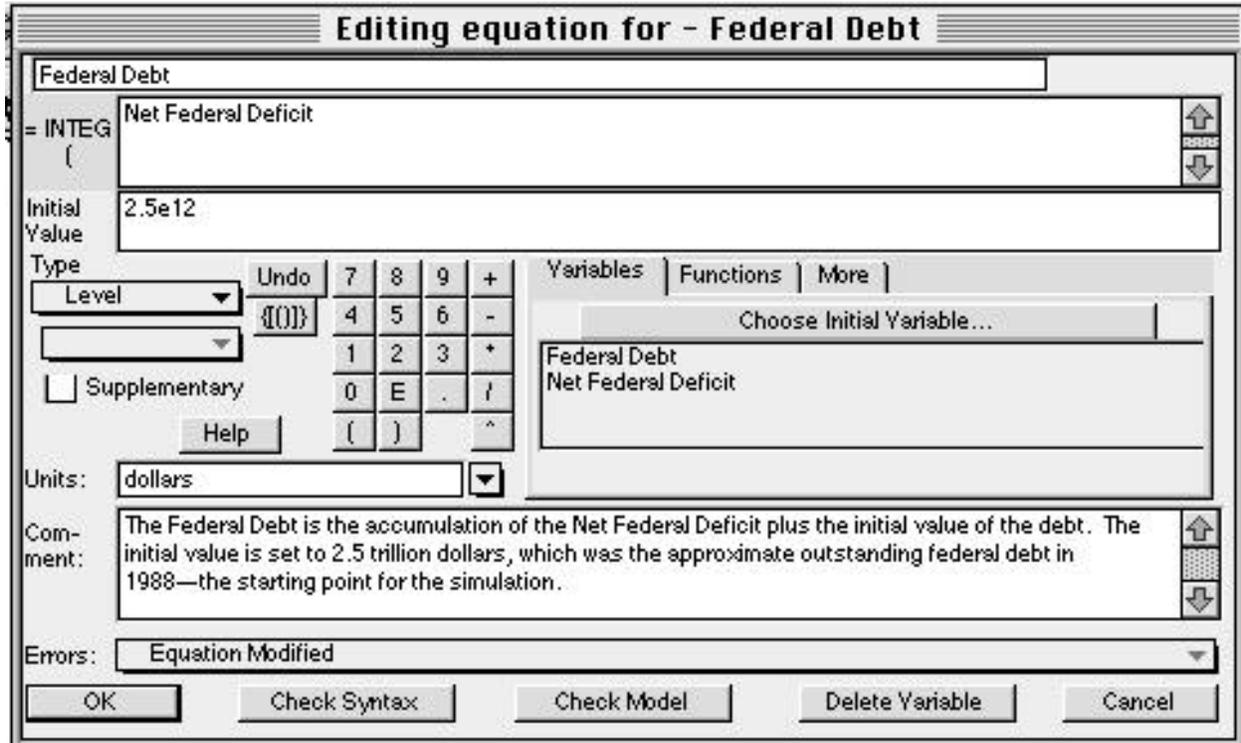
Click on **OK** or press return.

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

Using the ![tool icon] tool on the sketch tool bar, click on the **Interest Payments** variable. You should see a dialog box that looks like this:
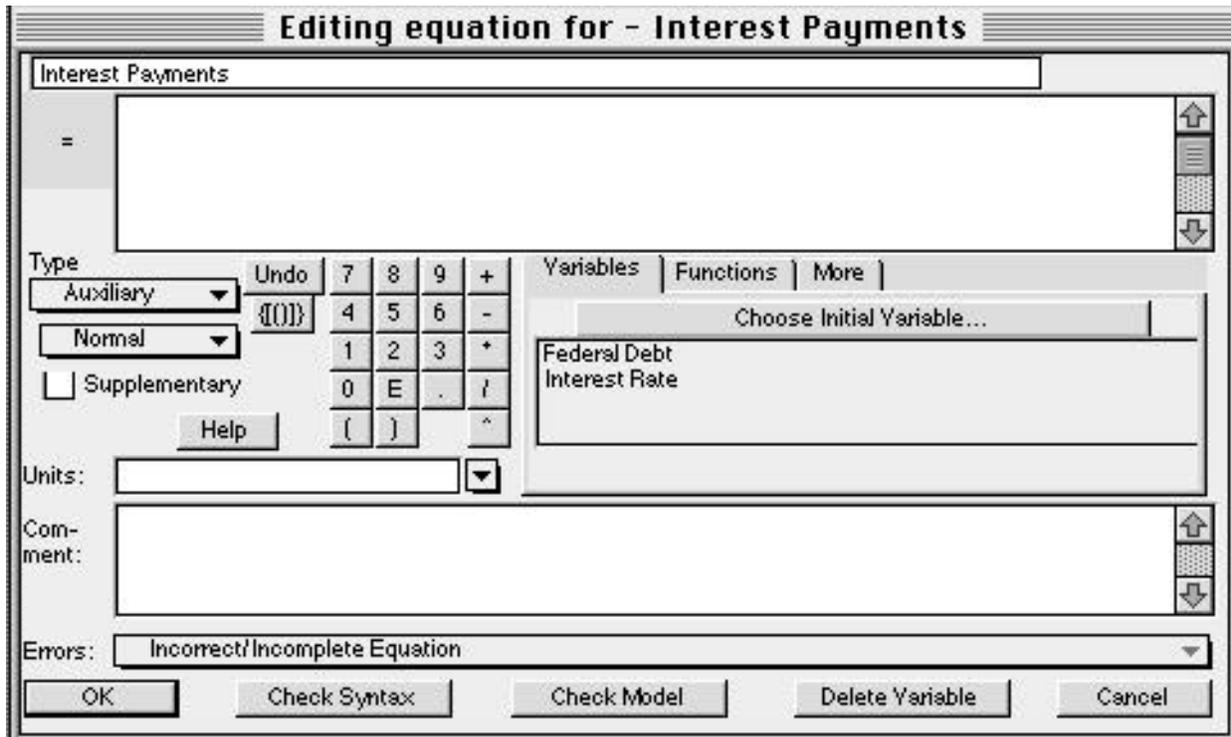
This box is identical to those used to specify the exogenous variables, but, in this case, there are two other variables in the **Variables** box; you are required to use these variables in the equation. When you developed the stock, flow, and feedback diagram, you drew causal arrows connecting the variable **Federal Debt** and constant **Interest Rate** to the variable **Interest Payments**. Vensim PLE has conveniently recognized this fact and has 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 variables, Vensim PLE will give you an error message.

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

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

>**The annual flow 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:

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.

By far the most important of these is the unit-checking tool.

An important feature of any system dynamics equation is *dimensional consistency*, which 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 so, then pressing the *apple* key and *u* (alternatively, you could select the **Model** menu, then select **Units Check**) simultaneously would yield the following message:
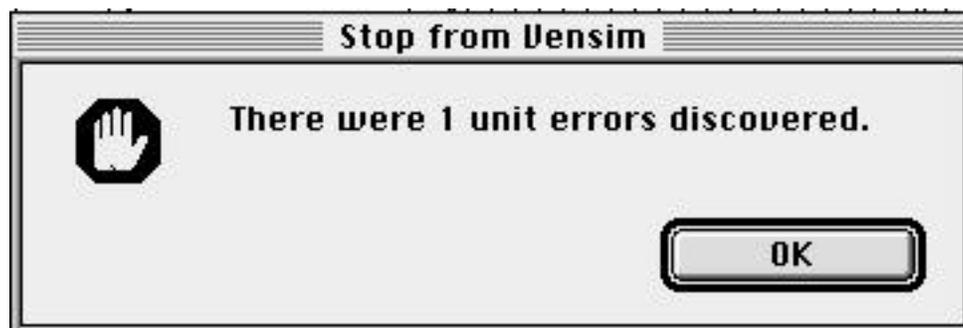
Followed by:
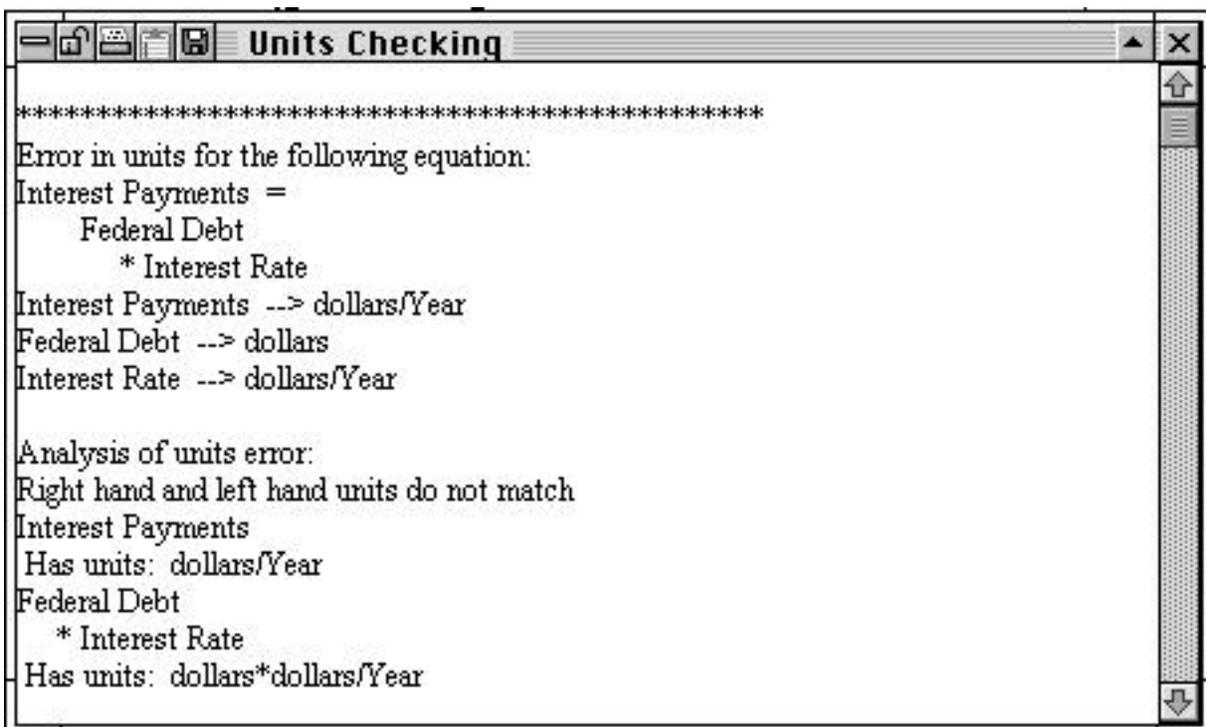
The problem is that, in this example, the equation for **Interest Payments** is not dimensionally consistent: the right and left sides of the equation have different units. The flow **Interest Payments** is measured in dollars per year. The **Federal Debt**, because it is a stock, is measured

in dollars. Multiplying **Federal Debt** by something with units in dollars/year results in a quantity that has units in dollars^2/year—hence the error.

The cause of the problem is that the unit of measure for **Interest Rate** is incorrect. The interest rate is not measured in dollars per year. An easy way to think about this fact is to recognize that the interest rate really has nothing to do with dollars. It could easily apply to any other currency or any other type of measurement unit. In fact, the interest rate has no unit of measure; it is dimensionless. Although it has no unit of measure, it is, nevertheless, time-dependent; an annual interest rate is not equivalent to a monthly one. As a result, the appropriate unit of measure for **Interest Rate** is 1/year. If you enter 1/year into the unit field of the interest rate variable and simultaneously press the *apple* key and u, you should receive the following message:
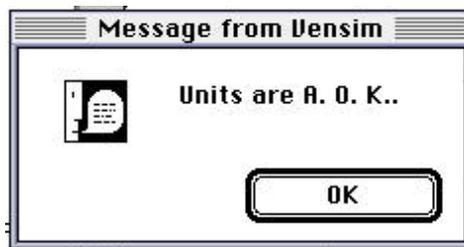

The units in your model now balance.

In this example, the unit-checking tool identified an incorrect assumption in a common mental model of the interest rate. Dimensional consistency is an important feature of system dynamics models, and Vensim PLE's unit-checking feature often helps you to 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 analysis tools that Vensim PLE provides can also be useful. The [A>C] and the [C<E] buttons create "causes" and "uses" trees for a variable. To use these tools, you need to first

"select" a variable. To select a variable, first click on the [arrow] button and then double-click on the variable you wish to select. You can tell what 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
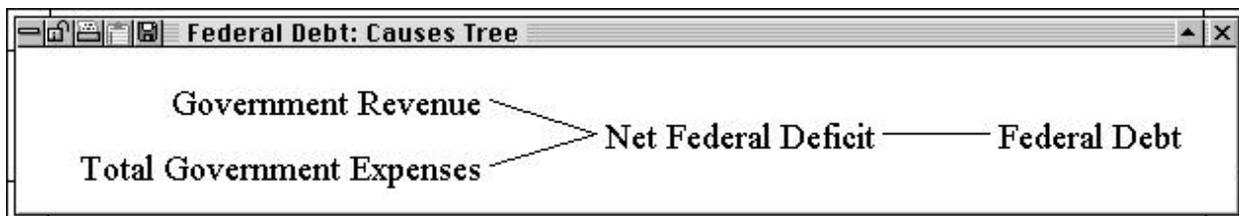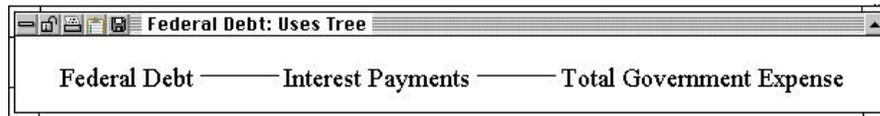
The **Doc** button on the analysis tool bar provides you with a complete listing of the equations in your model. The [tool icon] tool on the analysis tool bar identifies all the feedback loops of which the selected variable is a member.

V. Simulating Your Model

Vensim PLE also has tools to help you analyze the behavior of your model. Before analyzing the behavior, however, you must actually simulate the model so that you have some behavior to analyze.

To run a simulation, you first need to click on the running man [running man icon] icon on the top toolbar. Vensim may display the following dialog box.

```
═══════════════ Question from Vensim ═══════════════

  ⚠    Dataset Current already exists.  Do you want to
       overwrite it?

  [  No  ]            [  Cancel  ]      [[  Yes  ]]
```
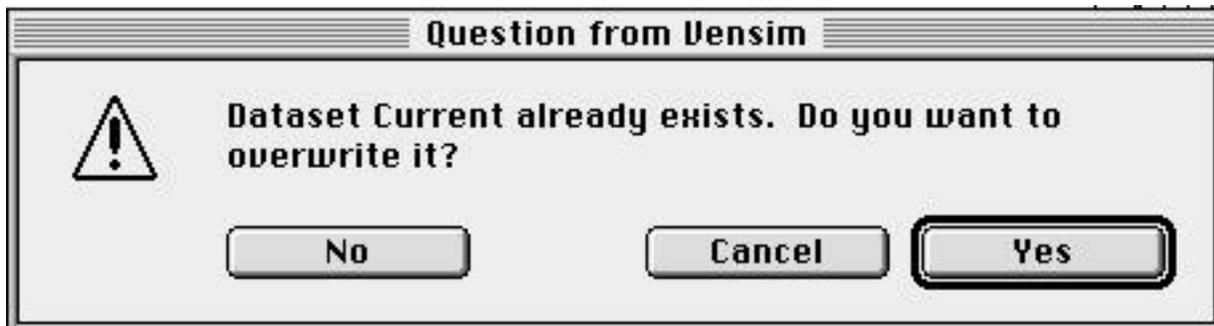
Clicking on yes will overwrite the "current" dataset displayed in the box to the right of the running man icon. Selecting "No" will allow you to create a different dataset. It is helpful to choose names that suggest some idea of what is being tested rather than simply using name like SIM1, SIM2, etc. Because this run is the base case run for your model, you might choose to call the run BASE.[*]

Click on **No**, type in BASE as your new dataset name, click on **Save** or hit return, 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 the most useful, of these tools is the strip graph. To create a graph of the **Federal Debt**, first click on the

[pointer tool icon] tool and then double-click on the stock to select the variable **Federal Debt**.

To see a strip graph, click on the [graph icon] button on the analysis tool bar.

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[*]   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 integration method, but it is also more computationally intensive. Generally it is better to use the Euler method and only change if you believe you are seeing integration error.

You then see:
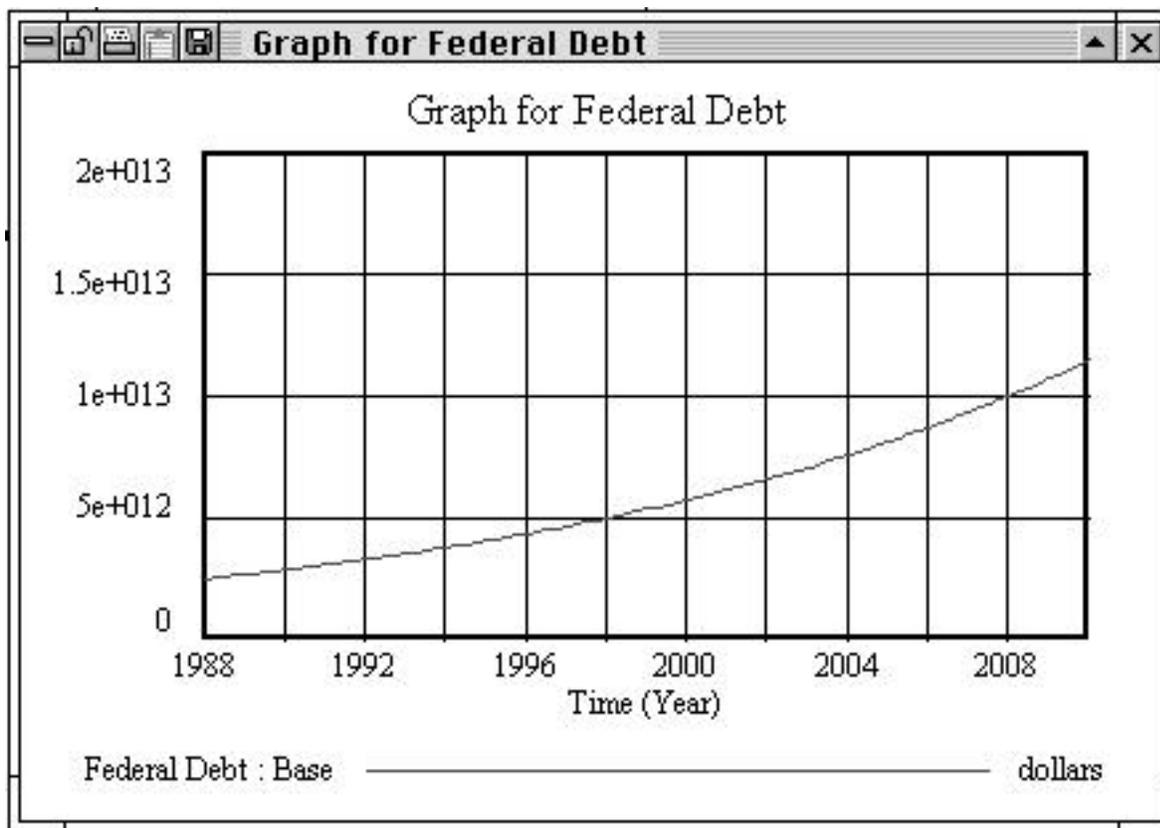
By the year 2010, given the current assumptions in the model, the federal debt will grow to more than 10 trillion dollars, four times its value in 1988.

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

The ![button icon] button displays a strip graph of the currently selected variable, along with graphs of all the variables that determine the value of the selected variable (the causes). Clicking on the button gives you:
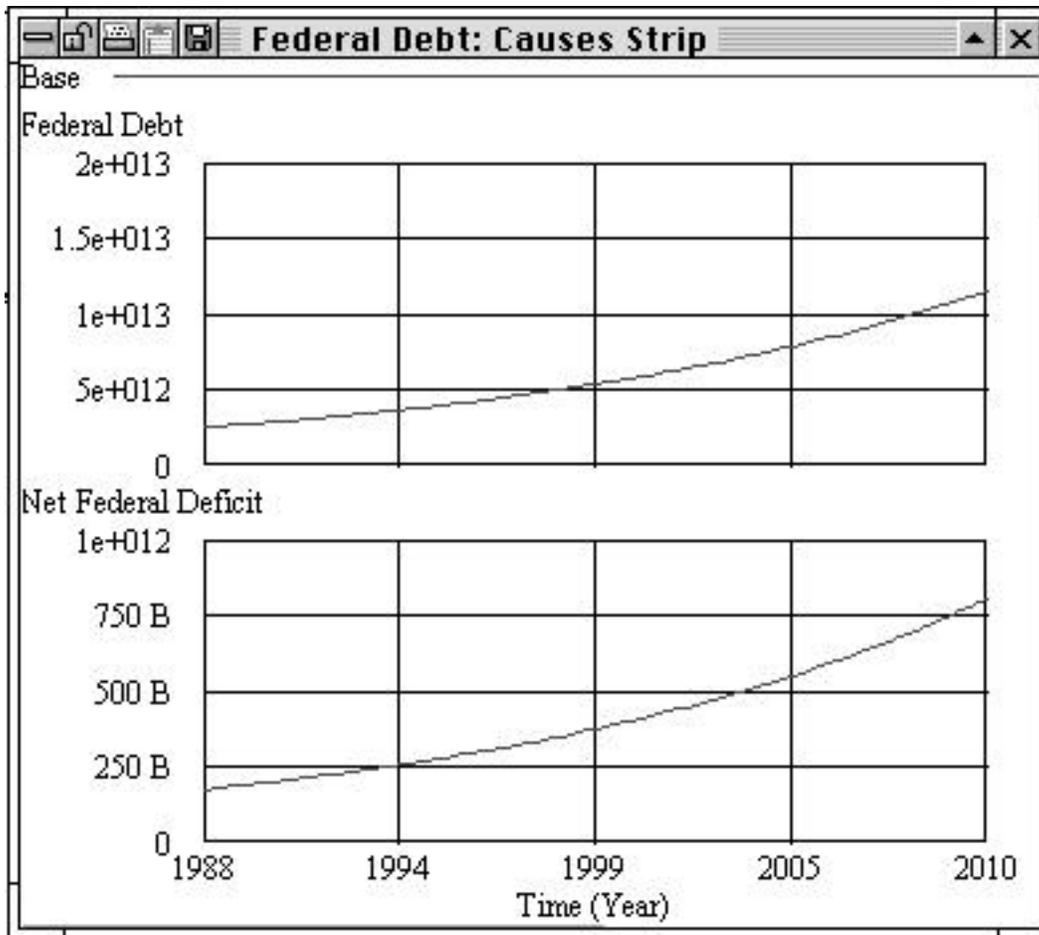
Vensim PLE also can present the output in the form of a table rather than a graph. To see a table of the selected variable simply click on the [image] button.

Having analyzed 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 change the parameter is to change the model equation in the original model. With the [image] button selected, click on **Interest Rate.** A dialog box will appear. In the constant box change the interest rate from 7% to 3.5%. Again, run this new simulation but do not overwrite the simulation named **Base**. Instead, name it **interest rate**.

Your new graph should look like this:
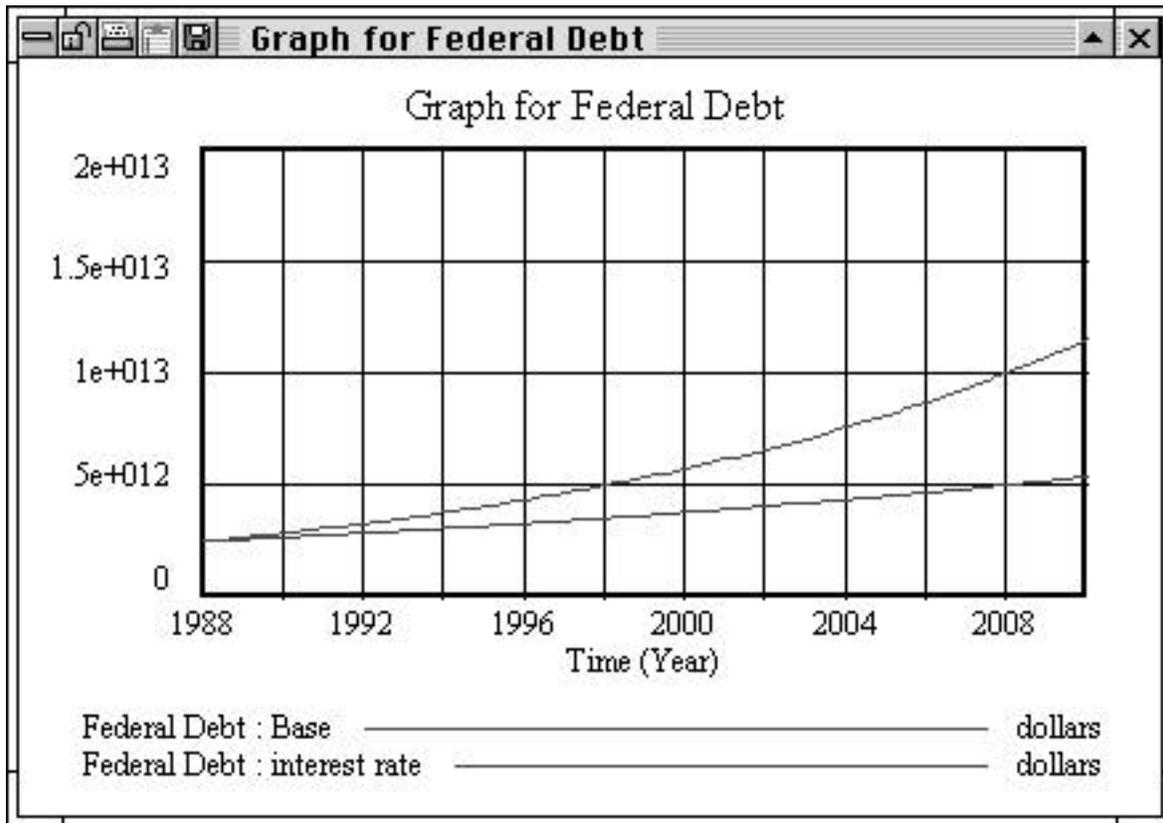
If you do not wish to see the previous run (base) displayed with the new simulation run, click on the ⊕ button on the upper toolbar. Your screen should look like this:
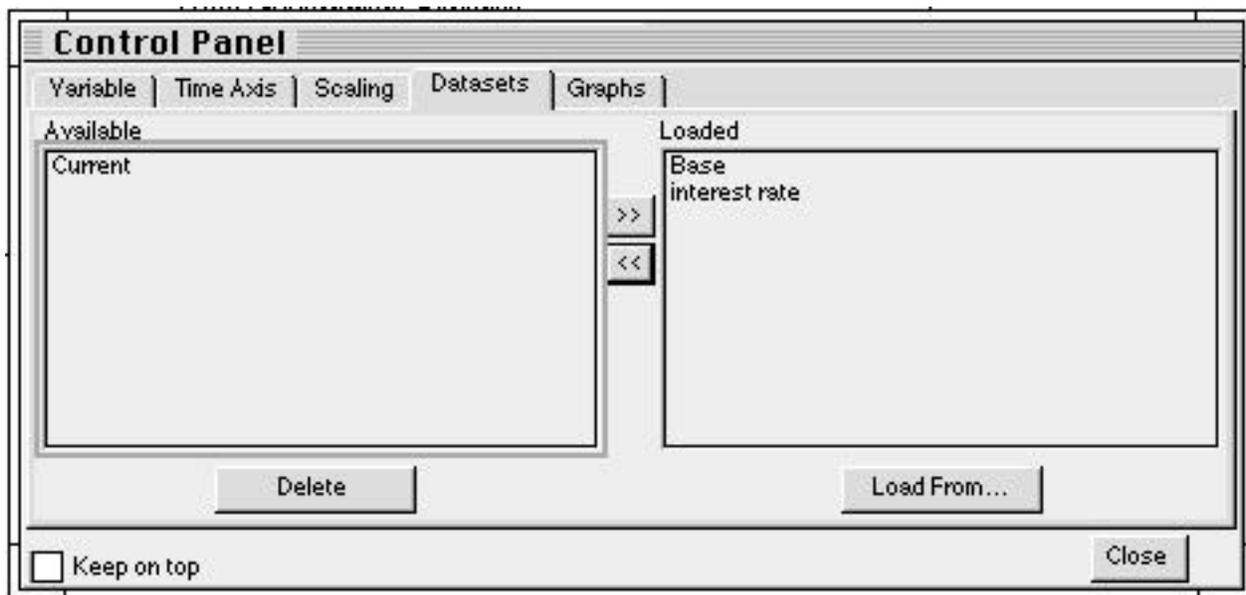
A dialog box appears and shows on the left side the two simulation runs you have created so far. Double-click on the name of the simulation run you wish to *remove* from the graph (or highlight it and click on the **<<** button to remove it from the right side of the dialog box). Close the **Datasets** window and close and re-display the strip graph. Now, only the new simulation run should appear.

You may also wish to run the model for a longer period of time. In this case, select **Time Bounds...** from the **Model** menu. You then see the same dialog box that you saw when you first started to develop your model.

You can extend your simulation by setting a new date for your final time. Run your model out to the year 2075.