SIMULINK A Tutorial by Tom Nguyen

Introduction

Simulink (**Simu**lation and **Link**) is an extension of MATLAB by Mathworks Inc. It works with MATLAB to offer modeling, simulating, and analyzing of dynamical systems under a graphical user interface (GUI) environment. The construction of a model is simplified with click-and-drag mouse operations. Simulink includes a comprehensive block library of toolboxes for both linear and nonlinear analyses. Models are hierarchical, which allow using both top-down and bottom-up approaches. As Simulink is an integral part of MATLAB, it is easy to switch back and forth during the analysis process and thus, the user may take full advantage of features offered in both environments. This tutorial presents the basic features of Simulink and is focused on control systems as it has been written for students in my control systems course.

This tutorial has been written for Simulink v.5 and v.6.

Getting Started

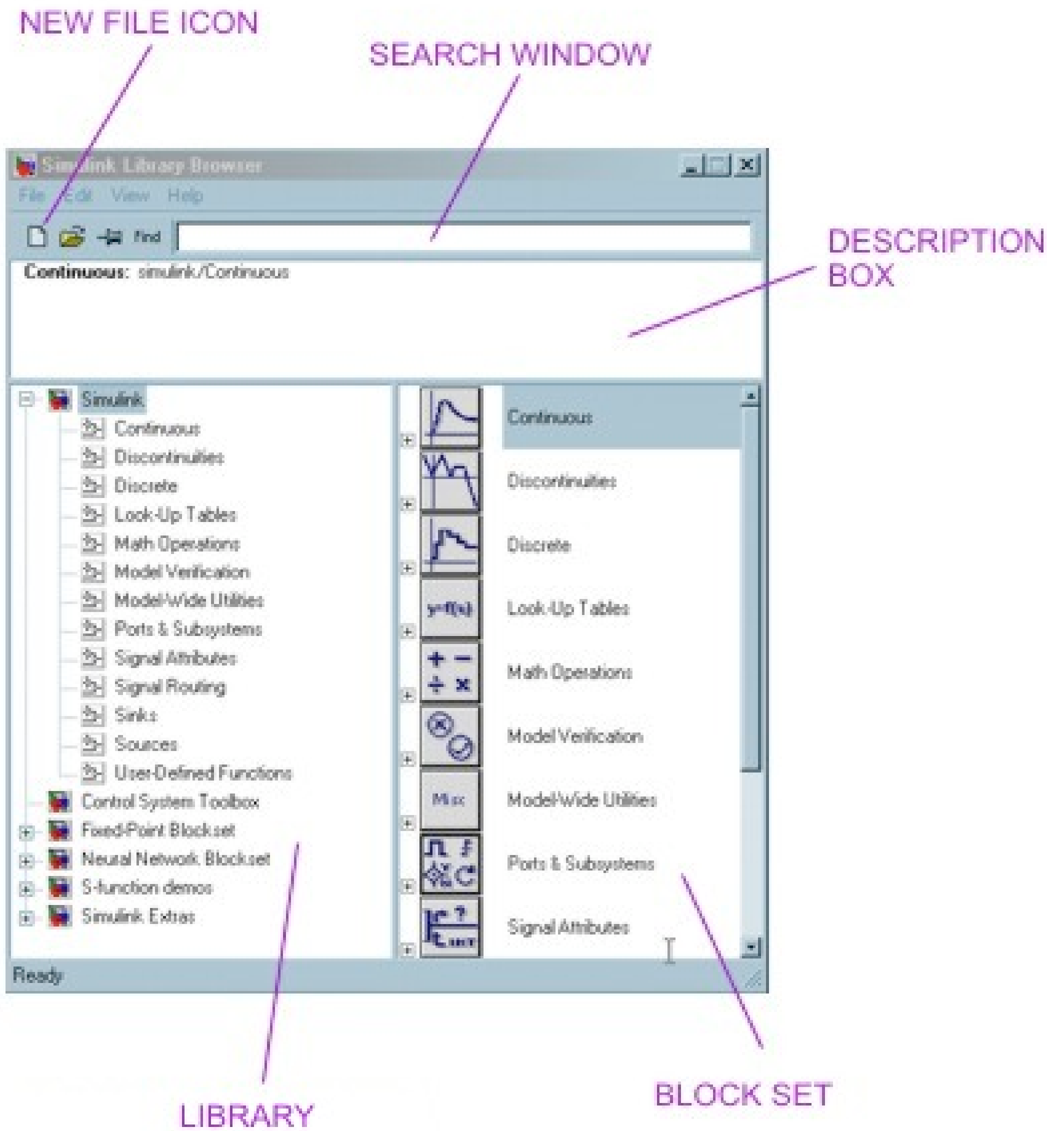
To start a Simulink session, you'd need to bring up Matlab program first.

From Matlab command window, enter:

>> simulink

Alternately, you may click on the Simulink icon located on the toolbar as shown:

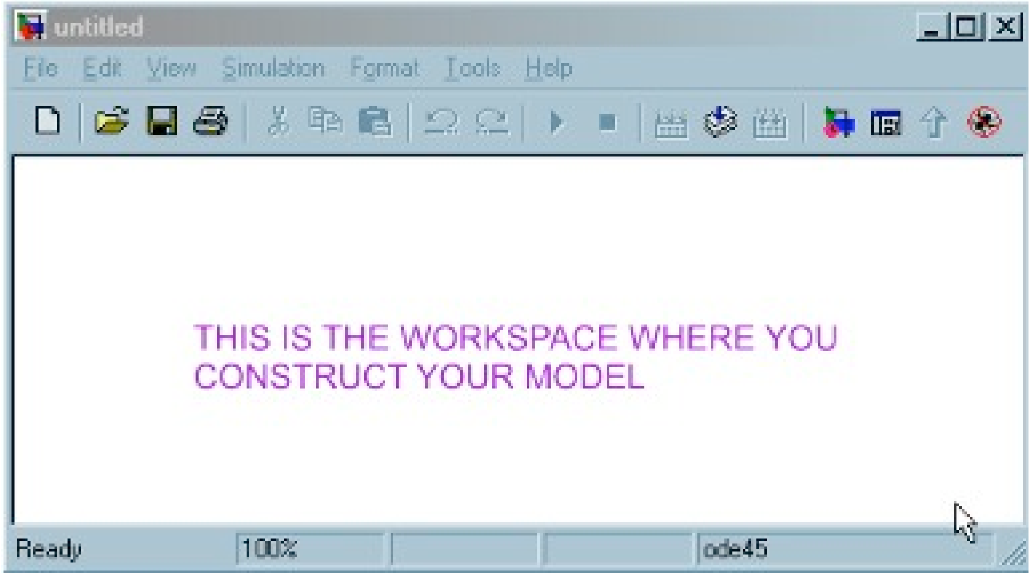
Simulink's library browser window like one shown below will pop up presenting the block set for model construction.



To see the content of the blockset, click on the "+" sign at the beginning of each toolbox.

To start a model click on the NEW FILE ICON as shown in the screenshot above. Alternately, you may use keystrokes **CTRL+N**.

A new window will appear on the screen. You will be constructing your model in this window. Also in this window the constructed model is simulated. A screenshot of a typical working (model) window that looks like one shown below:

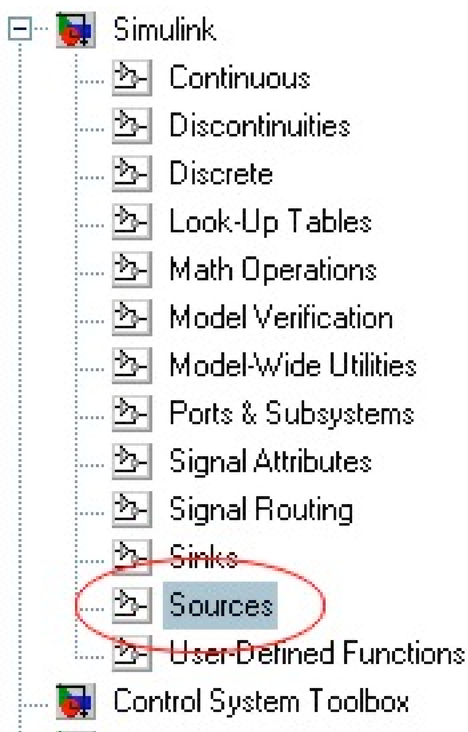


To become familiarized with the structure and the environment of Simulink, you are encouraged to explore the toolboxes and scan their contents. You may not know what they are all about but perhaps you could catch on the organization of these toolboxes according to the category. For instant, you may see Control System Toolbox to consist of the Linear Time Invariant (LTI) system library and the MATLAB functions can be found under Function and Tables of the Simulink main toolbox. A good way to learn Simulink (or any computer program in general) is to practice and explore. Making mistakes is a part of the learning curve. So, fear not, you should be.

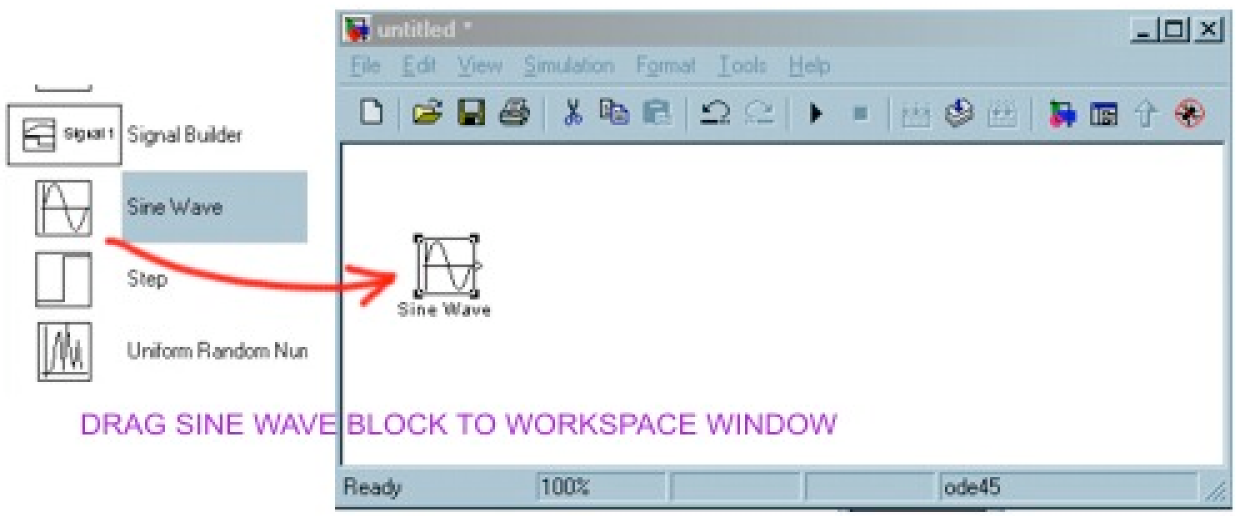
A simple model is used here to introduce some basic features of Simulink. Please follow the steps below to construct a simple model.

STEP 1: CREATING BLOCKS.

From BLOCK SET CATEGORIES section of the SIMULINK LIBRARY BROWSER window, click on the "+" sign next to the **Simulink** group to expand the tree and select (click on) **Sources**.



A set of blocks will appear in the BLOCKSET group. Click on the **Sine Wave** block and drag it to the workspace window (also known as model window).



Now you have established a source of your model.

NOTE: It is advisable that you save your model at some point early on so that if your PC crashes you don't loose so much time to reconstruct your model. This is among the reasons why I prefer Linux or Unix!

I am going to save this model under the filename: "simexample1". To save a model, you may click on the floppy diskette icon . or from FILE menu, select

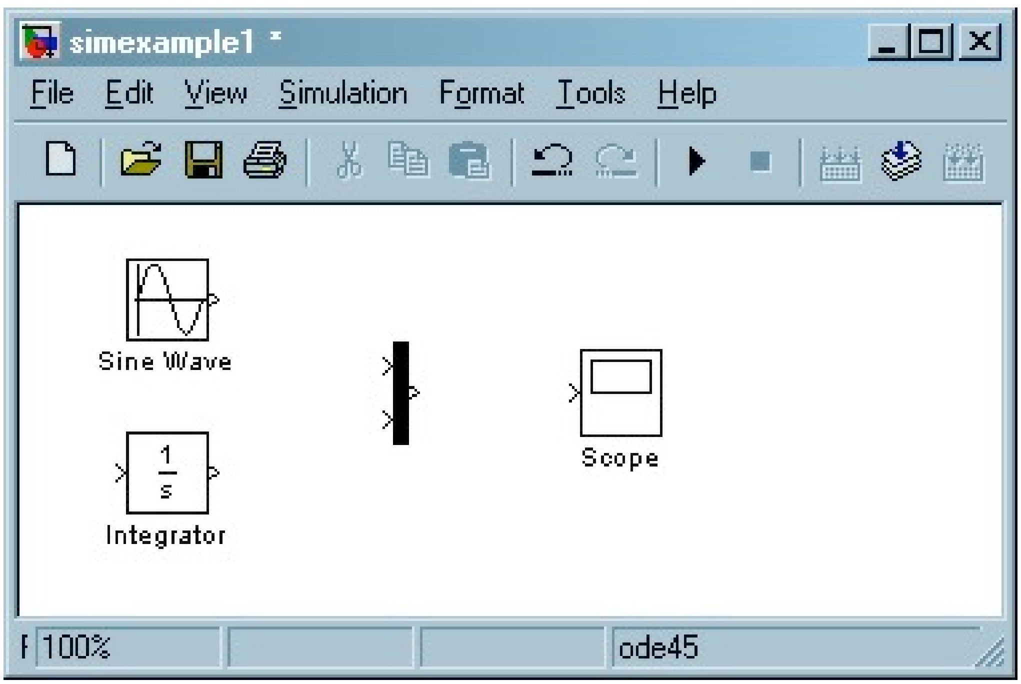
Save or CTRL+S. All Simulink model file will have an extension "**.mdl**". Simulink recognizes file with *.mdl* extension as a simulation model (similar to how MATLAB recognizes files with the extension .m as an MFile).

Continue to build your model by adding more components (or blocks) to your model window. We'll continue to add a **Scope** from **Sinks** library, an **Integrator** block from **Continuous** library, and a **Mux** block from **Signal Routing** library.

NOTE: If you wish to locate a block knowing its name, you may enter the name in the SEARCH WINDOW (at **Find** prompt) and Simulink will bring up the specified block.

To move the blocks around, simply click on it and drag it to a desired location.

Once all the blocks are dragged over to the work space should consist of the following components:



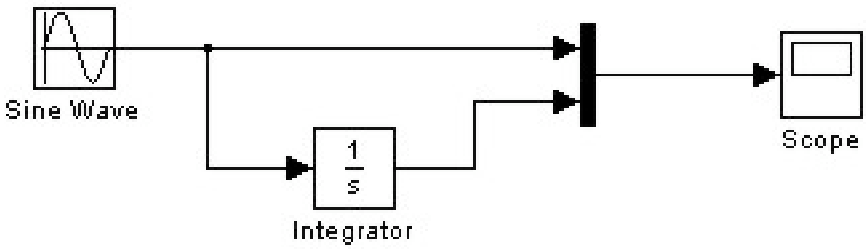
You may remove (delete) a block by simply clicking on it once to turn on the "select mode" (with four corner boxes) and use the DEL key or keys combination CTRL-X.

STEP 2: MAKING CONNECTIONS

To establish connections between the blocks, move the cursor to the output port represented by ">" sign on the block. Once placed at a port, the cursor will turn into a cross "+" enabling you to make connection between blocks.

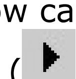
To make a connection: left-click while holding down the control key (on your keyboard) and drag from source port to a destination port.

The connected model is shown below.

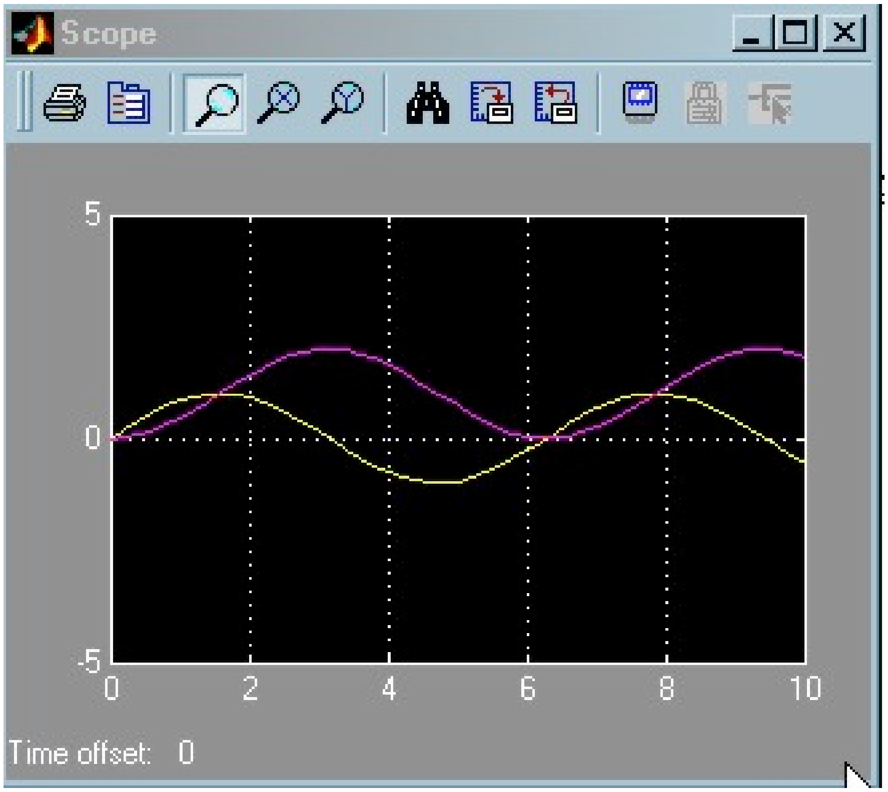


A sine signal is generated by the Sine Wave block (a source) and is displayed by the scope. The integrated sine signal is sent to scope for display along with the original signal from the source via the **Mux**, whose function is to mutiplex signals in form of scalar, vector, or matrix into a bus.

STEP 3: RUNNING SIMULATION

You now can run the simulation of the simple system above by clicking on the play button (, alternatively, you may use key sequence CTRL+T, or choose Start submenu under Simulation menu).

Double click on the Scope block to display of the scope.



To view/edit the parameters, simply double click on the block of interest.

Handling of Blocks and Lines

The table below describes the actions and the corresponding keystrokes or mouse operations (Windows versions).

Actions	Keystrokes or Mouse Actions
Copying a block from a library	Drag the block to the model window with the left button on the mouse OR use select the COPY and PASTE from EDIT menu.
Duplicating blocks in a model	Hold down the CTRL key and select the block with the left mouse drag the block to a new location.
Display block's parameters	Double click on the bloc
Flip a block	CTRL-F
Rotate a block	CTRL-R
Changing blocks' names	Click on block's label and position the cursor to desired place.
Disconnecting a block	hold down the SHIFT key and drag the block to a new location
Drawing a diagonal line	hold down the SHIFT key while dragging the mouse with the left button

Dividing a line	move the cursor to the line to where you want to create the vertex and use the left button on the mouse to drag the line while holding down the SHIFT key

Annotations

To add an annotation to your model, place the cursor at an unoccupied area in your model window and double click (left button). A small rectangular area will appear with a cursor prompting for your input.

To delete an annotation, hold down the SHIFT key while selecting the annotation, then press the DELETE or BACKSPACE key. You may also change font type and color from the FORMAT menu.

SIMULINK EXAMPLES

Example 1. Simulation of an Equation.

In this example we will use Simulink to model an equation. Let's consider

$$x(t) = A\cos(\varpi t + \varphi) \qquad (1)$$

where the displacement *x* is a function of time *t*, frequency *w*, phase angle *phi*, and amplitue *A*. In this example the values for these parameters are set as follows: frequency=5 rad/sec; phase=pi/2;A=2.

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1. From Simulink's library drag the following blocks to the Model Window

Blocks to be dragged	Location in Simulink library
Ramp	Sources
Constant	Sources
Gain	Math Operation
Sum	Math Operation
Product	Math Operation
Trigonometry Function	Math Operation
Scope	Sinks
Mux	Signal Routing

2. The next step is to connect these blocks as shown in Figure E1-1.

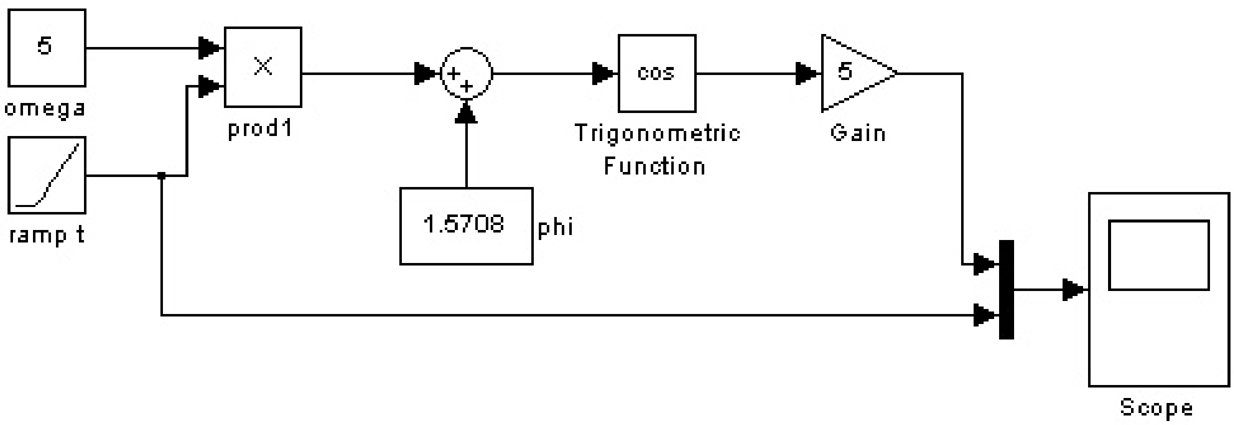
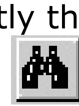


Figure E1-1

Double click on the blocks and enter the appropriate values as prompted by the pop-up dialog windows. Note that the cosine function can be selected from the pull-down menu in the pop-up window. In the arrangement shown above, the input signal (a ramp function) is to be displayed along with the output (displacement) via the use of the mux tool as demonstrated earlier in this tutorial. To view the plots, double click on the scope.

3. Make sure all blocks are connected correctly then run the simulation (CTRL+T).

You may need to select the Autoscale button  on the scope display window to obtain a better display of the plots.
You may find the sinusoidal plots to be a bit "jaggy". You may want to improve the resolution of the displayed plot by redefining the Max Step Side value ("auto" is set a default value) in Simulation Parameters window (with keystrokes CTRL+E in the model window). Just for fun, you may want to experiment with different choice of solver. ODE45 is a default choice. You are encouraged to learn more about the solver methods by checking out the help files in Matlab command window. For instance, **help ODE45** for parameters in non-stiff differential equations.

This example has demonstrated the use Simulink with built-in mathematical functions and other supporting toolboxes to simulate an equation. The same output/result can also be obtained with the following set of instructions entered in Matlab command window:

```
>> t=(0:.01:10);A=2;phi=pi/2;omega=5;
>> xt=A*cos(omega*t+phi);
>> plot(t,xt);grid
```

Example 2. Mass-Spring-Dashpot System Simulation

Consider a mass-spring-dashpot system where the spring and the dashpot are connected in parallel to the mass. The mathematical model for this system is described by

$$m\ddot{x} + c\dot{x} + kx = f(t) \qquad (2)$$

In this example I will illustrate how to use Simulink to simulate the response of this system to unit step input.

STEP 1
In Simulink, create a new model window (CTRL+N) and drag the following blocks from the Simulink library window:

Blocks to be dragged	Location in Simulink library browser
Step	Sources
Gain	Math Operation
Sum	Math Operation
Integrator	Continuous
Scope	Sinks
To Workspace	Sinks

STEP 2
By re-arranging Eqn 2 to yield an expression for the acceleration term, Eqn (2) becomes

$$\ddot{x} = \frac{1}{m}\left(f(t) - c\dot{x} - kx\right) \qquad (3)$$

Based on Eqn 3, we connect the blocks in the diagram as shown in Figure E2-2. Use CTRL+F and CTRL+R to flip and rotate the blocks as necessary (select the block first then execute the key sequence). Note that you can use CTRL+right mouse button to create branches of the connecting lines. Don't worry about the parameter values and the signs for these blocks at this point as we'll take care of this in STEP 3. Just get them connected first.

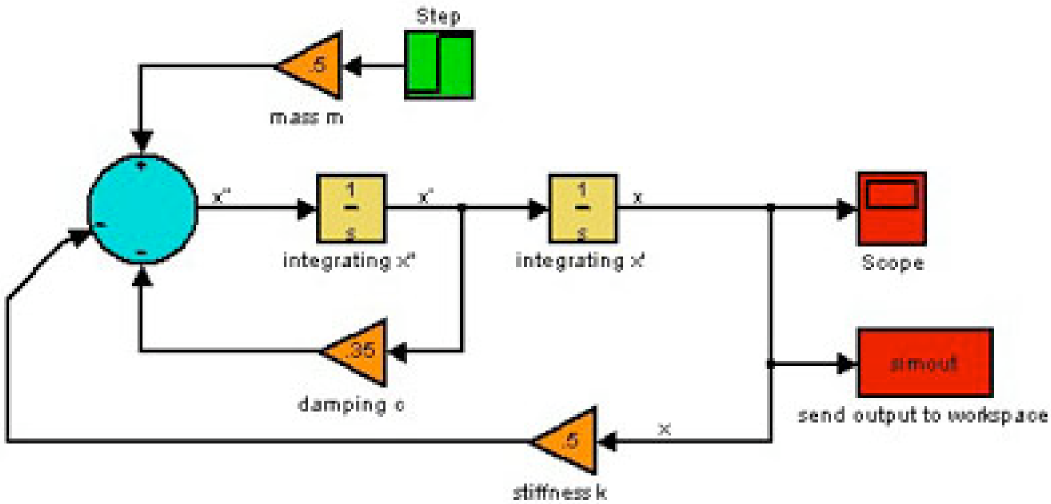


Figure E2-2

STEP 3
Enter the values of the parameters for each block. In this example, we will set m = 2.0; c=0.7; k=1. You are encouraged to try different values and observe the system's response to step input.

To show that you may obtain different form of output, I included another block (in addition to the scope block) called "simout". This block can be found in the Sinks group from the Simulink Library browser. The output from this block is used in Matlab workspace. To illustrate how this block works, I will select a name for the output called "simout" as the variable name in the block's parameter setting (double click on the "simput" block to bring up the parameter dialog window). In additon, I will need a time array from the simulation. This can be specifed as a parameter in the Simulation Parameter window (CTRL+E) under the Workspace I/O tab as shown in Figure E2-3.

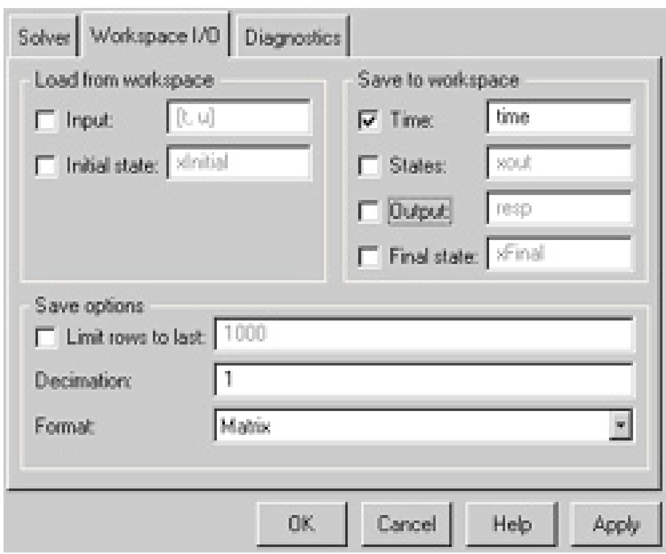
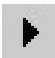


Figure E2-3

STEP 4

Run the simulation by clicking on the  button (alternately you may use keyboard command CTRL+T). The screenshot of the output from the Scope block is show in Figure E2-3.

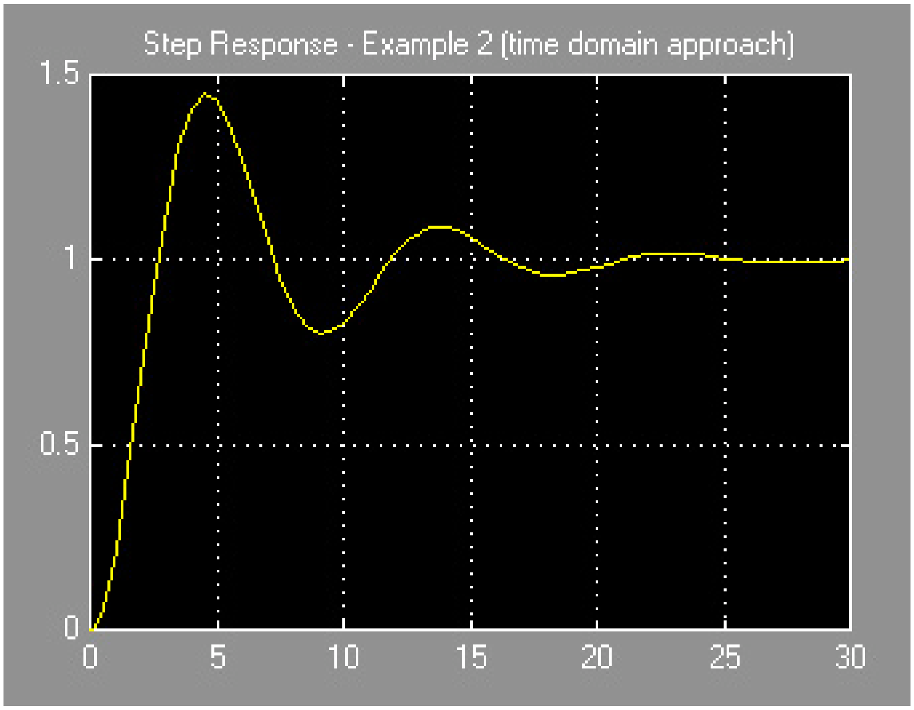


Figure E2-3

That's it! You have successfully modeled and simulated a second-order under-damped dynamic system. To exam different responses, feel free to change different values for *m*, *c*, and *k* in the gain blocks.

To see how you can use the output from the "simout" block (by the way, you may name the block whatever you wish), go to Matlab Command window and type

>> who

You should receive an echo from Matlab listing the following variables: "simout" and "time" (and perhaps others variables in the current workspace memory).

Now, you may create a plot of the system response identical to that shown in the Scope output. The command for creating this plot is:

>>plot(time,simout);grid

Note that the output format used in the example above is *matrix* type. The output sent to workspace can be used for further analysis and storage in ascii format.

Output to workspace allows more options in plot presentation and further data analysis as the arrays are in ascii format.

Example 3. Using the same system presented in Example 2, we will simulate the response using transfer function approach.

STEP 1
In a new Simulink model window, drag the following blocks from the Simulink library window: Step (from Sources), Transfer Function (from Continuous), Scope (from Sinks), and Save File to Workspace (from Sinks).

STEP 2
Arrange the blocks as shown in Figure E3-1 below.

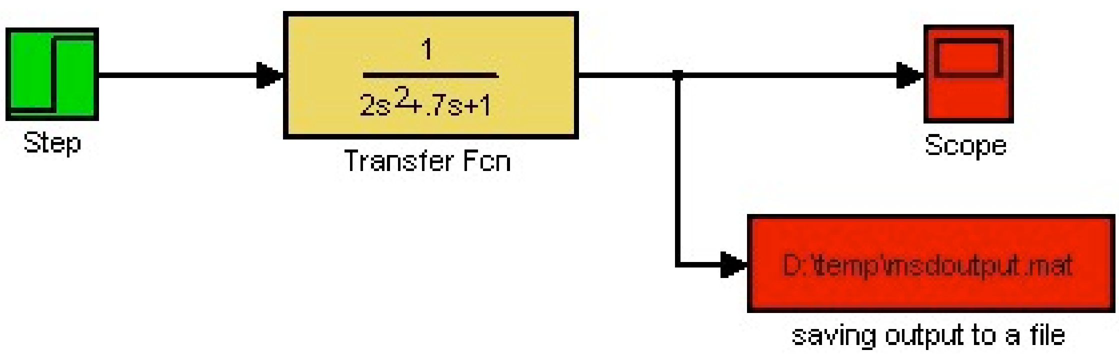


Figure E3-1

NOTE: Block's background color: Right click on the block and select the color from **Background Color** menu.

STEP 3
Entering blocks' parameters values.

We'll use the same values for *m*, *c*, and *k* as in Example 2. Double click on the transfer function to bring up the parameter dialog window and enter the values for the coefficients in the denominator as shown in Figure E3-2.

Note that the Transfer function block has a default form of first order in the denominator (s+1). You may specify different order for the numerator and the denominator by entering the coefficients associated with the polynomials.

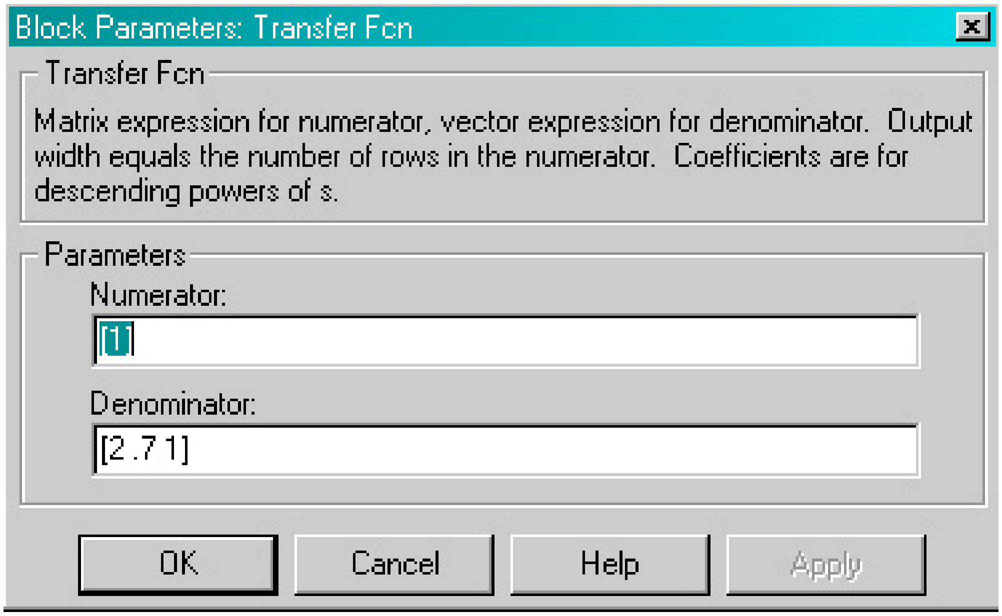


Figure E3-2

Click OK to close the dialog, Double click on the Save Output To A File block to open the dialog window as shown in Figure E3-3. In the Filename box specify the path *and* the name of the file you wish to save. The saved file will be in .MAT format (yes, it's in binary format! So don't try to read it). You will be able to load this file to Matlab workspace later on. Make sure to remember where you save the file to. In this example, I'll put the file in my D drive under "temp" directory and name the file "example3out.mat". You may choose other convenient location on your computer.

In the Variable name box, enter a name of your choice. Here I name the variable "simout".

Leave other parameters in default settings unless you wish to obtain more plot points by changing the Sample Time setting.

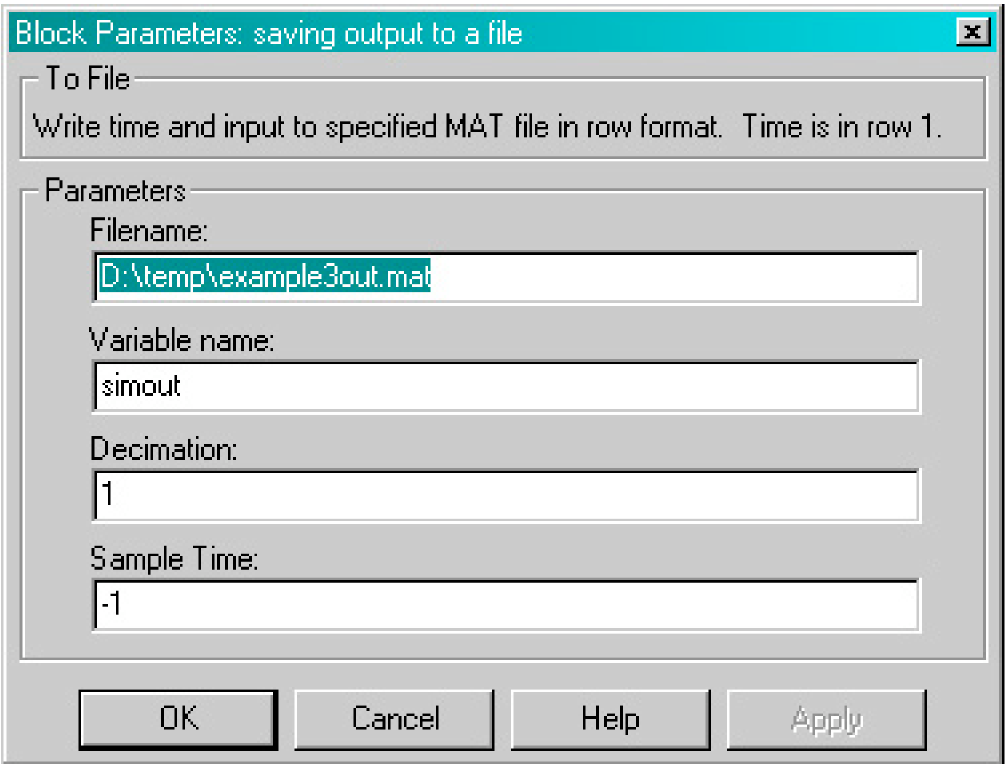


Figure E3-3

STEP 4
Run the simulation by clicking on the button (alternately you may use keyboard command CTRL+T). The screenshot of the output from the Scope block is show in Figure E3-4.

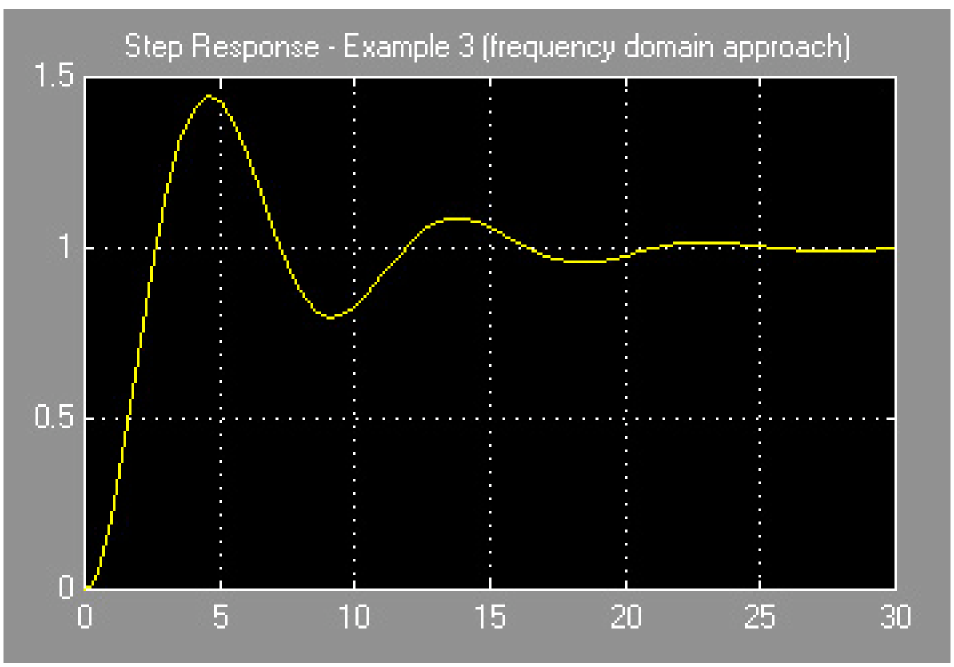


Figure E3-4

Now by comparing Figure E2-3 and Figure E3-4 you will see that the reponses are identical. No surprise here since these figures effectively represent the same system, only the latter involves fewer number of blocks!

LOADING MAT FILE

Use the **load** command to "import" the save *.mat file generated from the simulation.

Note: In this example, I set the path to the directory where the file "example3out.mat" is saved. If you do not set the path in Matlab, you have to specify the full path in the **load** command, e.g., >>load D:/temp/example3out.mat.

In Matlab command window, enter the followings:

>> load example3out

You may want to verify the loading by asking Matlab to list all of the variables in the current workspace:

>> who

If the loading is successful, you should see the variable you specified earlier listed the current workspace. In this example, Matlab echos:

Your variables are:

simout

"simout" is a 2 x *m* matrix, where m is number of columns reflecting the number of data points generated from the simulation. The first row contains the time array.

To generate a plot of the step input response from the simulation, simply use the **plot** command on "simout" matrix. For this example, the following command produces the plot shown in Figure E3-5.

>> plot(simout(1,:),simout(2,:));grid

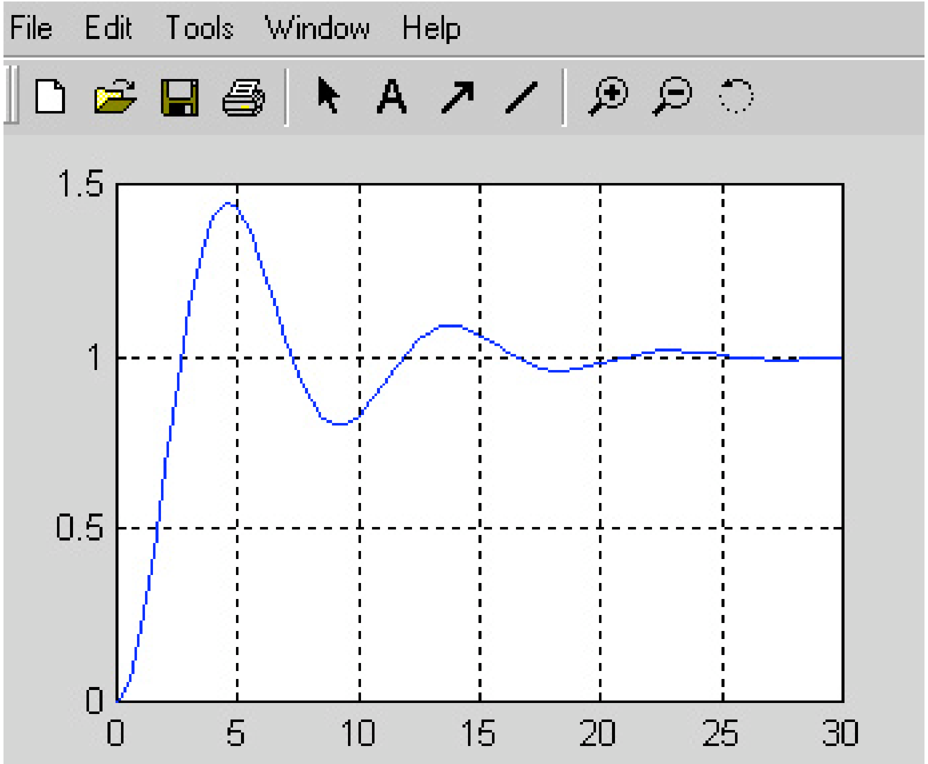


Figure E3-5

In summary, the simulations of a second-order continuous system modeled by Equation 2 have been shown using two different approaches. Different file output options from Simulink were also demonstrated.

Example 4.

In this example, we'll consider the same system as described in Example 3. But instead of using step input, we'll excite the second-order system with *impulse load.* In addition, we will simulate the response using a *state-space* model.

SOME NOTES ON IMPULSE FUNCTION

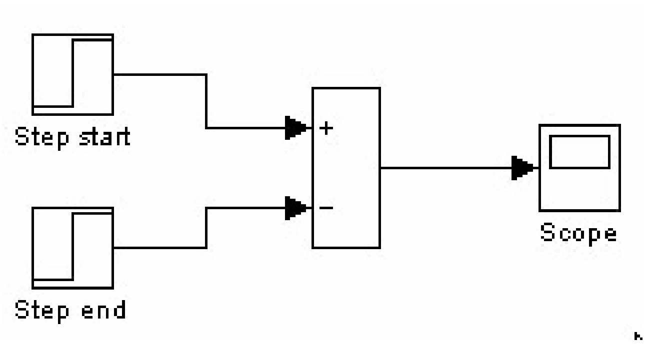
Impulse function is useful in the simulation of impact or sudden loads such as the striking of a the tip of the pole against a ball in a pool game. Unit impulse function at a desired instant a is defined by

$$\delta(t-a) = 0, \quad t \neq a$$

$$\int_{-\infty}^{\infty} \delta(t)\,dt = 1 \tag{4}$$

Equation 4 is also known as Dirac delta function.

To simulate unit impulse in Simulink, we'll use a two-block step function set as shown below.



SOME NOTES ON STATE-SPACE APPROACH

The concept of the state of the system is utilized extensively in the time-domain analysis and design of control systems. The state variables (along with the input functions) used in equations describing the dynamics of a system provide the future state of the system. Mathematically, the state of the system is described by a set of first-order differential equation in terms of state variables.

For our example, we will express the natural state variables, e.g., position and velocity, of the system in terms of the following variables:

$$x_1 = x$$
$$x_2 = \dot{x} = \frac{dx}{dt} \qquad (5)$$

where x1 represents the position and x2 represents the velocity of the system. With the new state variables defined in Eq. 5, Eq. 3 becomes

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = \frac{1}{m}\left(f - cx_2 - kx_1\right) \qquad (6)$$

In a matrix form:

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \begin{Bmatrix} 0 \\ f \end{Bmatrix} \qquad (7)$$

Equation 7 may be expressed in a more compact form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (8)$$

where **A** is known as the *system matrix* and **B** as the *input matrix*.
The output equation is expressed by

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \quad (9)$$

where

$$\mathbf{C} = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad (10)$$

and

$$\mathbf{D} = \mathbf{0} \quad (11)$$

C is called the *output matrix* and **D** is called the *direct transmittance matrix*.

MATLAB AND SIMULINK APPLICATION

In this problem we will first ask Matlab to convert the transfer function as shown in Figure E3-1 using the following command:

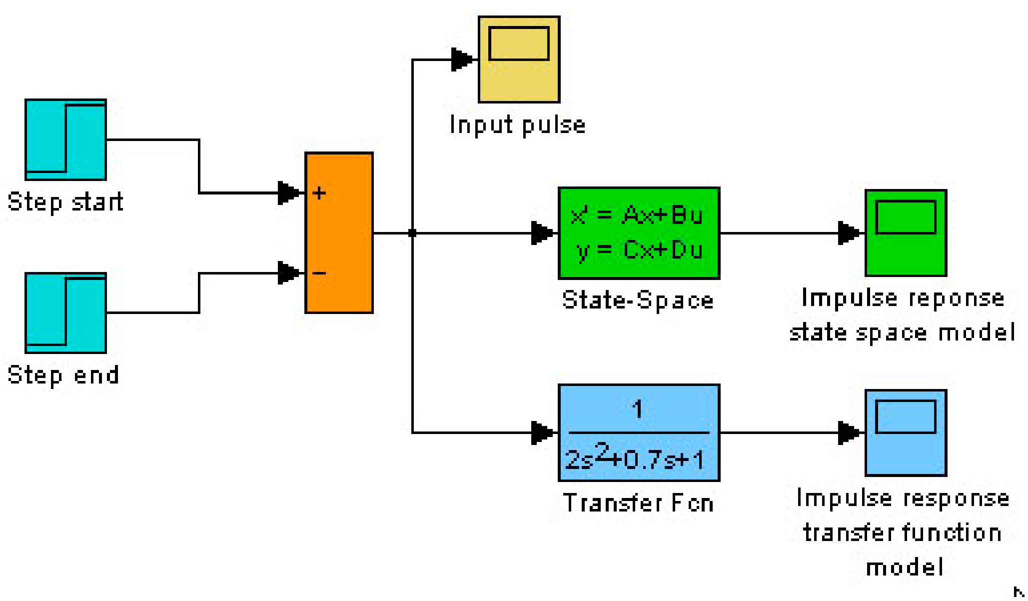
>> [A,B,C,D]=tf2ss(1,[2,0.7,1])

NOTE: You are encouraged to read the help file on **tf2ss** function (>> **help tf2ss**).

Matlab's answers:

```
A =

  -0.3500   -0.5000
   1.0000        0


B =

   1
   0


C =

        0    0.5000


D =

   0
```

Now, let's get back to SIMULINK window and construct the necessary blocks as shown below. Note that the additional blocks (Transfer Fcn and its "scope") shown in light blue are provided for comparison with the output from state-space block.



As demonstrated in previous examples, you may change the parameters in the state-space block or any other block by double clicking on it to bring up a parameter editing window.

For state space model, enter the following parameters:

A: **[-0.35 -0.5;1 0]**
B: **[1;0]**
C: **[0 0.5]**
D: **0**

Once the entries are completed, click OK button to close the panel and continue on making necessary entries for other blocks.

For the impulse simulation:

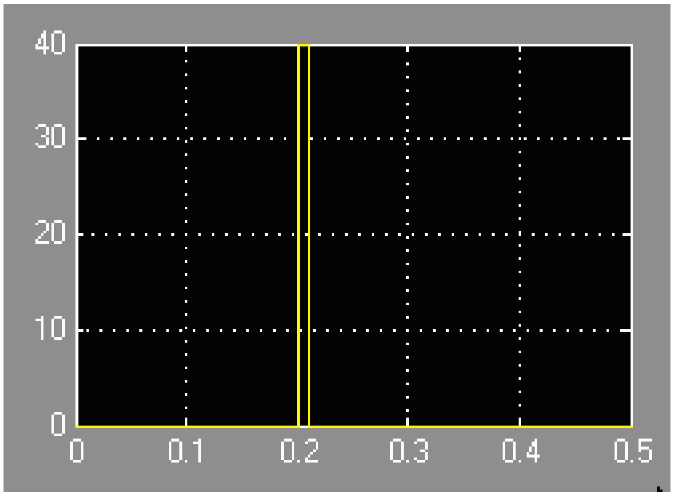
In this example, let's consider an unit impulse at 0.2 second with pulse duration of 0.01 second and a magnitude of 40. To simulate this impulse, we'll enter in the first block (Step start) the following parameters (double click on the block to bring up the parameter windows):

Step time: **0.2**
Initial value: **0**
Final value: **40**

For the second block (Step end):

Step time: **0.21**
Initial value: **0**
Final value: **40**

This will produce the following impulse:

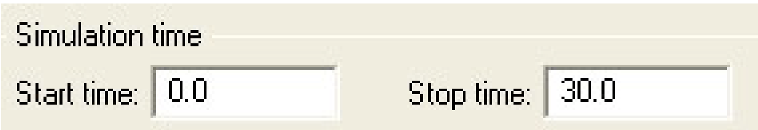


WARNING: Cares must be taken in selecting the proper pulse duration. A duration that is too short may yield computational error. A duration that is too long could misrepresent the dynamics of the modeled system.

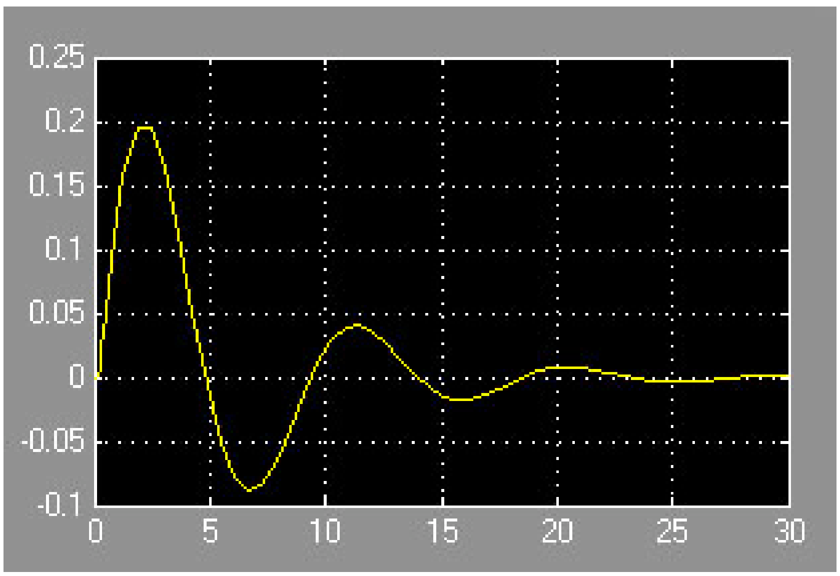
To run the simulation use keystrokes: CTRL+T or click on the button.

To change the simulation parameters and make adjustment to simulation duration, press CTRL+E or choose **Simulation parameters...** from Simulation menu.

Enter **30** for **Stop time**.



The screenshot below shows the *impulse response* of the system described by Eq. 2 with m = 2; k = 1; c=0.7



For the fun of it, you may want to make adjustments to damping ratio and/or spring stiffness parameters and run the simulation again to see how these changes would affect the response to the impulse input.

References and further readings:

1.Ogata, K., *Modern Control Engineering*, 3rd. Ed., Prentice Hall, NJ, 1997
2.Dorf, R., Bishop, R., *Modern Control Systems*, 8th Ed., Addison-Wesley, CA, 1998
3.Mathworks' documentations on Simulink